Title: The dynamics of difference

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Abstract: A proposal is made for a fundamental theory, which is hypothesized to be a completion of both quantum mechanics and general relativity, in which the history of the universe is constituted of diverse views of itself. Views are attributes of events, and the theoryâ€™s only be-ables; they comprise information about energy and momentum transferred to an event from its causal past. A dynamics is proposed for a universe constituted of views of events, which combines the energetic causal set dynamics with a potential energy based on a measure of the distinctiveness of the views, called the variety. As in the real ensemble formulation of quantum mechanics, quantum pure states are associated to ensembles of similar events; the quantum potential of Bohm then arises from the variety.
This theory brings together results from two lines of development: energetic causal sets, developed with Marina Cortes, and the real ensemble formulation of quantum mechanics.

The dynamics of difference

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Combines energetic causal sets, relative locality and the real ensemble formulation of quantum mechanics;

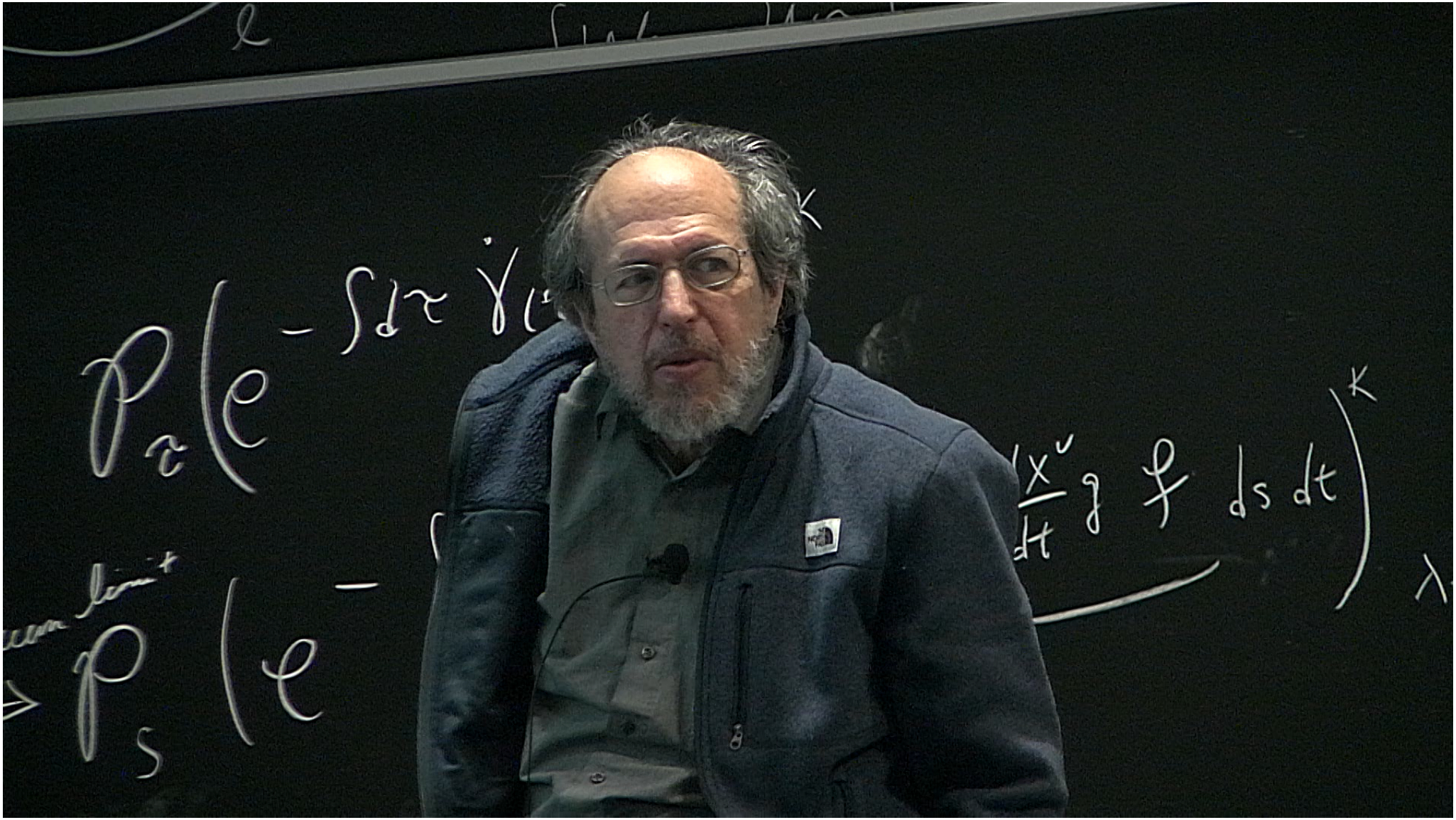
arXiv:1712.04799., Foundations of Physics DOI: 10.1007/s10701-018-0141-8

