Title: The emergence of quantum mechanics and space, from a fundamental, active time

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Abstract: "We propose a realist completion of quantum mechanics, in the sense of a complete description of individual events. The proposed fundamental theory assumes that time, events, causal structure, momentum and energy are fundamental. But space and the wave function are emergent.

The beables of the theory are the views of the events, which are a subset of their causal pasts. Thus, this theory asserts that the universe is a causal network of events, which consists of partial views of itself as seen by looking backwards from each event.

The theory is based on a simple action principle, which
extremizes the variety of the universe, which is a measure of the diversity of its partial views. The Schroedinger equation is derived, while to higher order, there are computable corrections, non-linear in the wave function, from which new physical effects may be predicted.

Finally, a relativistic version is sketched, in wqhich the views are built on the celestial sphere. "

The emergence of QM and space from a fundamental active time

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

Lee Smolin – Perimeter Institute
Quantizing Time June 8, 2021

Thanks: Marina Cortes, Fotini Markopoulou, Joao Magueijo, Roberto Mangabeira Unger, Stephon Alexander, Jaron Lanier, Stuart Kauffman, Andrew Liddle, Laurent Freidel, Clelia Verde,…..

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The Main Hypothesis:

Constructive time, or active, resolving time, in the sense of an active process that continually creates new events out of present events, each one of which resolves or makes definite a previous indefiniteness, and thus continually creates the world anew, is the most fundamental aspect of nature with which we are acquainted.

Everything else, including laws, space, matter, etc are emergent from it

Quantum mechanics in the present moment, C Verde & L Smolin

Views, variety and quantum mechanics: arXiv:2105.03539

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, Lee Smolin

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

Cosmological laws differ from local laws

Laws evolve on cosmological scale

cosmological natural selection

principle of precedent

Autodidactic universe

Time, as in causation, is fundamental

and irreversible

Ontology is unique events w energy + causal relations

Beables are views

Dynamics based on differences between unique views —> variety

Space emerges

Particle dynamics emerges

NR QM emerges

presentism & QM

Temporal relationalism

Time asymm. extensions of GR

Time symm. laws emerge from time asymm. laws

biocosmology and functional explanations

QBiology??

GR emerges

Relationalism is based on two principles formulated by Leibniz.

- ***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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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.

"Just as the same city
viewed from different directions,
appears entirely different
and, as it were,
multiplied perspectively,
in just the same way it happens that,
because of the infinite multitude of simple substances,
there are, as it were,
just as many different universes,
which are, nevertheless,
only perspectives on a single one,"

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What is fundamental, and what is emergent ?

Fundamental:

events,
causal relations,
energy momentum

But, what is an event: We define an event in a quantum presentist universe to be a process by which an indefinite property evolves to a definite property. Events thus are the mechanism for present moments to become past-and definite, whilst giving rise to an indefinite progeny. Events are what is happening in the present, to wipe out the past and gahether in and resolve the future.

What is fundamental, and what is emergent ?

Fundamental:

events

causal relations

energy-momentum

Emergent:

spacetime

(configuration) space

gauge fields

geometry

light cone

quantum mechanics

$[\cancel{x}, p] = [0,p] = \cancel{i\hbar} = 0$ the algebra of be-ables is commutative!!

THE CAUSAL THEORY OF VIEWS

BASIC IDEAS

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- ***What is real?***

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

More precisely: ***an event is an active process, which resolves some indefiniteness to definiteness, then gives rise to its descendents and is no longer.***

