Space, time, and spacetime, part II: emergent spacetime in quantum theories of gravity

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Recap of first part

- introduced the problem of whether spacetime has an independent existence
- presented the different answers of Newton, Leibniz, Mach, and general relativity (GR)
- ended with GR:
  - Wheeler: mass tells spacetime how to curve (and spacetime mass how to move)
  - $\Rightarrow$ What is it that is being curved?
  - hole argument seemed to favor relationism
  - spacetime structuralism: spacetime is real, but is complex of spatiotemporally related events rather than inert container
- discussion so far did not include quantum theory
Organization of talk

1. How space and time evaporate in quantum gravity
   - The problem of time and the dissolution of spacetime
   - Introducing loop quantum gravity

2. How emergence of spacetime might work
   - Re-emergence of spacetime
   - Conclusion
General relativity (GR) can’t be the last word: quantum effects must be taken into consideration in early universe and evolution of black holes

⇒ must find theory that combines quantum effects and (strong) gravitational fields

⇒ need a quantum theory of gravity

Various approaches, string theory and loop quantum gravity (LQG) most visible

Source: http://blog.michaelkcooke.com/
A road to unification for some

Source: http://sciencereview.berkeley.edu/articleex.php?issue=18&article=features_04_quantum
The two main rivals: (1) String theory

- starts out from the standard model of particle physics, a quantum thy
- sense in which gravity can be said to be “naturally” included; details far from clear
- originally developed assuming a spacetime background (as inert container), but questions have been raised about it (dualities: physically equivalent string theories use different spacetimes)
- outstanding problems: “landscape problem”, repeated false predictions of “supersymmetric particles”
How space and time evaporate in quantum gravity
How emergence of spacetime might work

The two main rivals: (2) Loop quantum gravity (LQG)

- starts out from GR, incorporates its core lessons (dynamical spacetime)
- tries to incorporate quantum effects by “quantizing” GR
- outstanding problems: (1) problem of time/ill-understood dynamics, (2) classical limit/emergence of spacetime from basic quantum structure

Question: what is the fate of spacetime in quantum gravity?
What, if anything, is “quantum spacetime”?

Thesis

Many approaches to quantum gravity (QG) suggest or imply that space and time do not exist at the most fundamental ontological level. Thus deprived of their former status as part of the fundamental furniture of the world, together, perhaps, with quarks and leptons, they merely “emerge” from the deeper physics that does not rely on, or even permit, their (fundamental) existence, rather like tables and chairs.
Parmenides’s revenge

- Parmenides: fundamentally, world is an immutable, unchanging, uncreated, indestructible whole
- changes are merely apparent, what exists in reality is temporally “frozen”
- Surprisingly, this brave hypothesis receives support from (Hamiltonian) GR and the quantum theories of gravity based on it!

Parmenides of Elea (ca. 540-480 BCE)
In relating the mathematical formalism of a physical theory to the world, the question arises whether mathematically distinct “models” truly represent physically distinct possible scenarios.

We have seen this: hole argument in GR; think also of freedom to use different coordinate systems to describe physical situation.

Transformations that map one model to a mathematically distinct but physically identical model are called **gauge symmetries**.

As it turns out, in a particular (Hamiltonian) formulation of GR the reparametrization of (space-)time is a gauge symmetry.

IOW, **change** is purely a redundancy of the representation!

This means that all genuinely physical magnitudes are constants of motion, i.e. **they don’t change over time**.
How space and time evaporate in quantum gravity
How emergence of spacetime might work
The problem of time and the dissolution of spacetime
Introducing loop quantum gravity

Parmenides’s revenge

Parmenides strikes back: there is no change at the most fundamental level!

This formulation of GR can’t be brushed aside easily (but it can somewhat): foundation for one of the most important approaches to formulating a QTG.

Sic transit gloria temporis.
How space and time evaporate in quantum gravity
How emergence of spacetime might work
The problem of time and the dissolution of spacetime
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Source: http://people.ischool.berkeley.edu/~nunberg/change.html
In string theory as well as in loop quantum gravity (LQG) (and other approaches to QG), indications are coalescing that space and time are no longer fundamental entities as classically conceived (substantivaly or relationally), but merely “emergent” phenomena that arise from the basic physics.

In particular (as in LQG): no continuous spacetime, discrete structure

In the language of physics: spt theories such as GR as “effective” and spacetime itself “emergent”, much like thermodynamics is an effective theory and temperature is emergent, as it is built up from the collective behaviour of gas molecules.

Unlike the fact that temperature is emergent, the idea that the universe is not in space and time shocks our very idea of physical existence as profoundly as any scientific revolution.
Lee Smolin

“I will discuss seven generic consequences [of the main postulates of a vast class of quantum theories of gravity, including LQG]. (i) Discreteness of quantum geometry and ultraviolet finiteness... [Discreteness is] well established.” (549)

philosophers have only just started to study the implications of QG and the disappearance of spacetime

Funded project with Nick Huggett (University of Illinois, Chicago): “Emergent Spacetime in Quantum Theories of Gravity”

joint framework, Huggett studies string theory, Wüthrich does LQG

The remainder of this talk focuses on my contribution to this project.
On the conceptual foundations of LQG

- LQG attempts to transpose the central lesson of GR into a quantum theory

- central innovation of GR: spacetime isn’t fixed “background,” which determined the inertial forces, but a dynamical structure which interacts with matter

- LQG is based on a reformulation of GR as a so-called “Hamiltonian system,” which re-interprets spacetimes as (3 + 1)-dimensional (instead of 4-dim), with constraints

  \[ \Rightarrow \] forces a “foliation” of spacetime by an equivalence relation in 3-dim “spatial” hypersurfaces, parametrized by 1-dim “time”

- 3-dim “space” considered as dynamical system which evolves over “time”; 3-dim hypersurfaces represent (instantaneous) states of dynamical theory
How space and time evaporate in quantum gravity

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Source: http://sciencereview.berkeley.edu/articleex.php?issue=18&article=features_04_quantum
But hasn’t relativity taught us that no one shall put asunder what Minkowski has joined together, i.e. that no dissection of spacetime into space and time can be privileged?