with M Cortes: arXiv:1307.6167, arXiv:1407.0032, arXiv:1703.09696 , arXiv:1902.05082,

arXiv:1104.2822, arXiv:1506.02938, arXiv:1205.3707

https://leesmolin.com/einsteins-unfinished-revolution/related-scientific-papers/

Thanks: Marina Cortes, Stephon Alexander, Wolfgang Wieland, Laurent Freidel, Fotini Markopoulou, Roberto Mangabeira Unger



Despite enormous effort from thousands of dedicated researchers over a century, the search for the quantum theory of gravity has not yet arrived at a satisfactory conclusion. We have indeed several impressive proposals, each of which partly succeeds in describing plausible quantum gravitational physics. Each tells a compelling story that has, for good reason, won it advocates. Each has also run into persistent roadblocks, which are pointed to by their skeptics. Looking back, before strings and loops, before causal sets, causal dynamical triangulations, asymptotic safety, amplitudes, twisters, shape dynamics, etc, to the early days of Bergman, Deser, DeWitt, Wheeler and their friends, who would have thought that there would turn out to be at least half dozen ways to get part way to quantum gravity?

Perhaps we might, for a moment, consider that the approaches so far pursued are not really theories, in the sense quantum mechanics, general relativity and Newtonian mechanics are theories. For those are based on principles and perhaps we can agree that we don't yet know the principles of quantum gravity.

Perhaps the different approaches are models of possible regimes of quantum gravity phenomenology?

What are we missing in our search for quantum gravity? arXiv:1705.09208.

The causal theory of views *is a recent proposal for a* ***model*** *of fundamental physics. (Not yet a theory!!)*

It combines elements of previous proposals, particularly energetic causal sets, developed with Marina Cortes, relative locality and the real ensemble formulation of quantum theory.

It is incomplete.

It is intended as a tool to model certain principles and hypotheses.

arXiv:1712.04799

We start with principles, then hypotheses.

Candidate principles for quantum gravity:

1) Relationalism
2) Duality
3) Weak holography
4) Quantum equivalence principle
5) Causation

arXiv:1610.01968, contribution to Paddy@60, a book in honour of Thanu Padmanabhan.

- ***The principle of sufficient reason (PSR):***

  There must be a rational answer to every question that can be imposed of the form of *"Why is the universe like X and not otherwise?"*

  Or: Progress in understanding nature is measured by decreases in the number of features of the universe that are arbitrary or not determined by equations of motion.

- **The principle of the identity of the indiscernible (PII):**

Any two events that have the same values of the physical fields are identified. i.e. no two events in the history of the universe have the same values of the physical fields.

Or: No two events have the same *views* of their causal pasts.

The view of an event: *What you see (incoming photons etc) looking out, and hence back from that event.*

These two principles of relationalism have many implications:

- *No fundamental symmetries. But there can be gauge and diffeomorphism invariances*
- *Theories must be background independent, ie not contain arbitrary fixed structures not determined by dynamics. These usually cash out as implicit references to fixed external reference structures, outside of the system being modeled.*
- *Realism*
- *Space and time are relational.*
- *The principle of explanatory closure: Everything that causally influences the behavior of a physical system within the universe must be another physical system within the universe*

- *The principle of reciprocity: There is nothing in nature that acts without being acted upon in return.*

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Candidate hypotheses for quantum gravity:

What is fundamental, and what is emergent ?

Fundamental:

energy
momentum
extended structures
events and causal relations
causal past="view"
beables

$[\not{x}, p] = [0,p] = \not{i\,h} = 0$ the algebra of be-ables is commutative!!

Candidate hypotheses for quantum gravity:

What is fundamental, and what is emergent ?

