Title: The dynamics of difference

Speakers: Lee Smolin

Series: Quantum Foundations

Date: November 20, 2020 - 2:00 PM

URL: http://pirsa.org/20110056

Abstract: A proposal is made for a fundamental theory, in which the history of the universe is constituted of views of itself. Views are attributes of events, and the theory's only be-ables; they comprise information about energy and momentum transferred to an event from its causal past.

The theory is called the causal theory of views (CTV) and is a candidate for a completion of QM. It is partly based on energetic causal sets (ECS),   an approach developed with Marina Cortes. A key result that applies also here is that spacetime is emergent from the ECS dynamics. This implies that the fundamental dynamics involve no notion of space, distance or derivatives. Instead I propose that a measure of similarity of views replaces derivatives as the basic measure of change and difference.

A measure of the diversity of views in a causal network is introduced, called the variety (originally invented with Julian Barbour). I postulate a dynamics for CTV based on an action involving the variety and show that in an appropriate limit, it reduces to Schrodinger quantum mechanics. A key result is that the variety reduces to Bohm's quantum potential.

Based on arXiv:1307.6167, arXiv:1308.2206 , arXiv:1712.0479 and a paper in preparation.

The dynamics of difference: a causal theory of views

A non-local relational hidden variable theory constructed from a dynamical theory of causal structure

Lee Smolin – Perimeter Institute
PI QF

Nov 20, 2020

Thanks: ***Marina Cortes,*** Stephon Alexander, Wolfgang Wieland, Stefan Stanjovic, Michael Toomy, Will Cunningham, David Wecker, Jaron Lanier, Stuart Kauffman, Andrew Liddle, Laurent Freidel, Roberto Mangabeira Unger, Clelia Verde

Dynamics of difference: arXiv:1712.04799.

Energetic causal sets with Marina Cortes:
arXiv:1307.6167, arXiv:1407.0032, arXiv:1703.09696 , arXiv:1902.05082, arXiv:1104.2822, arXiv:1506.02938, arXiv:1205.3707

Einstein's Unfinished Revolution:
https://leesmolin.com/einsteins-unfinished-revolution/related-scientific-papers/

How do we find local observables (beables) in diffeomorphism invariant theories?

Leibniz's principle of the identity of the indiscernible:

- Any two events that have the same values of the physical fields are identified. i.e. no two events in spacetime have the same values of the physical fields. —> ***No symmetries***

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

- All views are distinct. Therefore an event's view labels it, indeed overdetermines it.

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Ontology: the universe is nothing but the set of views, together with the causal relations they encode.

What is real?

Events, their causal relations, + energy-momentum transferred by the causal processes, + geometry of momentum space.

Equivalently:

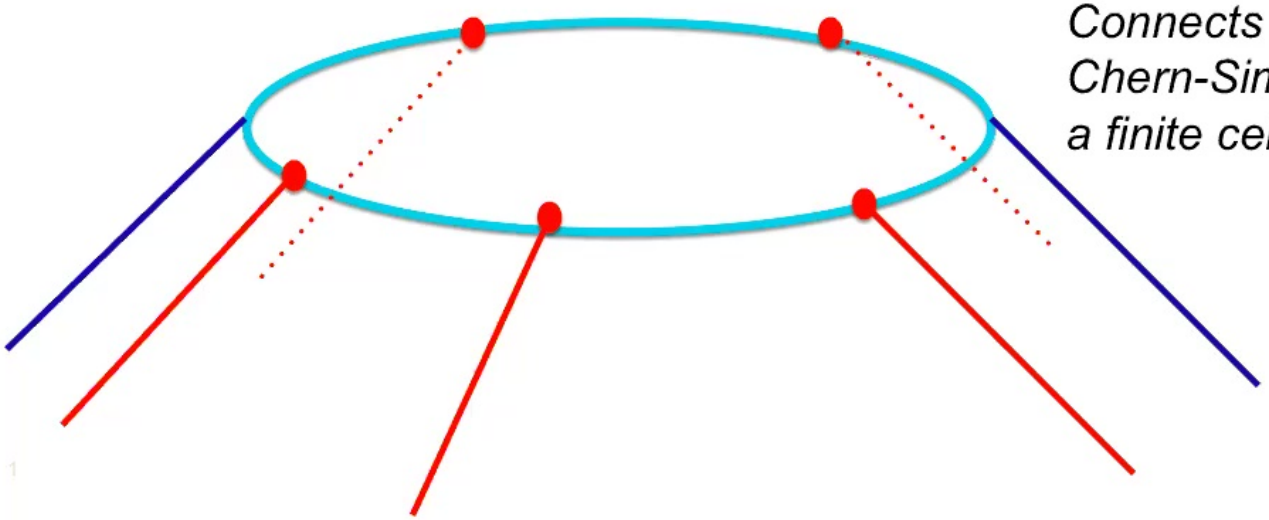
the VIEW from each event of its causal past, which consists of incoming energy-momentum vectors.

