Why we need quantum gravity and why we don’t have it

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The first appearance of quantum gravity

Einstein 1916: gravitational waves $\Rightarrow$ quantum theory must modify gravity

> 696 Sitzung der physikalisch-mathematischen Klasse vom 22. Juni 1916
>
> Gleichwohl müßten die Atome zufolge der inneratomischen Elektronenbewegung nicht nur elektromagnetische, sondern auch Gravitationsenergie ausstrahlen, wenn auch in winzigem Betrage. Da dies in Wahrheit in der Natur nicht zutreffen dürfte, so scheint es, daß die Quantentheorie nicht nur die Maxwellsche Elektrodynamik, sondern auch die neue Gravitationstheorie wird modifizieren müssen.

Start of a long journey . . .

The search for quantum gravity has given us

– Gauge-fixing and ghosts (Feynman, DeWitt)

– The correct understanding of constrained systems (Dirac, Komar)

– The effective action and effective potential formalism (DeWitt)

– The Hamiltonian formulation of general relativity (Arnowitt, Deser, Misner)

– A better understanding of observables in classical general relativity (many)

– Black hole thermodynamics (Bekenstein, Hawking, and others)

– Insights into cosmology (Hartle, Hawking, and others)

– Insights into the renormalization group (Weinberg)

– Slick was to calculate QCD amplitudes (many)

– Holography, with all of its implications ('t Hooft, Susskind, Maldacena)

–Twistor theory (Penrose)

What it hasn't given us is a quantum theory of gravity

What is quantum gravity?

Requirements

- Quantum mechanical

  –usual apparatus of operators, states in a Hilbert space

  – perhaps modified at some scales

  – perhaps with issues of interpretation ("wave function of the Universe")

- Reduces to general relativity in some classical limit

- Reduces to standard quantum mechanics in some weak gravity limit

Other desirable properties

- Explains black hole thermodynamics (probably)
- Explains other “universal” properties (maybe)
  - Short distance dimensional reduction?
  - Minimum length?
- Solves some other problems (if we’re lucky)
  - Singularities
  - Cosmological constant
  - QFT divergences

Do we really need quantum gravity?

Probably. . .

- Unity of physics ("everything else is quantum")
- Problem of coupling quantum matter to classical gravity
  - Try $G_{ab} = \kappa^2 \hat{T}_{ab}$
    or $G_{ab}|\Psi\rangle = \kappa^2 \hat{T}_{ab}|\Psi\rangle$ no good: components of $\hat{T}_{ab}$ don't commute
  - "Semiclassical gravity"
    $$G_{ab} = \kappa^2 \langle\Psi|\hat{T}_{ab}|\Psi\rangle$$
    $\Rightarrow$ nonlinear quantum mechanics
  - gravitational Heisenberg microscope
  - cosmology: quantum vacuum fluctuations $\Rightarrow$ density fluctuations
    inflationary power spectrum $\sim \hbar G$
  - conversion between gravitational and nongravitational energy

- Measurement problems
  - – distances below Planck length may be unobservable in principle

    (small distance $\Rightarrow$ high energy probe; high energy in small volume $\Rightarrow$ black hole)
  - – Hawking radiation and unitarity
- Indications from elsewhere in physics
  - – universality of black hole thermodynamics
  - – deep problems that quantum gravity might solve

    (singularities in general relativity, divergences in quantum field theory)
  - – the cosmological constant problem(s)

But this is probably ultimately an experimental question (a very hard one!)

- Gravitational fields of quantum superpositions of masses
  - cantilevers/oscillators
  - interference of nanoparticles
  - entanglement induced by exchange of gravitons
- Searches for nonlinearities in quantum mechanics
- Cosmology
  - searches for primordial gravitational waves
  - quantum effects magnified by inflation
- Broken symmetries
  - broken or deformed Lorentz invariance
  - equivalence principle violations
- Other possible signals
  - generalized uncertainty principle
  - nonlocality
  - modified geometry near black hole horizons
  - nonstandard noise correlations
  - effects of fluctuating geometry on light propagation