Fundamental:	Dualities	**Emergent:**
energy	⟷	spacetime
momentum		(configuration) space
extended structures		gauge fields
events and causal relations		geometry
causal past="view"		light cone
beables		quantum mechanics

$[\not{x}, p] = [0,p] = \not{i}\,\not{h} = 0$ the algebra of be-ables is commutative!!

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It appears that for each can conj pair: (x,p), one is fundamental while the other is emergent!

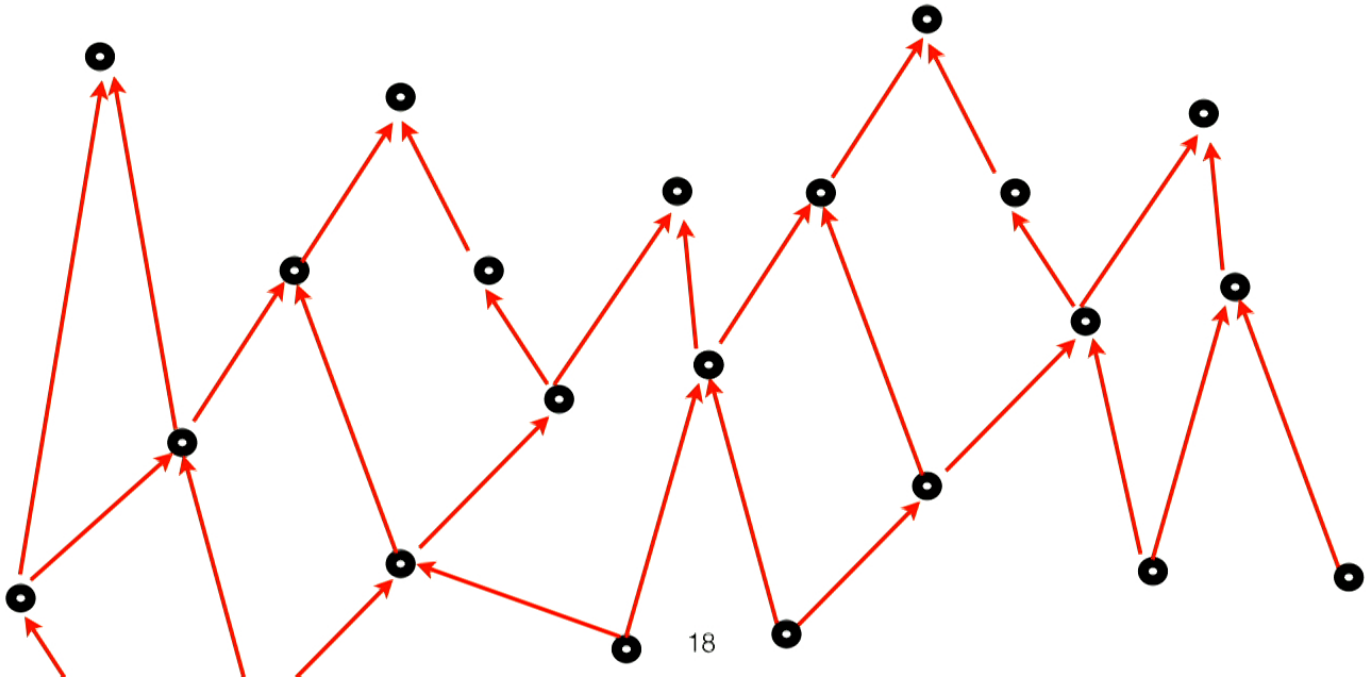
$[\not{x}, p] = [0,p] = -i\not{h} = 0$ the algebra of be-ables is commutative!!

So quantum mechanics must be emergent as well, therefor our theory could be a completion of QM.

How do we give dynamics to a universe of events, flows of energy and their causal relations?

The relational principles and the hypotheses we have chosen can be modeled by an Energetic Causal Set, which we invented and studied with Marina Cortes.

