

Spacetime Substantivalism and Quantum Gravity

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Motivation and Aim

«I find the thought that relations might be ontologically fundamental disquieting, but I admit that could change were the universe shown to require them. Until then, I shall hold out for a universe with nonrelational truthmakers for irreducible relational truths. If you disagree, if you are keen to have relations, then the ball is in your court. It is no good simply announcing the existence of relations alongside substances and properties. It is up to you to provide a tangible ontological story. From where I stand, the prospects do not look promising..»

J. Heil – *The Universe as We Find It*. OUP, 2012 (p.150).

Motivation and Aim

- I will argue that the above position is hardly tenable in the context of modern spacetime theories.
- I will show that, even theories where matter emerges from fundamental spatiotemporal degrees of freedom, still call for irreducibly relational features of the world.
- I will explain why recent developments in quantum gravity seem to strengthen the “metaphysical need” for fundamental relations.

Summary

- General Relativity.
- Wheeler's Geometrodynamics.
- Kaluza-Klein Gravity.
- Composite Preons in (Loop) Quantum Gravity.

General Relativity

$$R_{ij} - \frac{1}{2}g_{ij}R = \frac{8\pi G}{c^4}T_{ij}$$

«Space acts on matter, telling it how to move. In turn, matter reacts back on space, telling it how to curve.»

C.W. Misner, K.S. Thorne, J.A. Wheeler – *Gravitation*. Freeman & Co., 1973 (p.5).

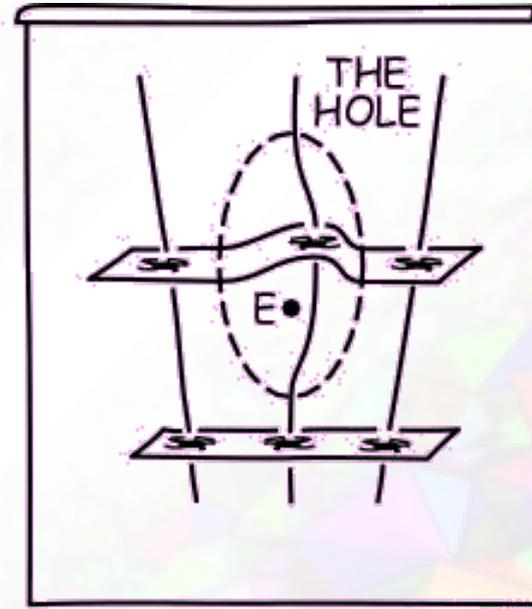
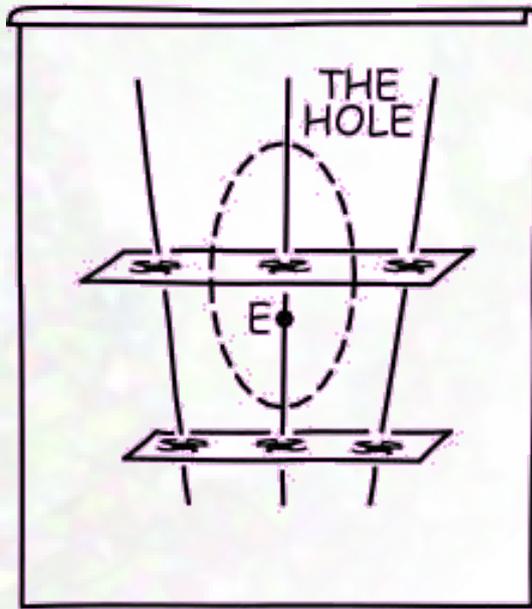
General Relativity

$$R_{ij} = 0$$

«[...] we may say that according to general theory of relativity space is endowed with physical qualities [...]»