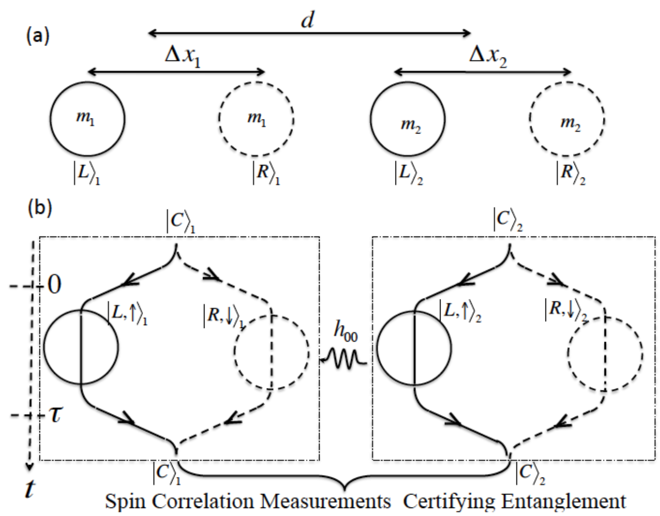


FIG. 1. **Adjacent interferometers to test the quantum nature of gravity:** (a) Two test masses held adjacently in superposition of spatially localized states $|L\rangle$ and $|R\rangle$. (b) Adjacent Stern-Gerlach interferometers in which initial motional states $|C\rangle_j$ of masses are split in a spin dependent manner to prepare states $|L,\uparrow\rangle_j + |R,\downarrow\rangle_j$ $(j = 1, 2)$. Evolution under mutual gravitational interaction for a time τ entangles the test masses by imparting appropriate phases to the components of the superposition. This entanglement can only result from the exchange of quantum mediators – if all interactions aside gravity are absent, then this must be the gravitational field (labelled h_{00} where $h_{\mu\nu}$ are weak perturbations on the flat space-time metric $\eta_{\mu\nu}$). This entanglement between test masses evidencing quantized gravity can be verified by completing each interferometer and measuring spin correlations.

Bose et al., arXiv:1707.06050 [quant-ph]

"A Spin Entanglement Witness for Quantum Gravity"

Is quantum gravity quantized general relativity?

Maybe. . .

Standard quantum field theory:

- Start with a classical theory
- “Quantize”
  - determine symplectic structure (Poisson brackets)
  - choose fundamental set of observables to promote to operators
  - $\{\bullet,\bullet\} \rightarrow \frac{1}{i\hbar}[\bullet,\bullet]$
  - define Hamiltonian, time evolution
- Impose constraints, if any
  - solve before quantizing (“reduced phase space”)
  - or impose after quantizing (“Dirac quantization”)

Procedure is not unique, but there are usually “obvious” choices

(though not so much in general relativity . . .)

Alternative:

Degrees of freedom of general relativity “emerge”

This is hard:

- How do you get consistent Lorentz invariance (only one “speed of light”)?
- How do you obtain the principle of equivalence?

  What ensures that your emergent metric couples universally?

  (Weinberg’s soft graviton theorem helps, but requires Lorentz invariance)
- What determines nonlinear interactions (strong equivalence principle)?
- How do you get diffeomorphism invariance?

  (This requires that there be no local observables!)
- How do you eliminate spin 0 and spin 1 components?
- How do you evade the Weinberg-Witten theorem?
- Where does the pregeometric theory “live”?

On the other hand. . .

– There may be fundamental limits on observability of small distances

– General relativity has no local observables

$\boxed{\textbf{Emergent gravity probably requires emergent spacetime}}$

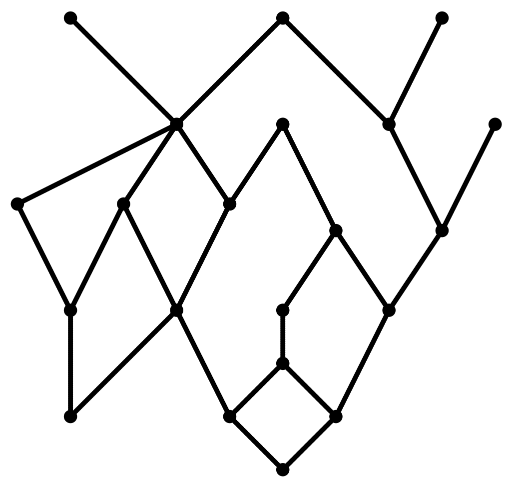
Some candidates:

– AdS/CFT correspondence

– Spacetime from entanglement

– Discrete models such as causal set theory

Causal set theory as an example



Simplest model of a spacetime with a causal structure

Build manifold-like causal sets by "sprinkling"

- Can reconstruct metric, volumes, distances, topology
- Can define combinatorial Laplacians, curvature

But most causal sets are not at all manifold-like

$\Rightarrow$ Manifold-like structure must emerge from dynamics

Why is this so hard?

Technical issues

- We don't know the general classical solution
  - If we did, could carry out covariant canonical quantization ("quantize space of classical solutions")
  - conceptual problems would be more sharply defined
  - works in 2+1 dimensions
- We don't know the renormalization group flow
  - quantum gravity could be asymptotically safe
  - conceptual problems would again be more sharply defined
- We don't know how to sum perturbation theory
  - perhaps quantum gravity is finite (DeWitt, Salam, Strathdee, Isham)