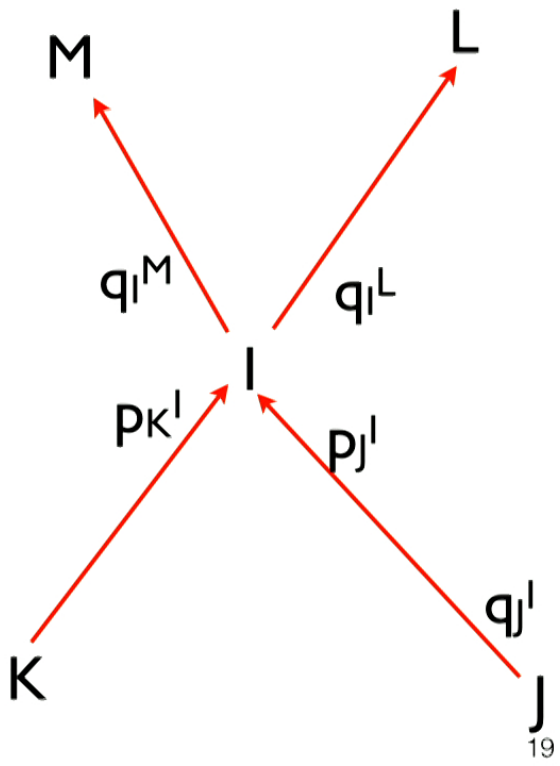
Causal sets:



Energetic causal sets:

Each link, connecting E_I to one of its parents, E_j, has two momenta, an incoming momenta $p_J{}^I$ and an outgoing momentum $q_I{}^J$.

The total momenta of an event $$P_a^I = \sum_J p_{aI}^J$$



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Dynamics of Energetic Causal Sets:

- *Sequential growth: There is a rule that grows the causal set. At each step it picks a set of n parent events who become the causal precedents of a new event.*
- *Each event can be parents to at most p child events. Thus those events with less than p children are potential parents and hence make up a thick present. Those events which have p children make up the past.*
- *The energy-momentum of the parents is distributed to the children by applying a set of constraints, which enforce conservation.*

Constraints:

The momenta are propagated to the new event and links by three constraints:

Conservation at each event: $$\mathcal{P}^I_a = \sum_K p^I_{aK} - \sum_L q^L_{aI} = 0$$

Parallel transport on each edge: $$\mathcal{R}^K_{aI} = p^K_{aI} - \mathcal{U}^{Kb}_{Ia} q^K_{bI} = 0$$

Energy-momentum relations:

$$\mathcal{C}^I_K = \frac{1}{2}\eta^{ab} p^I_{aK} p^I_{bK} + m^2 = 0$$

$$\tilde{\mathcal{C}}^I_K = \frac{1}{2}\eta^{ab} q^I_{aK} q^I_{bK} + m^2 = 0$$

Dynamics:

The action is the sum of constraints:

$$S^{ECS} = \sum_I z^a_I \mathcal{P}^I_a + \sum_{(I,K)} (x^{aI}_K \mathcal{R}^K_{aI} + \mathcal{N}^K_I \mathcal{C}^I_K - \tilde{\mathcal{N}}^K_I \tilde{\mathcal{C}}^I_K)$$

lagrange multipliers

Classical physics from the critical points of the action:

$$S = \sum_I z_I^a \mathcal{P}_a^I + \sum_{(I,K)} (x_K^{aI} \mathcal{R}_{aI}^K + \mathcal{N}_I^K \mathcal{C}_K^I - \tilde{\mathcal{N}}_I^K \tilde{\mathcal{C}}_K^I)$$

lagrange multipliers

Constraints:

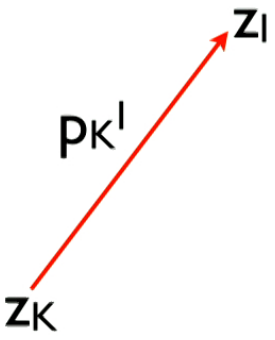
$$\mathcal{P}_a^I = \sum_K p_{aK}^I - \sum_L q_{aI}^L = 0 \qquad \mathcal{R}_{aI}^K = p_{aI}^K - \mathcal{U}_{Ia}^{Kb} q_{bI}^K = 0$$

$$\mathcal{C}_K^I = \frac{1}{2}\eta^{ab} p_{aK}^I p_{bK}^I = 0 \qquad \tilde{\mathcal{C}}_K^I = \frac{1}{2}\eta^{ab} q_{aK}^I q_{bK}^I = 0$$