A. Einstein – Ether and the Theory of Relativity. *Sidelights on General Relativity* Dover, 1923 (p.23).

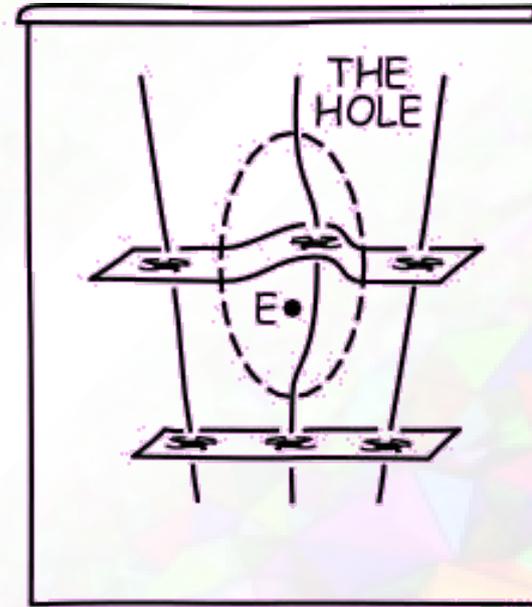
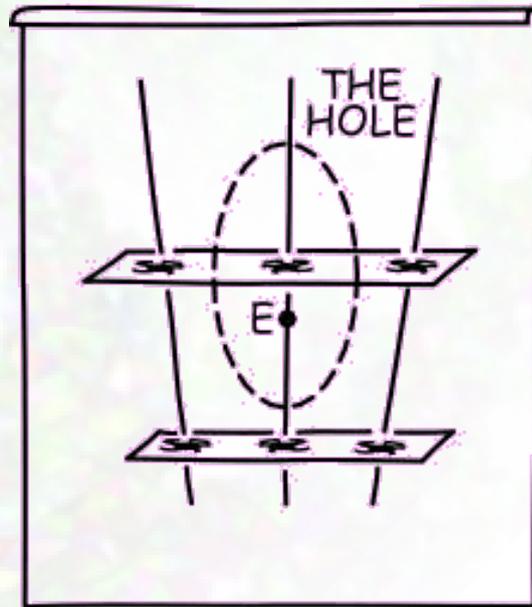
General Relativity



$$\langle \mathcal{M}, g_{ij}, T_{ij} \rangle \implies \langle \mathcal{M}, f^* g_{ij}, f^* T_{ij} \rangle$$

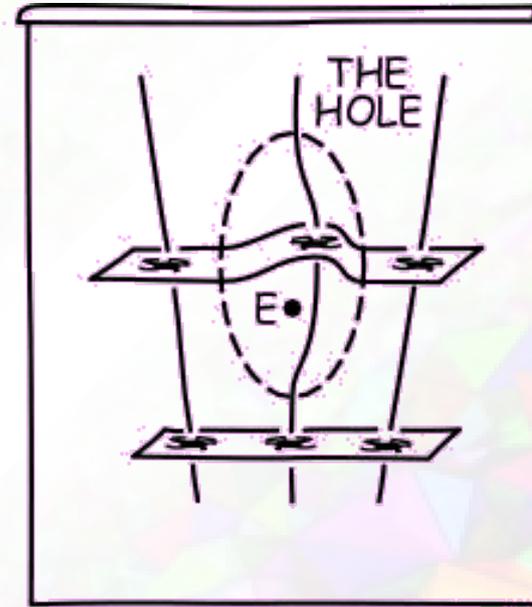
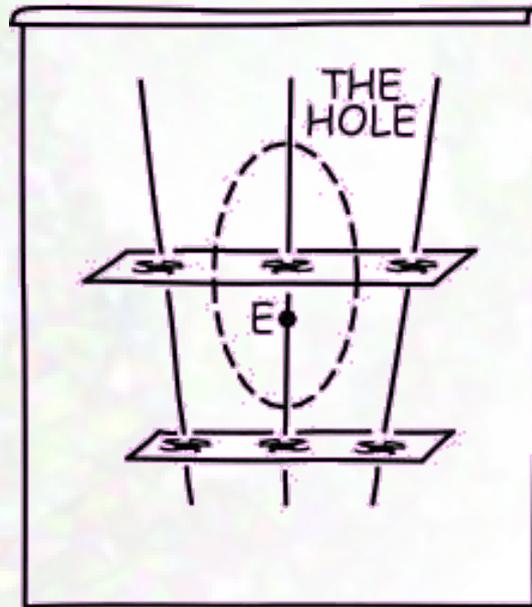
$$f \in \text{Diff}(\mathcal{M})$$

