Pitfalls for emergent gravity: an outsider's view

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“Emergent gravity” has become pretty popular lately

To summarize, AdS/CFT duality is an example of emergent gravity, emergent spacetime, and emergent general coordinate invariance.

– Gary Horowitz and Joe Polchinski, 2006

While classical gravity is based on space-time geometry and thus metric tensors, this structure is viewed as emergent only at large scales in canonical quantum gravity.

– Martin Bojowald, 2006

Causal dynamical triangulations at a glance: . . . a highly non-classical quantum regime around the Planck scale, and an emergent, extended background geometry on large, macroscopic scales.

– Renate Loll, 2007

Can gravity be emergent?

Trivial sense: quantum spacetime is not classical spacetime

But then

– photons are “emergent” from QED

– the hydrogen atom is “emergent” from quantum mechanics

Most people want more than that!

This may work, but dangers lurk

Here I’ll summarize some issues that any “emergent gravity” theory must address

Lorentz invariance

Maybe not too hard to get Lorentz invariance for an individual matter field

(though unitary Poincaré irreps are infinite-dimensional. . .)

But why is the maximum speed the same for every field?

Observationally: $|(c_n - c_\gamma)/c_\gamma| < 10^{-29}$ (nuclear quadrupole moments)
$|(c_e - c_\gamma)/c_\gamma| < 10^{-16}$ (cosmic γ rays)

What won't work: "They're all excitations of the same medium"

(Compare longitudinal and transverse waves in a solid)

"They're unified at some high energy/small scale"

(Even if so, RG flow may tend to separate them)

What might work: RG flow *may* unify speeds at low E (Anber, Donoghue)

(But it must be *fast*)

Start with Lorentz invariant system

(But Lorentz invariance $\Rightarrow$ metric; why not already dynamic?)

Principle of equivalence

We observe that all forms of energy couple to gravity at the same strength

Observationally: parametrize $m_{grav} = m_I + \eta \frac{E}{c^2}$

$\eta_{strong},\ \eta_{EM} < 10^{-10}$, $\eta_{KE} < 10^{-6}$

Why should this be true for emergent gravity?

What won't work: "Massless spin two gives GR"

(proofs assume universal coupling)

"The energies are all aspects of the same medium"

(even *kinetic* energy?)

What might work: Weinberg soft graviton theorem

(but requires Lorentz invariance, conserved $T^{\mu\nu}$)

Self-coupling

Equivalence principle holds for gravitational energy as well;
this requires a very special self-coupling

Observationally: $\eta_{grav} < 10^{-3}$

What won't work: "Massless spin two gives GR"
(again, proofs assume universal coupling)

What might work: Universal coupling from conservation
(but again requires Lorentz or diffeo invariance)

Aside: universality

For both Lorentz invariance and principle of equivalence,

key issue is universality

Standard general relativity:

- Spacetime structure comes first
- Symmetries $\Rightarrow$ Lorentz invariance
- Single physical geometry $\Rightarrow$ PoE

If spacetime and matter emerge simultaneously, or matter comes first,

universality seems much more artificial

Diffeomorphism invariance: version 1

Slightly tricky: every theory is coordinate invariant

real issue is absence/decoupling of background structures

Emergent gravity necessarily has some sort of background structure;
Can it decouple for low-energy observers?

In particular:

- Is “pre-emergent” structure dynamical?
- If not, where does time come from?
  (and how are wave functions normalized?)
- If so, is “pre-emergent” time related to “emergent” time?
  (and how can this be reconciled with emergent diffeo invariance?)
- Are some “coordinate singularities” real (Volovik, Klinkhamer)?