Equations of motion:

$$z_I^a - z_K^a = p_K^{aI} \mathcal{M}_I^K$$

$$\mathcal{M}_I^K = \tilde{\mathcal{N}}_I^K - \mathcal{N}_I^K$$

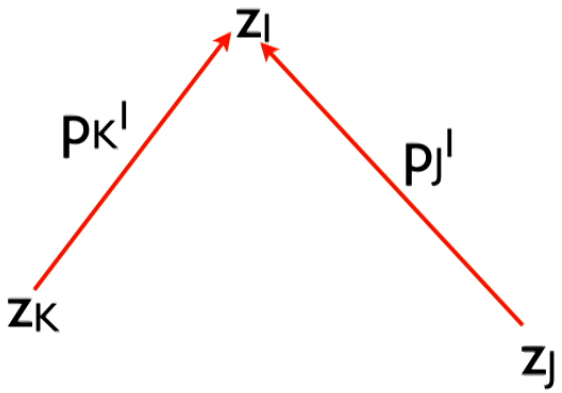


Spacetime emerges when there are consistent solutions to all the equations:

$$z_I^a - z_K^a = p_K^{aI} \mathcal{M}_I^K$$

rescale z --> z/h to give spacetime coordinates units of length.

h is purely conventional.

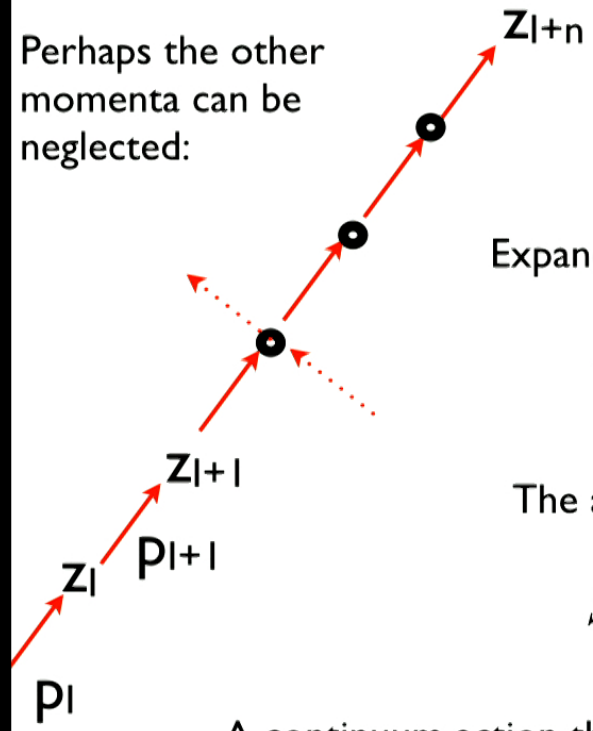


Spacetime inherits its metric from momentum space:

$$|z_I^a - z_K^a|^2 = (z_I^a - z_K^a)(z_I^b - z_K^b)\eta_{ab}$$
$$= (\mathcal{M}_I^K)^2 |p_K^{aI}|^2 = 0$$

U=1 gives flat spacetime

Consider a long chain of simple events (one in and one out):



Equations of motion: $p_a^I = p_a^{I+1} = p_a$

$$z^a_{I+1} - z^a_I = p^{aI}\mathcal{M}_I$$

Expand in a small time interval: $z^a_{I+1} = z^a_I + \dot{z}^a(t)\Delta t$

The EoM is now: $\dot{z}^a(t) = \dfrac{\mathcal{M}_I}{\Delta t} p^a_I = n p^a_I$

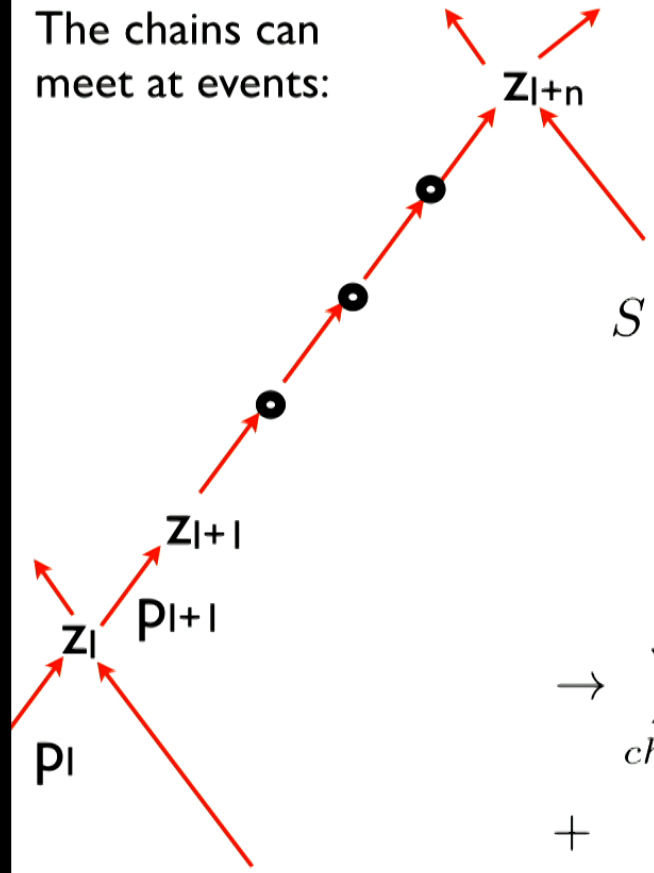
The action is now:

$$S = \sum_I p^I_a (z^a_{I+1} - z^a_I) - \frac{1}{2}\mathcal{M}_I p_I^2$$

A continuum action that gives the same classical physics: $\rightarrow \int dt \left(p_a(t)\dot{z}^a(t) - \frac{1}{2} n(t) p(t)^2 \right)$

which is the action for a free relativistic massless particle:

The chains can meet at events:



$$S = \sum_{chains} \sum_{I} p_a^I (z_{I+1}^a - z_I^a) - \frac{1}{2}\mathcal{M}_I p_I^2 + \sum_{interactions} z_I^a \mathcal{P}_a^I$$

$$\rightarrow \sum_{chains} \int dt \left(p_a(t)\dot{z}^a(t) - \frac{1}{2} n(t) p(t)^2 \right) + \sum_{interactions} z_I^a \mathcal{P}_a^I$$

which is the action for relativistic particles with local interactions.

STEP 2: From casual sets to views

We now switch from an ontology of events and their causal relations to a dual ontology which contains just the views of the various events.

According to this "view-ontology", the universe is nothing but the set of views, together with the causal relations they encode.

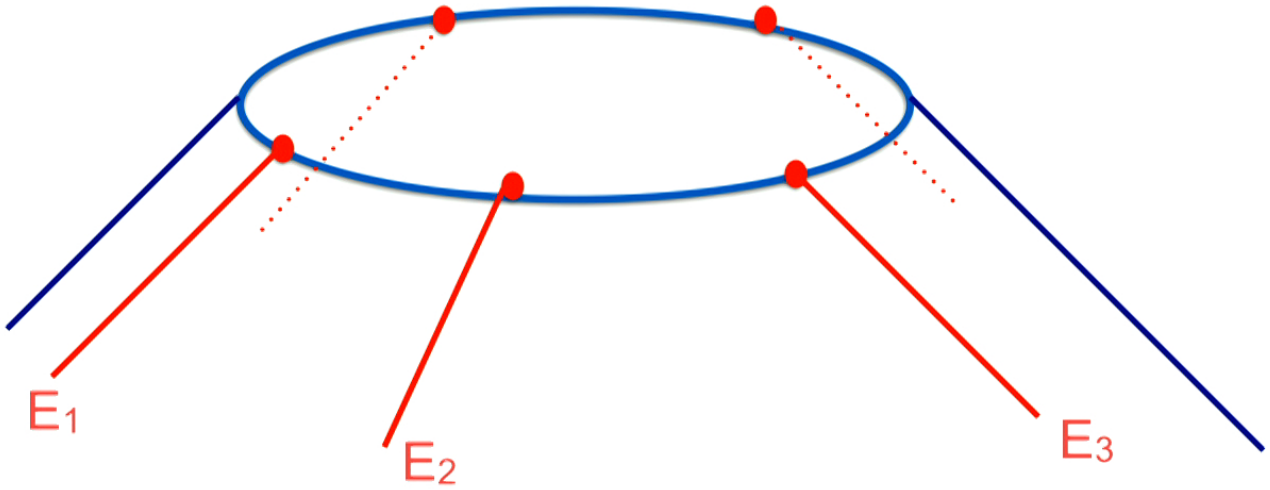
The ***view of an event*** is the set of physical fields evaluated there.

By the PII, all views are distinct. Therefor an event's view labels it, indeed overdetermines it.