The fundamental action is a function of these views only.

Views as punctured two spheres

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.



Connects to boundary Chern-Simons theory and a finite celestial sphere

What is emergent?

Space, spacetime, quantum mechanics. Hence ħ, CCR.

How is dynamics defined?

By a path integral: a sum over causal processes and an integral over momentum and energy they transmit

What replaces locality and distances?

Differences in views: Given events I,J:
D(I,J)= differences in their views

What replaces kinetic energy?

Differences of views of causally related events

What replaces potential energy?

Variety, $\mathcal{V}$: a measure of the diversity of causally unrelated views.

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

What does the quantum state represent?

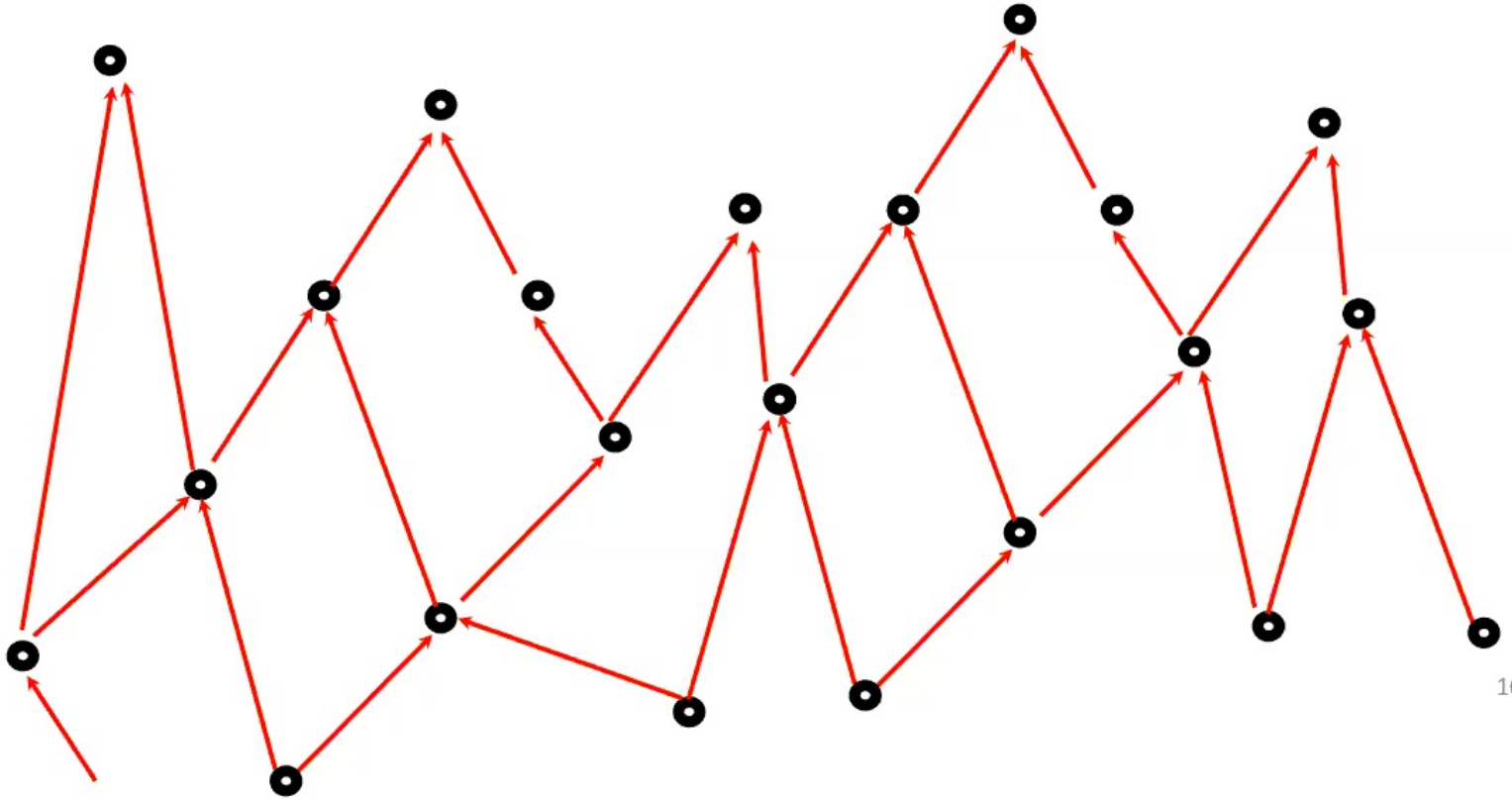
A real ensemble of N events with similar views,
but spread through the universe.