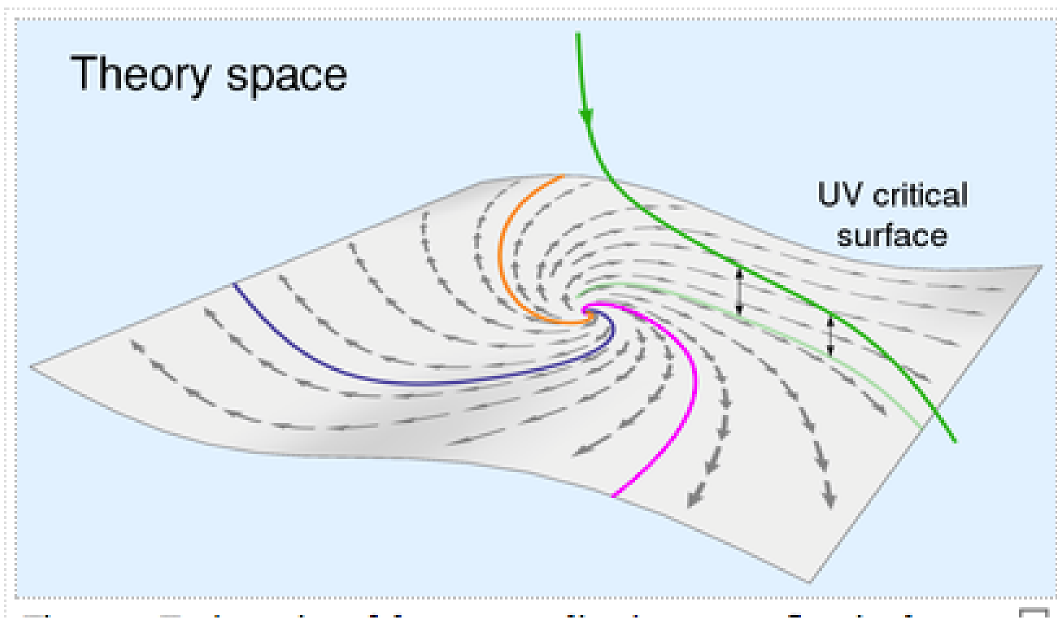
Aside: asymptotic safety

Starting point:

– in any QFT, coupling constants flow with energy/scale

– flow is in infinite-dimensional “theory space”

– parameters can “go bad,” become unphysical ⇒ “effective theory”



Andreas Nink et al. (2013), Scholarpedia, 8(7):31015

Renormalizable theory:

– some trajectories remain in a subspace
  parametrized by a small number of local coupling constants

Asymptotically safe theory:

– trajectories that reach a ‘safe” UV fixed point
  parametrized by a finite-dimensional critical surface

– infinitely many local coupling constants determined by a few parameters

If gravity is asymptotically safe, ordinary QFT might be good enough

But if any of this is right, we’re doing perturbation theory wrong

Gravity is fundamentally different at short distances

Conceptual issues

- Standard quantum theory requires fixed spacetime background
  - time needed to define inner products, normalize probabilities
  - causal structure needed to define structure of commutators

    $[A(x), B(x')] = 0$ if x and x' are spacelike separated
  - local observables needed to define basic structure of QFT
  - Hamiltonian needed to describe time evolution
- None of this works in general relativity
  - no preferred time-slicing

    (in QFT, Schrödinger evolution differs with different slicings!)
  - causal structure depends on state

    (Zych et al.: superpositions of causal order can violate Bell-like inequalities)
  - diffeomorphism invariance $\Rightarrow$ no local observables

    (boundary observables may sometimes be almost complete, but very nonlocal)
  - Hamiltonian is purely a boundary term

Observables and the reconstruction of spacetime

Torre (1993): *"Gravitational Observables and Local Symmetries"*

Diffeomorphisms "move points"

$\Rightarrow$ "points" have no physical meaning

$\Rightarrow$ no local observables in general relativity

$\Rightarrow$ must somehow reconstruct spacetime from nonlocal observables

– AdS/CFT, asymptotic approaches: observables defined "at infinity"

– Quasilocal bulk observables $\Leftrightarrow$ highly nonlocal boundary observables (e.g., "precursors" in string theory)

– reconstructed spacetime is typically only semiclassical

– asymptotically flat, de Sitter cases much more poorly understood

– nonlocal "dressing" already occurs at lowest order in G_N

– Planck scale geometry probably very different (e.g., dimensional reduction)

A few known examples in 2+1 dimensions:

typically need to know classical solutions to reconstruct local geometry

Where do we go from here?

First: we probably *don't* just tackle the conceptual problems directly

Need concrete frameworks in which to think about them

For example, fluctuations of causal structure could mean

– we need different variables (twistors? causal sets?)

– quantum mechanics breaks down for causal superpositions

– causality is hidden in the correct rules for superpositions

– causality is emergent (along with spacetime?)

Quantization programs

– string theory/gauge-gravity duality, connections with entanglement

– loop quantum gravity, spin foams, group field theory

– asymptotic safety, other QFT approaches

– lattice approaches such as causal dynamical triangulation

– discrete models such as causal set theory

– models based on noncommutative geometry

Other ways in

– quantum black holes

– lower dimensional models

– small scale structure: dimensional reduction, minimum length, . . .

– cosmology of the very early universe

– experiment/quantum gravity phenomenology

The Moral

While we may not always get paid for it,
quantum gravity physicists are probably guaranteed
lifetime employment.