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

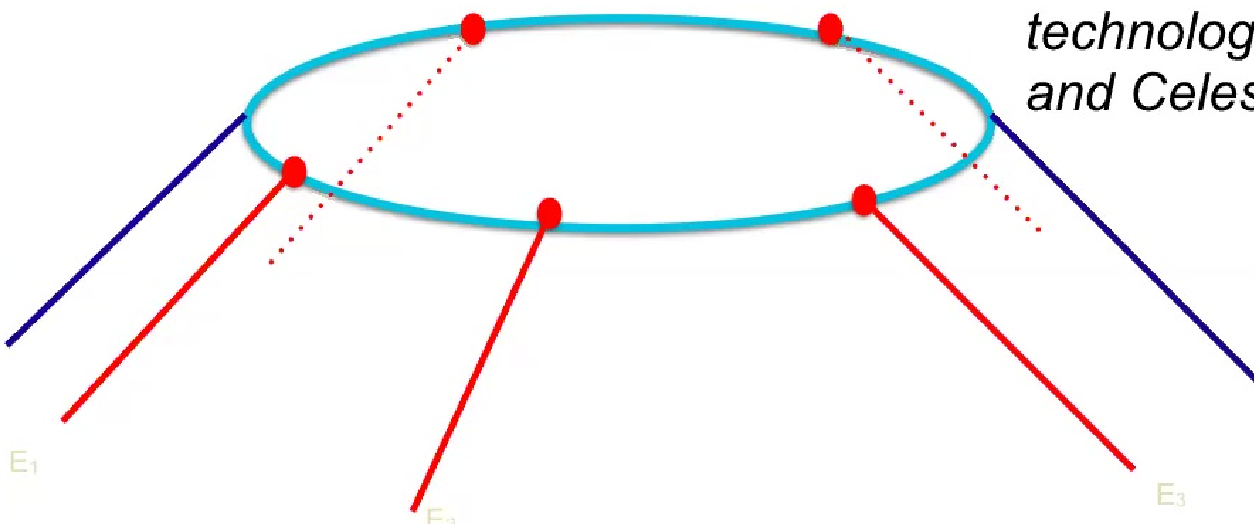
The fundamental action is a function only of these only.

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. $\{ p_{a\,I}^{J} , p_{a\,I}^{K} , \dots \}$.

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

Connects to boundary Chern-Simons technology and Celestial CFT



❖ ***What is emergent?***

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

❖ ***How is dynamics defined?***

- *By a half-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)= difference in their views

❖ ***What replaces kinetic energy?***

Differences of views of causally related events

❖ ***What replaces potential energy?***

Variety, Q: a measure of the diversity of causally unrelated views.