What are the claims? *(N —> ∞, non-relativistic)*

- *Schrödinger QM emerges.*
- *Variety acausal relations —> Bohm's quantum potential*
- *Variety causal relations —> kinetic energy*
- *For finite N there are computable corrections, which are non-linear corrections to Schrödinger dynamics.*

ENERGETIC CAUSAL SETS

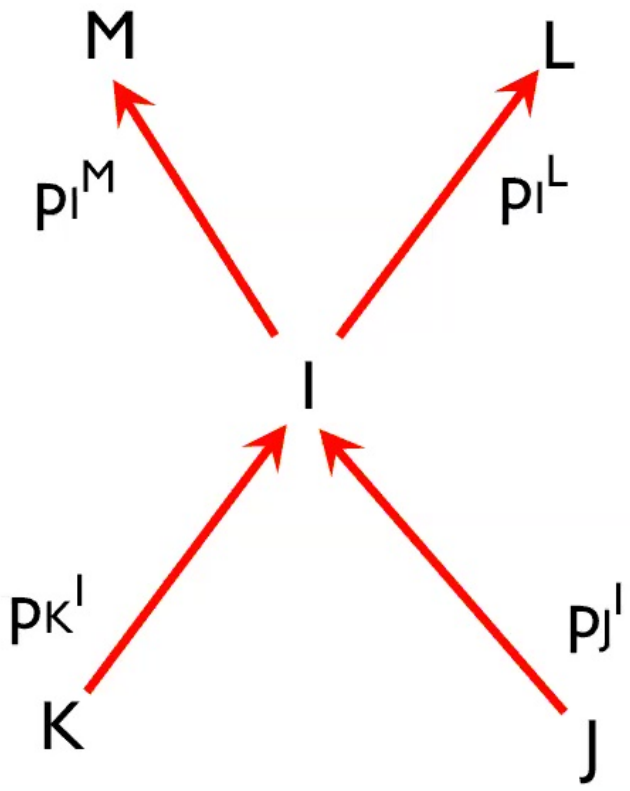
CAUSAL SETS



ENERGETIC CAUSAL SETS

The total momenta of an event

$$\mathcal{P}_a^I = \sum_K p_{aK}^I - \sum_L q_{aI}^L = 0$$



Constraints

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

Conservation at each event: $\mathcal{P}_a^I = \sum_K p_{aK}^I - \sum_L q_{aI}^L = 0$

No spacetime

The only geometry that comes in is the metric and connection of momentum space.

The total amplitude is defined by integrating over momenta, imposing constraints, for energy-momentum conservation, weighed by the variety.

$$\mathcal{A}[P] = \int \prod_{I>J} dp_{a\,J}^{\ I} \prod_{I} \delta(\mathcal{P}_a^I)\ e^{\imath g \mathcal{Q}(p)}$$

$$\mathcal{P}_a^I = \sum_K p_{aK}^I - \sum_L q_{aI}^L = 0$$

This is the complete definition of the theory.

No $\hbar$

No space or spacetime

No commutation relations

No uncertainty principle

Non-local, because variety $\mathcal{V}$ is.

Half quantum

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EMERGENCE OF SPACETIME FROM ENERGETIC CAUSAL SETS

Classical physics from the stationary phase approximation:

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

lagrange multipliers

Constraints:

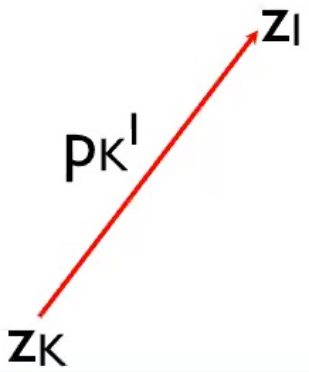
$$\mathcal{P}_a^I = \sum_K p_{aK}^I - \sum_L q_{aI}^L = 0 \qquad \mathcal{R}_{aI}^K = p_{aI}^K - \mathcal{U}_{Ia}^{Kb} q_{bI}^K = 0$$

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

Equations of motion:

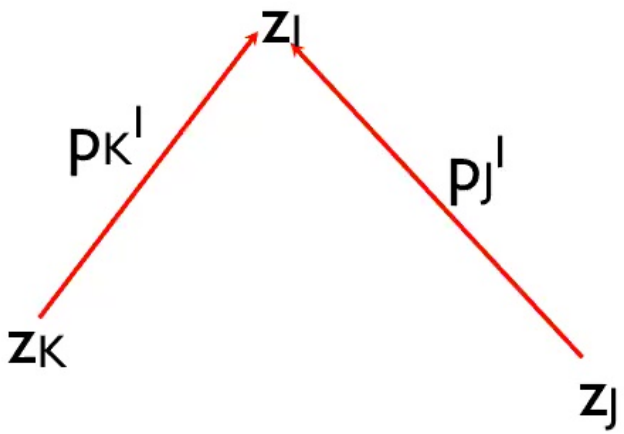
$$z_I^a - z_K^a = p_K^{aI} \mathcal{M}_I^K$$

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



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

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



Spacetime inherits its metric from momentum space:

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

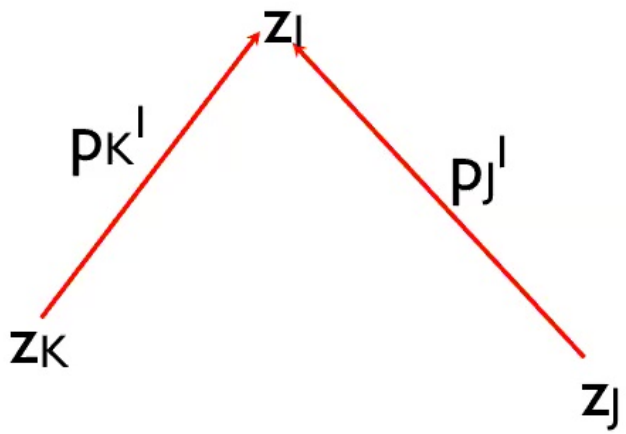
U=I gives flat spacetime

Spacetime emerges when there are consistent solutions to all the equatio

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

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

h is purely conventional.



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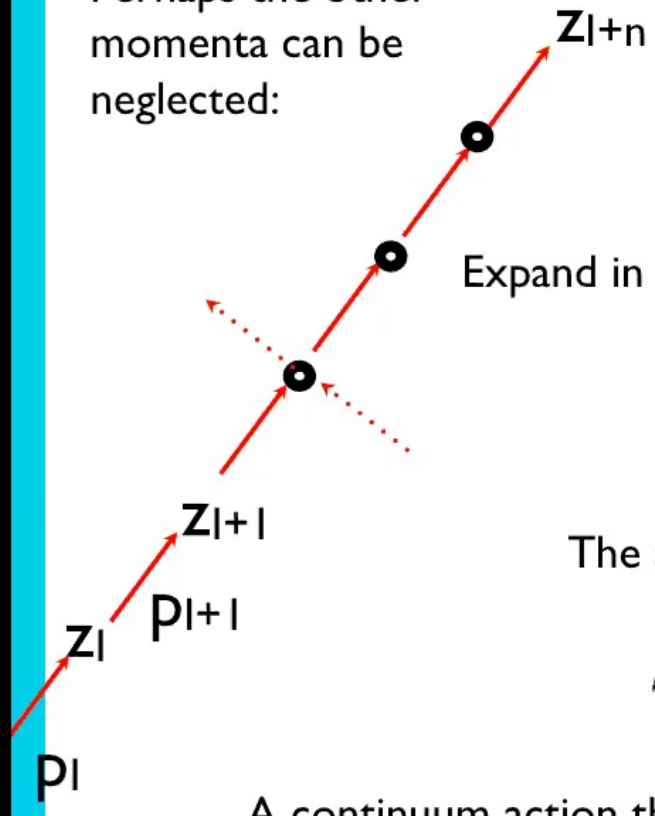
$$= (\mathcal{M}_I^K)^2 |p_K^{aI}|^2 = 0$$

U=1 gives flat spacetime

EMERGENCE OF PARTICLES FROM ENERGETIC CAUSAL SETS

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

Perhaps the other momenta can be neglected:



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: $\dot{z}^a(t) = \frac{\mathcal{M}_I}{\Delta t} p^a_I = n p^a_I$