General Relativity



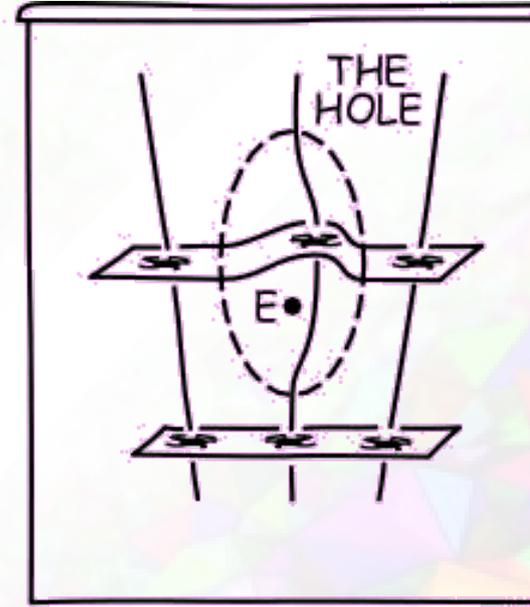
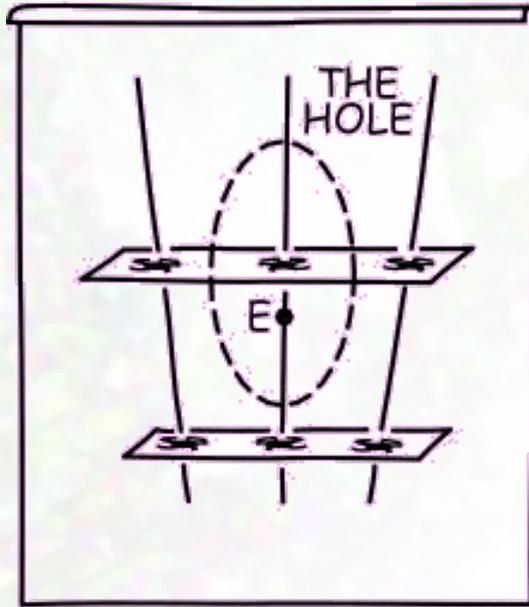
- Consider the proposition “The wordline of the galaxy in the middle passes through E ”.
- A (hypothetical) truth-maker for such statement would be transparent to physics.

General Relativity



- Consider, now: “The length of the galaxy's worldline inside the hole is $d(P, Q)$ ”.
- The theory is able to point out a physically meaningful truth-maker for such proposition (“observable”).

General Relativity



- Moreover, the theory tells us that the physical characterization of such a truth-maker is unaffected by whatever $f \in Diff(\mathcal{M})$.

$$d(P, Q) = f^* d(f(P), f(Q))$$

General Relativity

- General relativity is naturally interpreted in terms of a dualistic ontology (spacetime points plus point-particles).
- However, the hole argument prevents us from considering spacetime points as individuals endowed with intrinsic (metrical) properties.
- It seems more natural to consider spacetime points as individuals lacking intrinsic identity instantiating a network of metrical relations.
- Hence, there is not much room for “nonrelational truthmakers for irreducible relational truths”.

Wheeler's Geometrodynamics

Main features of Geometrodynamics:

- Particles are gravitational wave packets confined to a compact region of spacetime and held together by the gravitational attraction of the field energy of the wave itself (geons).
- Spacetime is a foliation of space-like surfaces. Once given the geometry on an initial spatial "slice", the vacuum Einstein equations describe how geometry "evolves" through the other surfaces.

