Causality and dynamical spacetime

Vincent Lam

University of Lausanne

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Introduction

- Standard approaches to causation crucially involves spatio-temporal aspects.
- The theory of general relativity fundamentally modifies our understanding of spacetime.

Aim

What are the implications of general relativity (and beyond) for the standard approaches to causation?

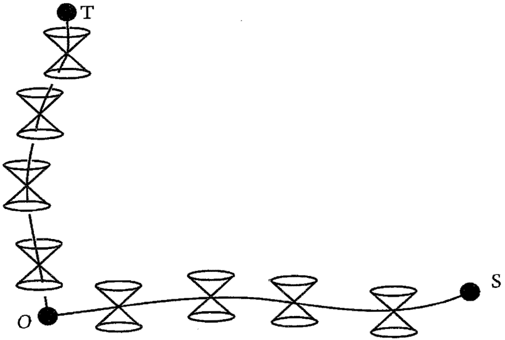
Outline

- General relativity: dynamical spacetime
- Process theory of causation and dynamical spacetime.
- Causal powers and dynamical spacetime.
- Counterfactuals and dynamical spacetime.
- A note on quantum gravity.

General relativity: dynamical spacetime

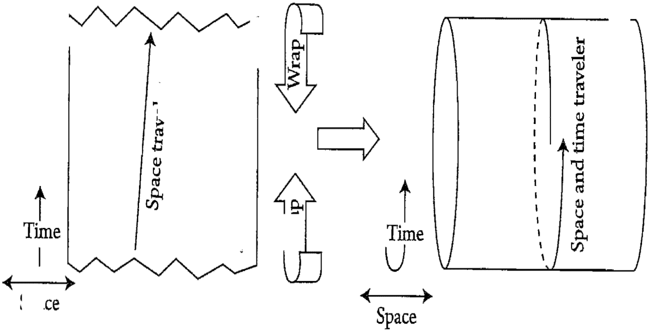
- Spacetime represented by (M, g_{ab}), where g_{ab} satisfies Einstein field equations $G_{ab}[g_{ab}] = \kappa T_{ab}$.
- Geometry and gravitation aspects of the same dynamical structure.
- No fixed spacetime background.
- Local light cone ('causal') structure $\sim$ 'necessary' conditions for causal connectibility.
- Non-trivial global spacetime topologies.

Causal connectibility



from Norton (2015)

Non-trivial global topology



from Norton (2015)

Conserved quantity theory of causation (Salmon, Dowe, ...)

Empirical analysis of causation in terms of objective (fundamental) physical features of the actual world.

- **Causal interaction**: intersection of worldlines that involves an exchange of a conserved quantity.
- **Causal process**: worldline of an object that possesses a conserved quantity.
- Candidate: (mass-)energy (see Russell, Reichenbach, ...)
- There is a **causal relation** between two events iff they are linked by a set of causal processes and causal interactions.

No energy conservation in dynamical spacetime

- Conserved energy $\sim$ Noether charge associated with temporal translation invariance.
- Only if the metric 'does not change' (along the Killing flow, i.e. stationary spacetime).
- Non-dynamical (background) structure.

!! No such structure if the metric is (truly) dynamical ('evolving in time').

!! No energy conservation because of the dynamical spacetime structure.

  - Although relevant and useful in many (idealized) physical situations, generic GR spacetimes are not stationary.
  - No gravitational energy localization (with respect to what?)—no unique local gravitational energy density.

GW150914

- LIGO detectors, 14 September 2015, 9:50 45s: first observation of gravitational waves.
- Merging of two black holes with masses of $36M_\odot$ and $29M_\odot$ into a $62M_\odot$ final black hole $\rightsquigarrow$ $3M_\odot$ radiated in gravitational waves.
- Cause: binary black hole merger.
- Effect: oscillatory deformations of the arms of the interferometer.
- However, strictly speaking, not a causal process in the sense of the CQ theory (no 'propagation' of conserved gravitational energy 'along the way').

Biting the bullet

"[. . .] it is possible to view energy loss by a gravity wave source as genuine loss, without insisting that the energy is still around somewhere. (The point that emerges from the received view is that we cannot say anything about *where* such energy has gone to, even if we wanted to.) Similarly, energy gain in a gravity wave detector could be thought of as genuine gain, without our having to say that the energy existed somewhere beforehand. Such a perspective seems to strain our general cause-effect intuitions by positing a cause-effect relationship without an intermediary carrier."

Hoefer (2000, 196)

Consequences for the conserved quantity theory of causation

- In general, the distinctive characterization of ‘causal’ for interactions and processes loses its fundamental meaning and there is no unambiguous fact of the matter as to whether two events are causally related or not.
- Still relevant for idealized (highly symmetric, e.g. FLRW cosmology) cases, and if one considers (ad hoc) non-dynamical background structures (e.g. at infinity for isolated systems).

Causal powers (Schoemaker, Mumford, Bird, . . .)

- Fundamental physical properties understood in terms of irreducible powers or dispositions to produce certain effects.
  - Causation (**'locally'**) anchored in the very nature of (fundamental physical) properties.
- Non-Humean metaphysics of causation: necessary causal connections.
- Causation as (ontological) production (causes as ontological ground for the effects).
  - Ultimately, the idea is this: the whole spacetime distribution of fundamental particular facts (e.g. the Humean mosaic) is **produced** by the fundamental dispositional properties (causal powers) instantiated by the intial state of the world.
  - 'Advantage': the whole spacetime distribution of fundamental particular facts need not be taken as primitive.