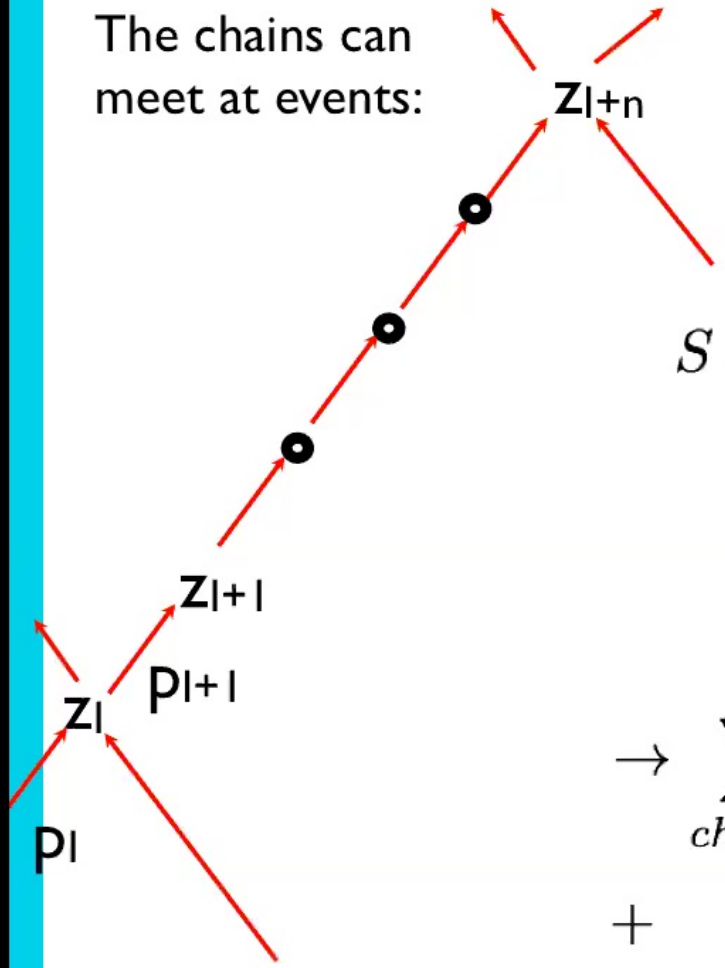
The action is now:

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

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.

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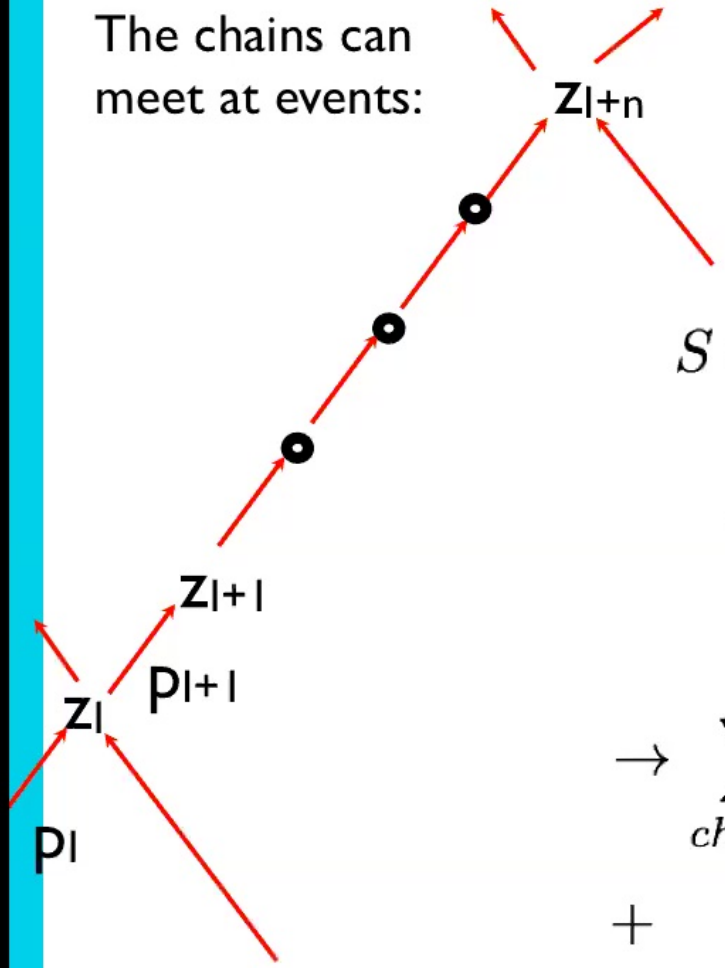


"pre-relative locality"