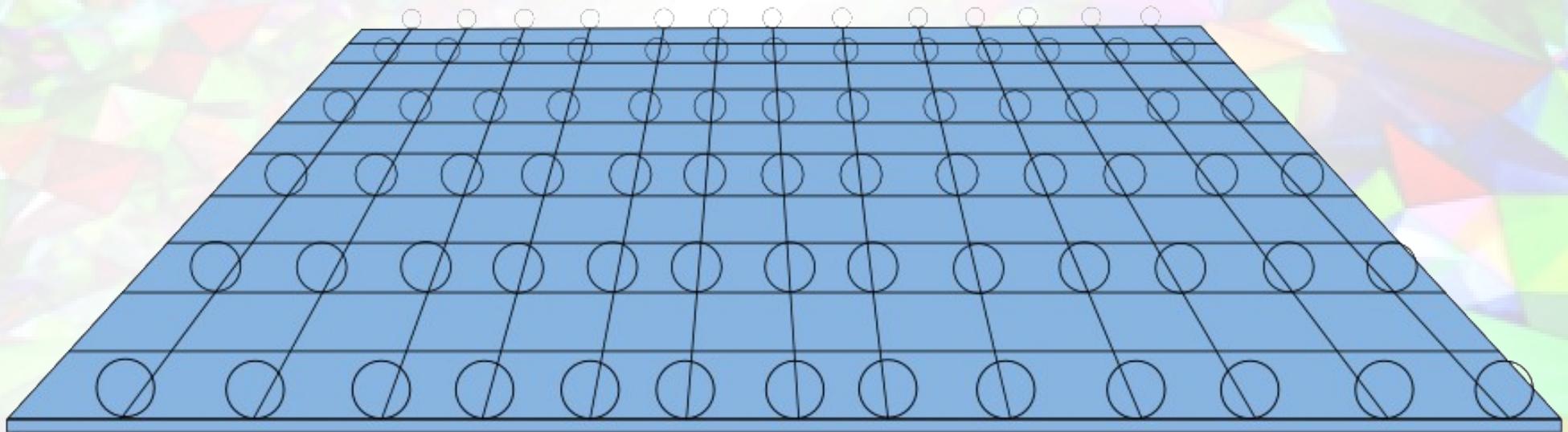
Wheeler's Geometrodynamics

- Geometrodynamics describes matter in motion as emerging from a wave-like propagation of “thickenings” of space in (coordinate) time.
- As such, it commits to a monistic ontology of spacetime points.
- The dynamics of the theory is diffeomorphism invariant.
- This means that the dynamical description just relies on relational features of spacetime and cannot be reduced in a physically meaningful way to non-relational features of spacetime points.

Kaluza-Klein Gravity

Main features of KK theory:

- Addition of an extra spacelike dimension topologically compactified as a circle (compactification condition).



Kaluza-Klein Gravity

- Field equations in KK theory:

$$R_{AB} = 0$$

- Metric tensor in KK:

$$g_{AB} = \begin{pmatrix} g_{ij} + \kappa^2 \phi^2 A_i A_j & \kappa^2 \phi^2 A_i \\ \kappa^2 \phi^2 A_j & \phi^2 \end{pmatrix}$$

Kaluza-Klein Gravity

The "Kaluza-Klein Miracle":