Views as punctured two spheres: *the sky!*

The view of an event is a collection of null or timeline energy momentum vectors, representing incoming information about the past. $\{ p_{a\,l}{}^{J} , p_{a\,l}{}^{K} , \ldots \}$.

We can represent the directional information as points on an S2, with labels which are the energy.



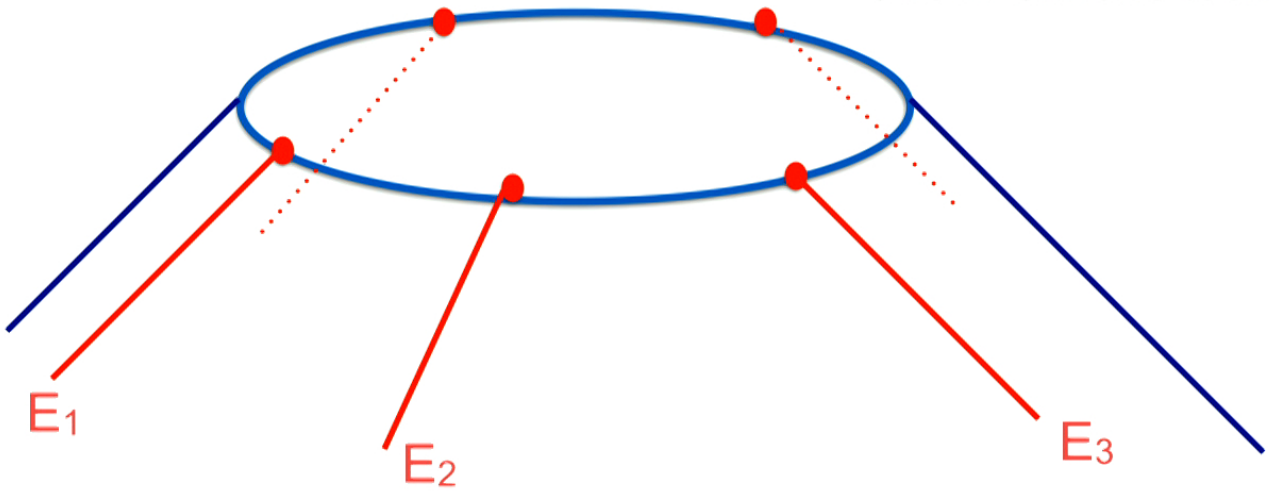
Views as punctured two spheres:

e views are the beables (because space isn't presesnt).

Spacetime is emergent from the causal set of views.

The observables are functions on punctured S^2's representing the views.

Connects to boundary Chern-Simons technology



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STEP 3: Add non-local interactions that encourage diversity, or variety

We now add to the relativistic particle-like model a highly non-local interaction, which acts to extremise the diversity of the set of views of and in the universe.

As there is fundamentally no space, the potential energy cannot depend on distances on space, or spatial derivatives.

Instead, the potential energy is a function of the differences amongst the views.

~~"Systems more likely to interact if they are nearby in spacetime".~~

"Systems more likely to interact if they have similar views of their causal pasts;"