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

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

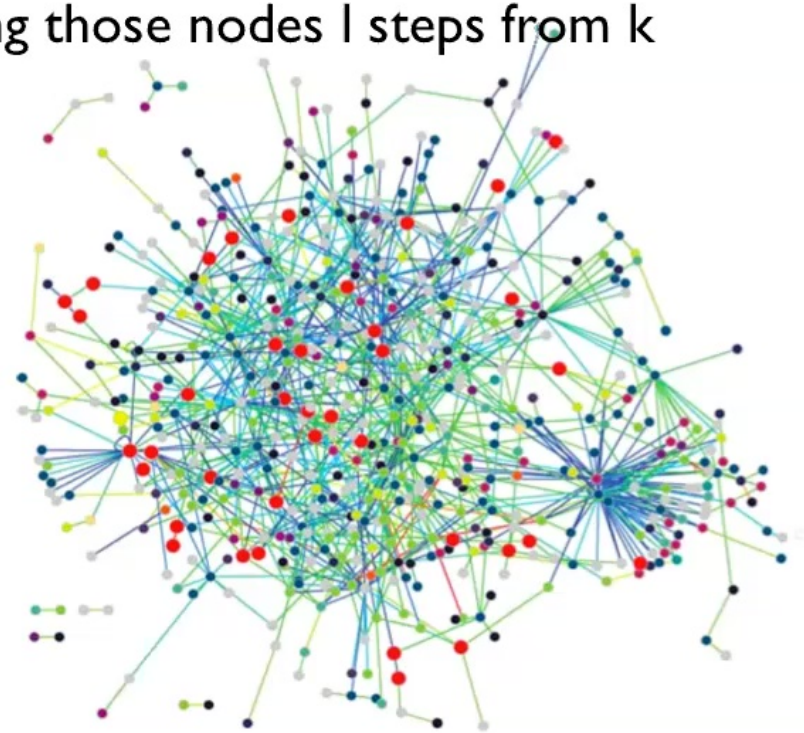
which is the action for relativistic particles with local interactions.

VARIETY

BASIC IDEAS

The variety of a network, G,

- N_l (k) is the l'th neighborhood of node k
- This is the subgraph of G including those nodes l steps from k



- For any pair of nodes,
n_{kl} is the smallest n such that
N_n (k) is not isomorphic to N_n (l)

- The distinctiveness of the pair is

$$D(k,l) = \frac{1}{n_{kl}}$$

- The variety of G is

$$\mathcal{V} = \frac{1}{N(N-1)} \sum_{k \neq l} D(k,l) = \frac{1}{N(N-1)} \sum_{k \neq l} \frac{1}{n_{kl}}$$

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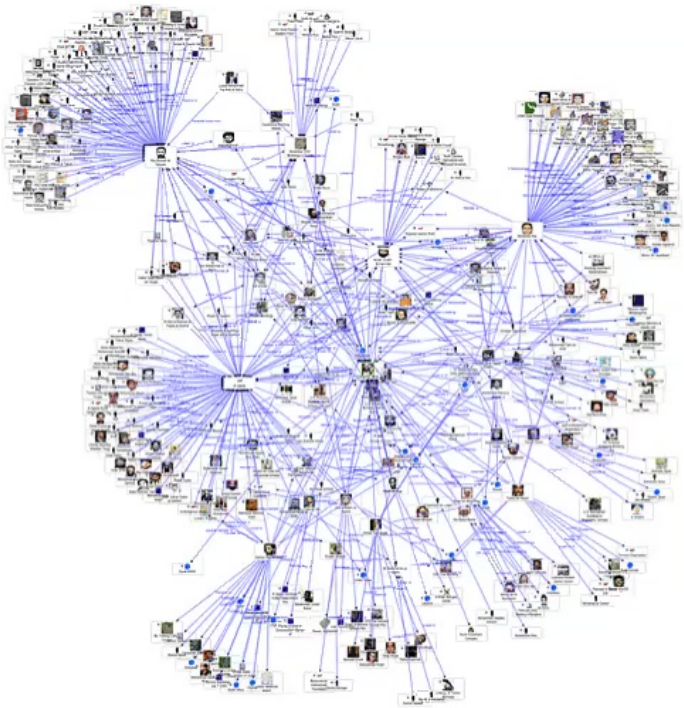
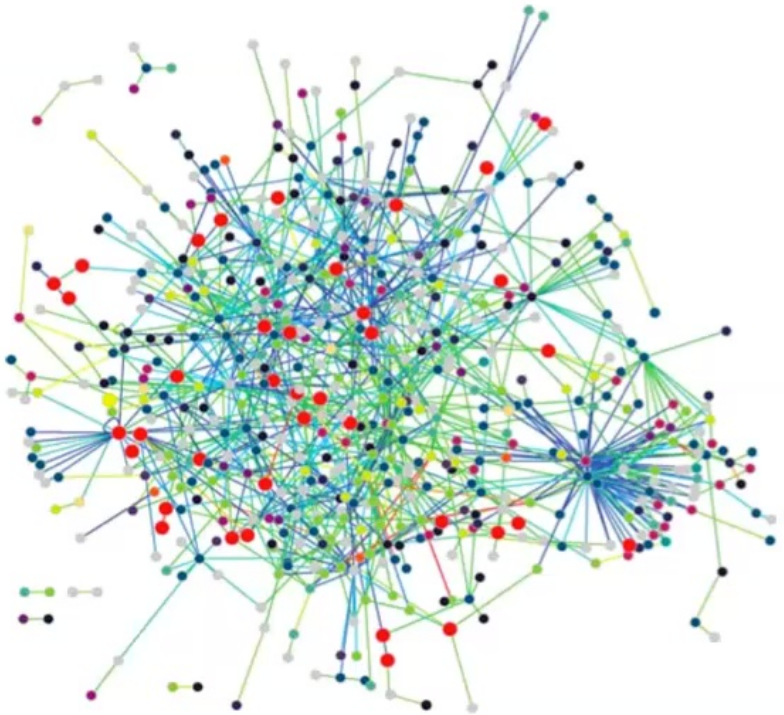