⇒ True, but in order to make up for this, the Hamiltonian systems is subject to “constraints,” which mathematically “undoes” the dissection.

Limitations of approach: not all models of GR are considered (only vacuum models, non-time-travel models).

(Dynamical equations play somewhat different role, as we’ll see; matters of interpretation and observation will arise)
Quantized space

- "spin network states": quantum states of the gravitational field; physical space is supposed to be quantum superposition of spin network states
- These spin network states can be represented by **labelled graphs** embedded in some space:
Quantized space: spin network states

(To be precise: we should really be looking at abstract graphs and equivalence classes of spin network states, as how the spin networks are embedded in manifold is physically irrelevant.)

“spin”-representations on vertices (represented by nodes in graph) correspond to “size” of the “space atoms”, those on edges correspond to “size” of the surface connecting adjacent “chunks” of space

⇒ space is “granular” at Planck scale

⇒ The smooth space of the classical theory is supplanted by a discrete quantum structure.

⇒ Space, as it figures in our conceptions of the world, is emergent phenomenon.
The problem of time in canonical QG

- Dynamics of theory is given by Hamiltonian operator $\hat{H}$, which is defined on space of spin network states, via the equation
  \[ \hat{H}\ket{\psi} = 0. \]

  This is the so-called Wheeler-DeWitt equation.

- Problem of time becomes unavoidable in canonical QG

- Indication: Unlike in the Schrödinger equation of the usual quantum thys,
  \[ \hat{H}\ket{\psi} = i\hbar \frac{\partial}{\partial t}\ket{\psi}, \]

  the RHS of the Wheeler-DeWitt equation vanishes.

- Time is part of the physical system which is quantized

  $\Rightarrow$ no external fiducial time with respect to which the dynamics could “play out”

- (analogue gauge symmetries are present)
quantization: “context of discovery”

taking the classical limit: “context of (partial) justification”

⇒ understanding how (classical) spt re-emerges is not only important to save the appearances, accommodate common sense etc, but also a methodologically central part of the enterprise of QG (to retrieve GR as limit).
The present situation regarding emergence

- mapping from set of quantum states to set of classical spacetimes **not one-to-one**, but many-to-one and for some quantum sets, there’s no classical analogue
- so far: classical limit of LQG has defied understanding
  \[\Rightarrow\] role for philosophers: explore landscape, map possibilities, bring lit on emergence/reduction to bear on issue

(Complete?) bibliography of phil lit on emergence in context of QG:

The Butterfield-Isham scheme

Ultimately, full analysis will depend on full articulation of theory; in the meantime, limit focus to “kinematical level”, which describes the quantum structure of “space” (⇒ don’t have to deal with problem of time, unlike Butterfield and Isham)

My job: apply concepts from Butterfield and Isham for emergence of full spacetime (rather than just time)

Butterfield and Isham (1999) identify three types of reductive relations between theories:

1. Definitional extension
2. Supervenience
3. Emergence

first two won’t work, let’s focus on third...
The general scheme of relating the theories

**Definition (Emergence)**

For Butterfield and Isham, a theory $T_1$ *emerges* from another theory $T_2$ iff there exists either a limiting or an approximating procedure to relate the two theories (or a combination of the two).

**Definition (Limiting procedure)**

A *limiting procedure* is taking the mathematical limit of some physically relevant parameters, in general in a particular order, of the underlying theory in order to arrive at the emergent theory.

⇒ won’t work, at least not alone, bc of technical problems (maximal loop density; Rovelli: “more loops give more size, not a better approximation to a given [classical] geometry” (2004, §6.7.1)), conceptual problems (superpositions don’t vanish)
Definition (Approximating procedure)

An approximating procedure designates the process of either neglecting some physical magnitudes, and justifying such neglect, or selecting a proper subset of states in the state space of the approximating theory, and justifying such selection, or both, in order to arrive at a theory whose values of physical quantities remain sufficiently close to those of the theory to be approximated.

- “Approximandum”: not full GR, but only those models that were initially considered
- How does selection of subset of states happen? Is there a mechanism that would “drive the system” to the right states?
- ⇒ a host of issues known from traditional problem of understanding relation quantum to classical mechanics arise
- Candidate mechanism: decoherence; but usually understood as resulting from a system’s interaction with its “environment”
- How can there be an environment if the system at stake is spacetime (all of it)?
How space and time evaporate in quantum gravity
How emergence of spacetime might work
Re-emergence of spacetime

Conclusion

Limiting procedure
Approximating procedure

\( \langle \mathcal{H}, \{\hat{O}\} \rangle \)

Approximating procedure

Limiting procedure
Thesis (Or should I say “Promissory Note”?)

At least to the extent to which LQG is a consistent theory, (a close cousin of) GR can be seen to emerge from LQG if a delicately chosen ordered combination of approximations and limiting procedures is applied.

I have sketched how this can work, and will continue to work out its details in the future; but for now, I am running out of steam (and time...), so let me conclude:
I have shown how classical space and time “disappear” in modern physics and in QG, and how they might be seen to re-emerge from the fundamental, non-spatiotemporal structure.

This is relevant and interesting for at least two reasons:

1. important foundational questions concerning the interpretation of, and the relation between, theories are addressed, which can lead to conceptual clarification of the foundations of physics

2. relevant consequences for specifically philosophical (particularly metaphysical) issues are studied ⇒ QG is fertile ground for the metaphysician