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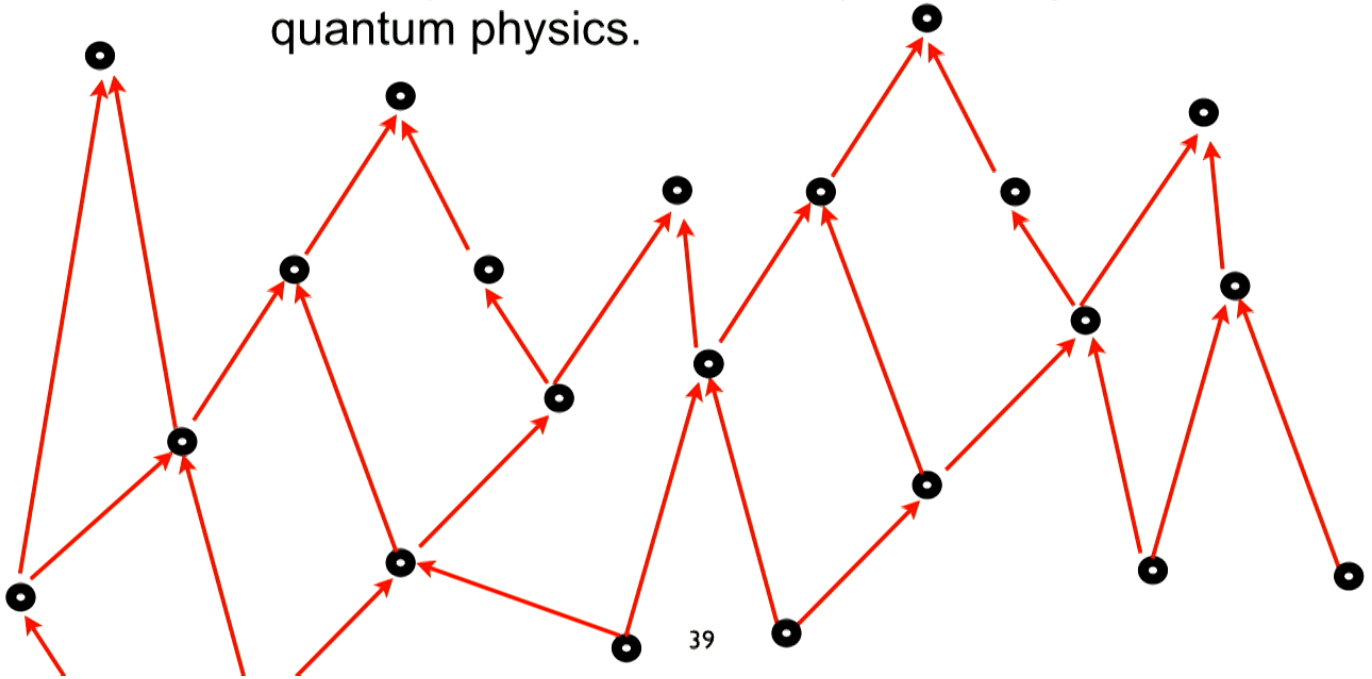
~~"Systems interact if they are nearby in spacetime".~~

"Systems interact if they have similar views of their causal pasts;"

There are real ensembles of similar systems that mutually interact non-locally. These give rise to quantum physics.



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Differences and variety

There is a metric, D_{IJ}, on the space of views, measuring the difference between the views, V_I.

$$h_{IJ} = \mathcal{D}_{IJ}$$

The variety of the causal set is

$$\mathcal{V} = \frac{1}{N(N-1)} \sum_{I \neq J} \mathcal{D}(I, J)$$

We posit that variety contributes to potential energy

$$S^{RE} = -g\mathcal{V}$$

ie the universe evolves so as to increase its variety.

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We derive quantum mechanics in the non-relativistic approx. in which we neglect differences in the frames of an event.

We define ε ensembles, a set, S, of events such that

$$\mathcal{D}_{IJ} < \epsilon, \qquad \forall I, J \in \mathcal{S}$$

We posit that the quantum state describes this ***real ensemble*** of similar systems. The variety potential gives a non-local interaction which resists similarity. That is to say, there is a strong repulsive force between similar views.

Consider an ε ensemble of similar views. Because of their strong mutual interactions, we conjecture that they thermalize, defining a steady state distribution ρ(w)) on the space of views. We can estimate the <V> in this ensemble. This becomes the Bohmian potential,

$$\mathcal{V} = \frac{1}{4}\int dwds\ \rho\ (\frac{1}{\rho}\partial_i\rho)^2$$

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This is ultimately the explanation of quantum phenomena.

$$< S^{ECS} + g\mathcal{V} >= \int_{\mathcal{V}} dw \int ds\rho[w,s] \left[\dot{S}(w,s) - mc^2 - \frac{(\partial_i S)^2}{2m} + \frac{g}{4}(\frac{1}{\rho}\partial_i \rho)^2 \right]$$

The equations of motion,

$$m = m' + U$$

$$\dot{\rho} = -\frac{1}{m}\partial_i(\rho \partial^i S)$$

$$\dot{S} = \frac{1}{2m}(\partial_i S)^2 + U + g\frac{\nabla\sqrt{\rho}}{\sqrt{\rho}}$$

are the real and imaginary parts of the Schrodinger equation.

$$\imath\hbar\frac{d\psi}{dt} = \left[-\frac{\hbar^2}{2m}\nabla^2 + U \right]\psi \qquad \psi = \sqrt{\rho}e^{\frac{\imath}{\hbar}S}e^{-\imath mc^2 s}$$

$$g = \frac{\hbar^2}{2m}$$

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