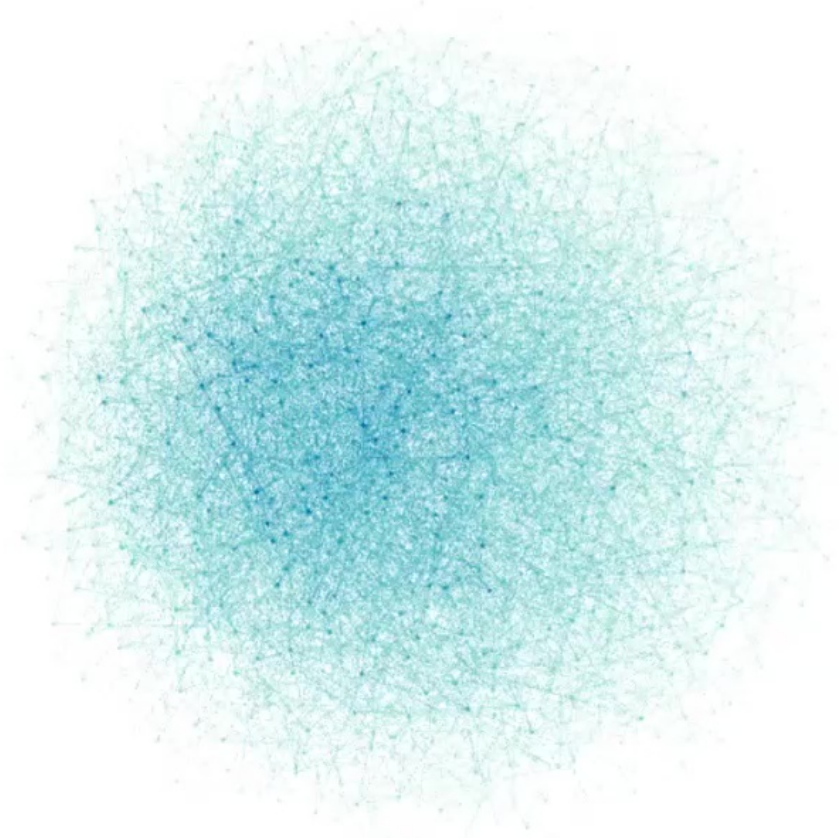
High variety

healthandsociety.columbia.edu

http://en.wikipedia.org/wiki/Interactome

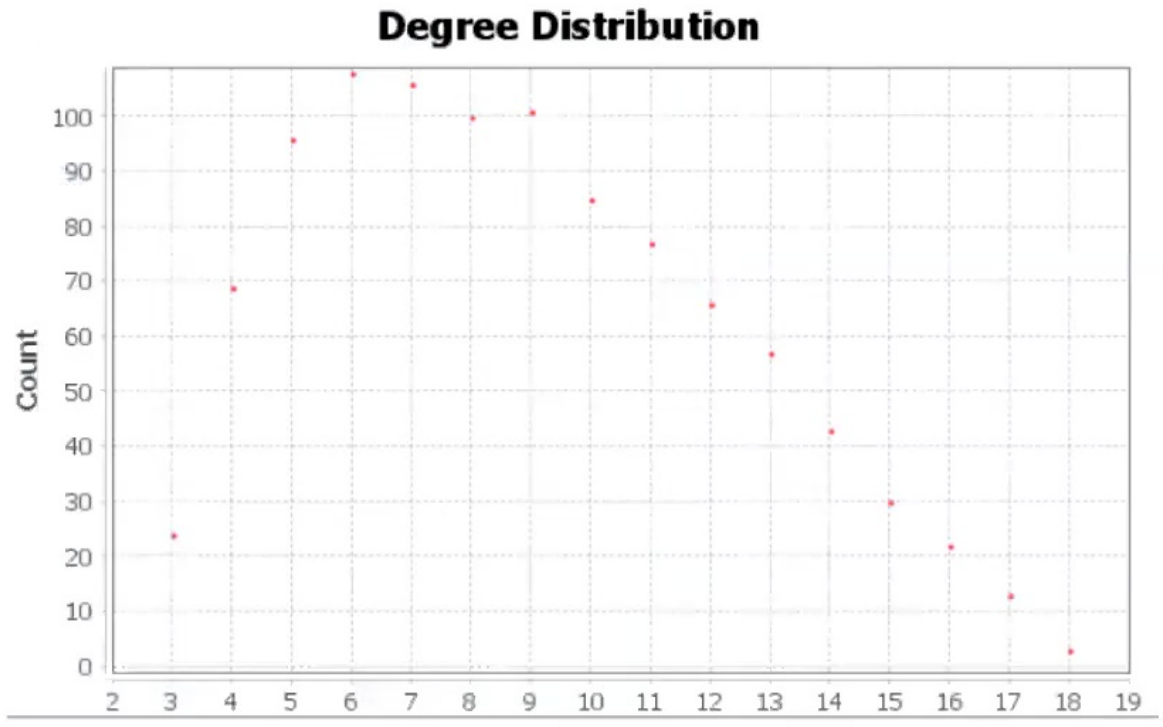
High variety

The 1000 node high-variety graph generated through a simulated annealing procedure



Stefan Stanjovic, Michael Toomy, Will Cunningham, David Wecker, Stefan Alexander, Jaron Lanier, LS (MS research, PI)

High variety



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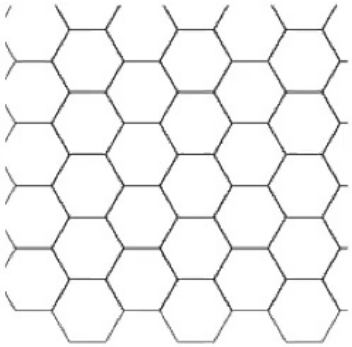
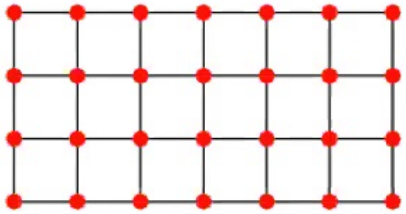
Low variety





http://mathworld.wolfram.com/HexagonalGrid.html

$$\mathcal{V} = \frac{1}{N(N-1)} \sum_{k \neq l} D(k,l) = \frac{1}{N(N-1)} \sum_{k \neq l} \frac{1}{n_{kl}}$$

THE REAL ENSEMBLE FORMULATION

BASIC IDEAS

BASIC IDEAS

1) ***Quantum mechanics is a description of subsystems of the universe.*** *It is an approximation to a different theory, which might be applied to the universe as a whole.*

2) ***The real ensemble hypothesis:*** *A quantum state refers to an ensemble of similar systems present in the universe at a given time. By similar systems we mean systems with the same constituents, whose dynamics are subject to (within errors that can be ignored) the same Hamiltonian, and which have very similar histories and hence, in operational terms, the same preparation.* arXiv:1104.2822

BASIC IDEAS 2/2

3) The basic hypothesis: similar systems have a new kind of interaction with each other, just by virtue of their similarities. This interaction takes place amongst similar systems, regardless of how far apart they may be situated in space, and thus, this is how non-locality enters quantum phenomena. *These interactions prevent similar systems from becoming identical and hence protect the principle of the identity of the indiscernible.*

4) The principle of maximal variety. *The variety of a system of relations, V, is a measure of how easy it is to distinguish the neighborhood of every element from that of every other. This can be used as a measure of complexity, or self-organization. We also proposed this as a dynamical principle. This principle turns the identity of the indiscernible into a dynamical principle that introduces a repulsive interaction to prevent two subsystems from having isomorphic neighborhoods. (Julian Barbour and LS,* hep-th/9203041*)*

Differences and variety

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

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

The variety of the causal set is

$$\mathcal{V} = \frac{1}{N(N-1)} \sum_{k \neq l} D(k,l) \qquad \mathcal{V} = \frac{1}{N(N-1)} \sum_{k \neq l} \frac{1}{n_{kl}}$$

We posit that variety contributes to potential energy

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

ie the universe evolves so as to increase its variety.