Causal powers and closed timelike curves

- Dynamical spacetimes of general relativity allow for closed timelike (lightlike) curves (CTCs).
- Difficulty for the theory of causal powers: self-causation or self-production on a CTC?
- Possible move: exclude spacetimes with CTCs by imposing global topological constraints.

Hierarchy of 'causality conditions'

Chronological: no closed timelike curves

$\Uparrow$

Causal: no closed causal curves

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Distinguishing: two different space-time points have different chronological futures (pasts)

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Strongly causal: no 'almost closed' curves

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Stably causal: no slight perturbation of g_{ab} (slight 'opening out' of the local light cones) produces closed timelike curves

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...

Hierarchy of ‘causality conditions’

. . .

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Stably causal $\Leftrightarrow$ *global (or cosmic) time:* strictly increasing function(s) along (future) timelike curves

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Causally continuous

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Causally simple

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Globally hyperbolic: the topology of M **is** $\mathbb{R} \times \Sigma$

Causal powers in dynamical spacetime: global constaints

- A ‘well-posed’ initial value (Cauchy) formulation of GR requires global hyperbolicity (global topological constraint).
- Natural (necessary) framework for causal powers.
- Although it does not want the whole Humean mosaic as primitive, the theory of causal powers has to acknowledge global features of spacetime.
- Whether an event A is the cause of an event B not only depend on the nature (causal power) of A (which, let's assume, is to produce B), but also on global properties of the whole spacetime structure.
- Tension with the non-Humean, singularist spirit of the causal power/dispositionalist approach to causation.

Counterfactuals in dynamical spacetime

Curiel, E. (2015). If Metrical Structure Were Not Dynamical, Counterfactuals in General Relativity Would Be Easy. *arXiv:1509.03866*

- Counterfactual analysis requires fixed, non-dynamical (spacetime) background for comparison.
- No such background in GR $\rightsquigarrow$ counterfactual changes may be ambiguous.
- Ex.: what would happen to the trajectories of the planets if one were to remove the sun?
  - Within Newtonian gravitational theory, unambiguous answer with respect to the same Newtonian spacetime background.
  - Strictly speaking, no such unambiguous answer in GR.
  - No unique limit to the continuously varying family of Schwarzschild spacetimes as the central mass goes to zero.
- The GR metric is not fully determined by the distribution of mass-energy.
  - Several (non-trivial) vacuum solutions.

Quantum gravity: no spacetime?

Many research programs in quantum gravity suggest that space and time may not be part of their fundamental ontology. This raises 2 sets of conceptual worries (at least):

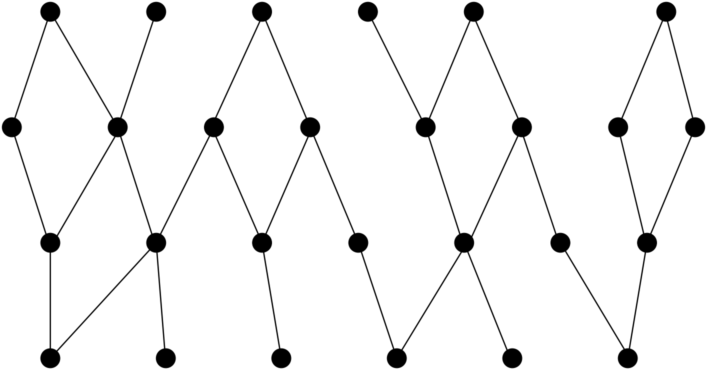
- *Threat of empirical incoherence*: empirical evidence for a physical theory ultimately always involves some physical objects having a certain position in space at a certain time.
- *Physical ontology without space and time*: what makes such an ontology without space and time physical in contrast to an ontology of abstract, mathematical entities?

Causation in quantum gravity: causal set theory

The fundamentally discrete structure consists of a partially ordered set of elementary events. The ordering is essentially causal.

- **Theorem in GR**: given causal structure and volume information, one finds dimension, topology, differential structure, and metric of manifold (Hawking et al. 1976, Malament 1977)
- In other words, causal structure determines geometry (but not 'size')
- Motivates causal set approach: the fundamental structure is a **causal set**.
- At the level described by CST, there are causal relations, but no spacetime.
  - No dimensionality, no topological or metric structure.

A causal set:



Hasse diagram: dots represent elements of C, lines relations not implied by reflexivity and transitivity.

Causal functionalism

"And the thing to keep in mind is that what it is to be a table or a chair or a building or a person is—at the end of the day—*to occupy a certain location in the causal map of the world*. The thing to keep in mind is that the production of geometrical appearances is—at the end of the day—a matter of *dynamics*." (127)

David Z. Albert. *After Physics*. Cambridge, MA: Harvard University Press (2015).

Causation in quantum gravity: functional emergence of spacetime

- The strategy is to focus on the **spacetime functions**—that is, on the spatio-temporal or **'spacetime-like' roles**—the QG entities may instantiate in certain circumstances.
- Relevant spacetime features (e.g. for empirical evidence) understood in terms of their functional role (which need not be causal).
  - Intuition: spacetime need not be fully recovered—to emerge—in some strong ontological sense in order to provide a ground for empirical evidence.
- What needs to be done: to show in concrete cases to what extent QG entities can play the right sort of functional roles.

Thank you for your attention!

vincent.lam@unil.ch