$$R_{ij} - \frac{1}{2}g_{ij}R = \frac{8\pi G}{c^4}T_{ij}^{EM}$$

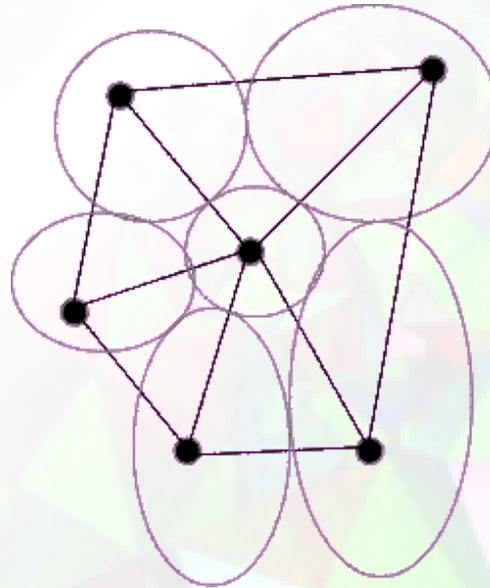
$$\nabla^i F_{ij} = 0$$

Kaluza-Klein Gravity

- Also Kaluza-Klein gravity commits to a monistic ontology of spacetime points.
- However, this theory is nothing but vacuum general relativity in 5 dimensions.
- Hence, all the arguments discussed in the case of general relativity are rigidly translated to this context.

Quantum Gravity

- Quantum gravitational states are represented by labelled graphs.
- The nodes/edges structure of a graph represents a configuration of elementary extension of space related by a contiguity relation.



Quantum Gravity

- Any configuration of atoms of space approximates at large scales a smooth 3-geometry.
- The dynamical laws describe how a configuration “evolves” in coordinate time.
- A smooth 4-dimensional spacetime dynamically emerges in a suitable continuum limit.
- If we allow “braiding” of edges, then matter degrees of freedom emerge from such complex topological structures.

Quantum Gravity

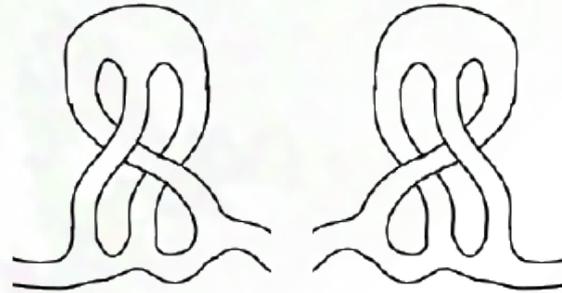


FIG. 16: The electron neutrino and anti-neutrino – two uncharged states.

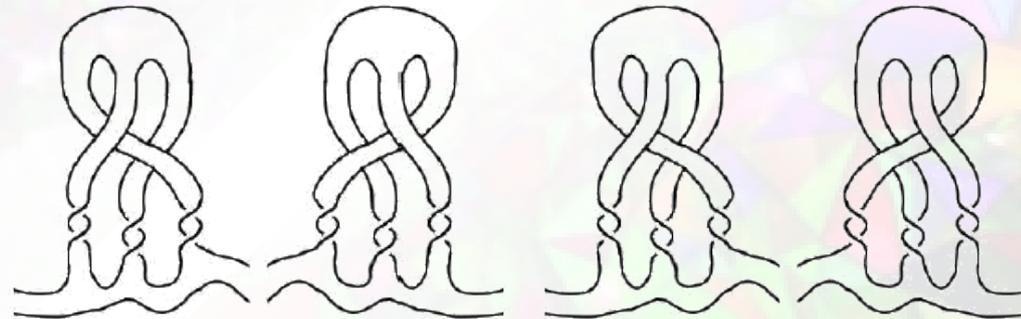


FIG. 17: The electron and positron — four maximally charged states.

S.O. Bilson-Thompson, F. Markopoulou, L. Smolin – Quantum Gravity and the Standard Model. *Classical and Quantum Gravity* 24, 2007 (p. 3987).

Quantum Gravity

- According to such a model, at the fundamental ontological level we have atoms of space *plus* a contiguity relation.
- The emergence of spacetime and matter cannot be reduced to non-relational features of atoms of space. What physically matters is how atoms of space are related.
- The relational features encoded in configurations of atoms of space are too much complex to be simply reduced to intrinsic features of such atoms.

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http://www.einstein-online.info/spotlights/spin_networks