Some dangers

"Every theory is coordinate invariant"... but not necessarily trivially so

E.g.: Hořava-Lifshitz gravity:

Choose preferred foliation; action depends on extrinsic curvature K_{ab}

$\Rightarrow$ not *manifestly* diffeomorphism-invariant

To covariantize: new scalar field ("time function") T, constant on slices

$$n_a = \frac{\partial_a T}{\left(g^{bc}\partial_b T \partial_c T\right)^{1/2}}, \qquad K_{ab} = \nabla_a n_b$$

– action now nonpolynomial in T

– need to fine-tune coefficients to get Hořava action at given order

What happens in an emergent theory?

Diffeomorphism invariance: version 2

Diffeomorphism invariance $\Rightarrow$ four first class constraints

$\Rightarrow$ eight degrees of freedom removed

$\Rightarrow$ only massless spin 2 degrees of freedom

How do you decouple spin 0 and 1 degrees of freedom in an emergent theory?

What might work: Emergent gauge invariance (but this risks being circular)

Vainshtein mechanism (how universal?)

Should also check constraint algebra (anomalies?)

Aside: emergent diffeomorphism invariance is tricky

Transformation of the metric:

$$\delta_\xi g_{ab} = g_{ac}\partial_b \xi^c + g_{bc}\partial_a \xi^c + \xi^c \partial_c g_{ab}$$

Last term is crucial:

unlike gauge transformations, diffeomorphisms “move points”

But at linear order around a flat background ($g_{ab} = \eta_{ab} + h_{ab}$)

$$\delta_\xi h_{ab} \approx \eta_{ac}\partial_b \xi^c + \eta_{bc}\partial_a \xi^c$$

To see emergent diffeomorphism invariance, one must either

– go beyond linear order

– expand around an arbitrary background

Where does emergent theory live?

The genie is out of the bottle:

Now that we know spacetime can be dynamical,
we can no longer simply assume a flat background

What won't work: "Flat background is simplest"

(Even if no initial action for metric, one will be induced;
$R_{abcd} = 0$ is a real field equation, must be *derived*)

What might work: Background dynamics doesn't include Einstein-Hilbert action

(Sakharov-style induced gravity)

No background that has the characteristics of a geometry

(truly emergent spacetime)

Connection to diffeo invariance v1: where does time come from?

Aside: the Weinberg-Witten theorem

Theorem: Suppose a theory:

– can be defined perturbatively around a flat background
– has a conserved, Lorentz covariant stress-energy tensor in that background

Then that theory can contain no massless field –
elementary or composite, fundamental or emergent – with spin $j > 1$

GR escapes: no covariant, conserved gravitational stress-energy tensor

Same must be true for any emergent theory (barring another loophole)

Nonlocality?

The usual problems of quantum gravity

An emergent theory does not automatically escape
the usual problems of quantum gravity

For example: “problem of observables”

No local diffeomorphism-invariant observables in GR

If emergent theory is diffeo-invariant, same issue

Even if not, Weinberg-Witten $\Rightarrow$ no local conserved energy

For example: “problem of time”

If background has no preferred time, usual problems

If background has preferred time, no Hamiltonian constraint

Note: no conserved energy (Weinberg-Witten)

$\Rightarrow$ no preferred time translation invariance

Aside: what about black holes?

Black hole thermodynamics $\Rightarrow$ lots of microscopic degrees of freedom

(not classical gravitational hair)

Sign of emergence?

- Normal field theory: boundary conditions $\Rightarrow$ fewer degrees of freedom
- Gauge field theory: boundary conditions $\Rightarrow$ more degrees of freedom

Horizon boundary conditions $\Rightarrow$ new "would-be diffeo" degrees of freedom

Number determined by symmetry breaking (analogous to Goldstone mechanism)

So we learn very little about underlying degrees of freedom. . .

These problems all interact. . .

A good solution to any of these might help with others

For example:

Lorentz invariance $\Rightarrow$ Weinberg soft graviton theorem

$\Rightarrow$ equivalence principle

But the converse also holds:

No equivalence principle $\Rightarrow$ Weinberg soft graviton theorem must fail

$\Rightarrow$ no Lorentz invariance

What does all this mean for emergent gravity?

I don’t know. . . you tell me!