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

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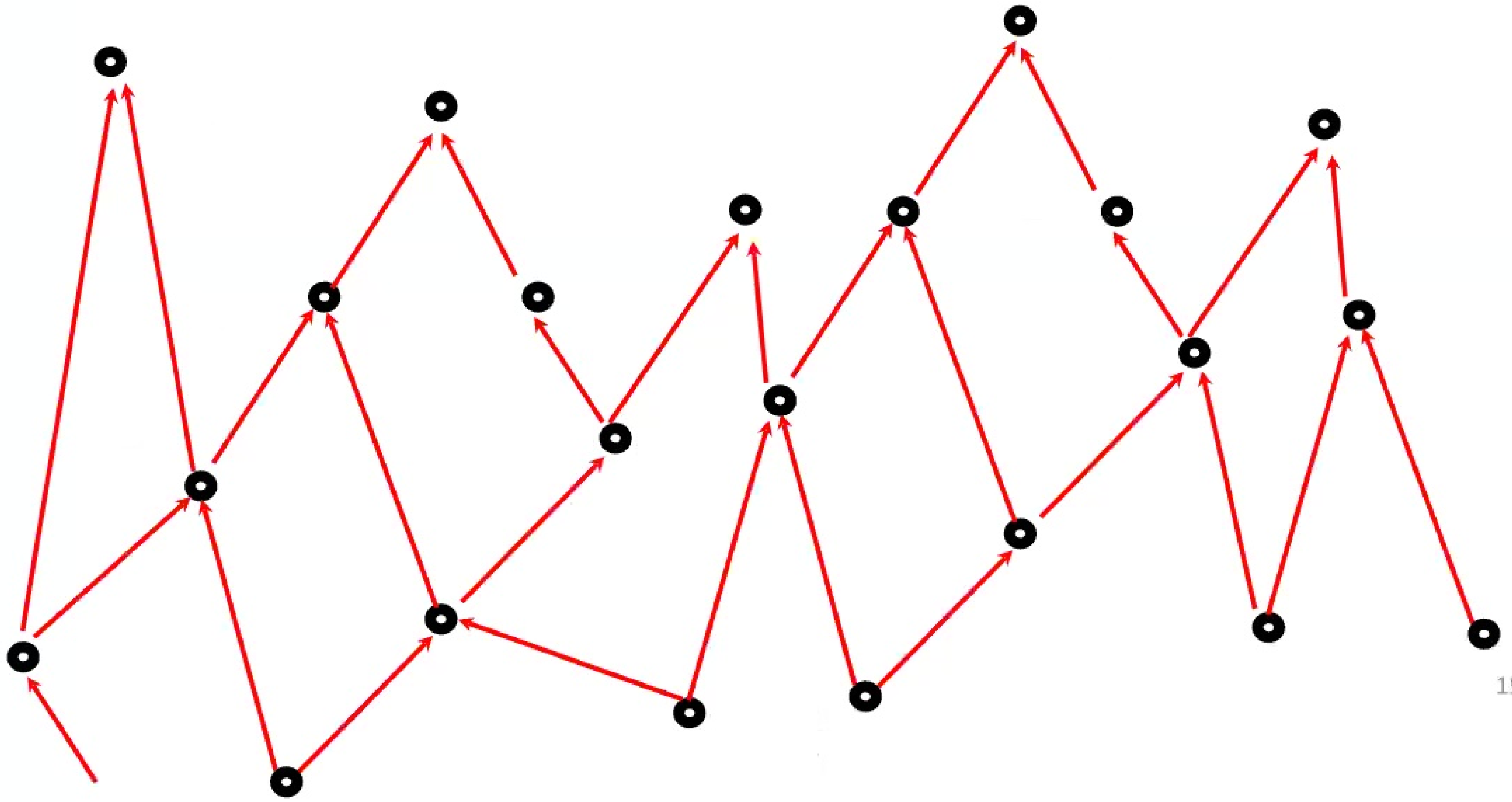
CAUSAL SETS



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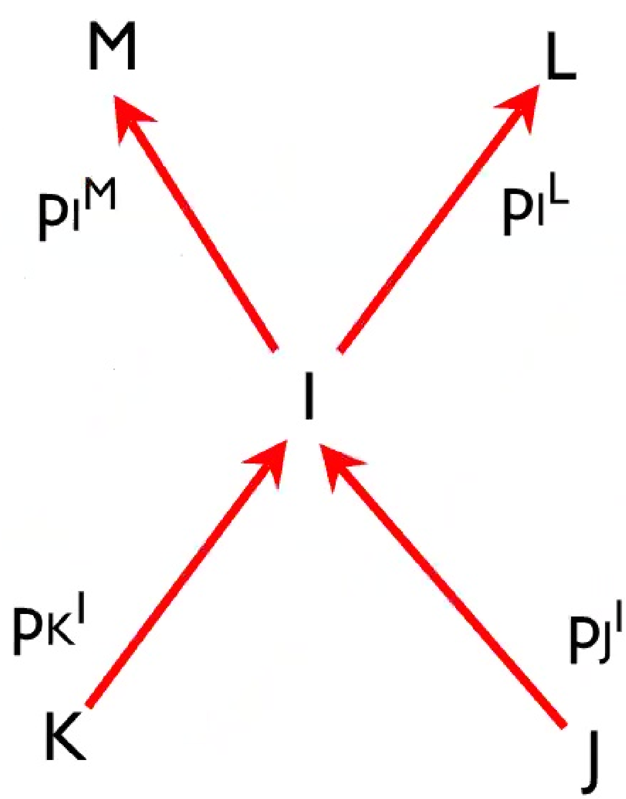
ENERGETIC CAUSAL SETS



The total momenta of an event

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

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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.

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Dynamics has two acts:

1) ***Pick a process (causal structurre, or graph)***

2) ***Sum over unconstrained energy-momentum***

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

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

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

This is the complete definition of the theory.

No hbar

No space or spacetime

No commutation relations

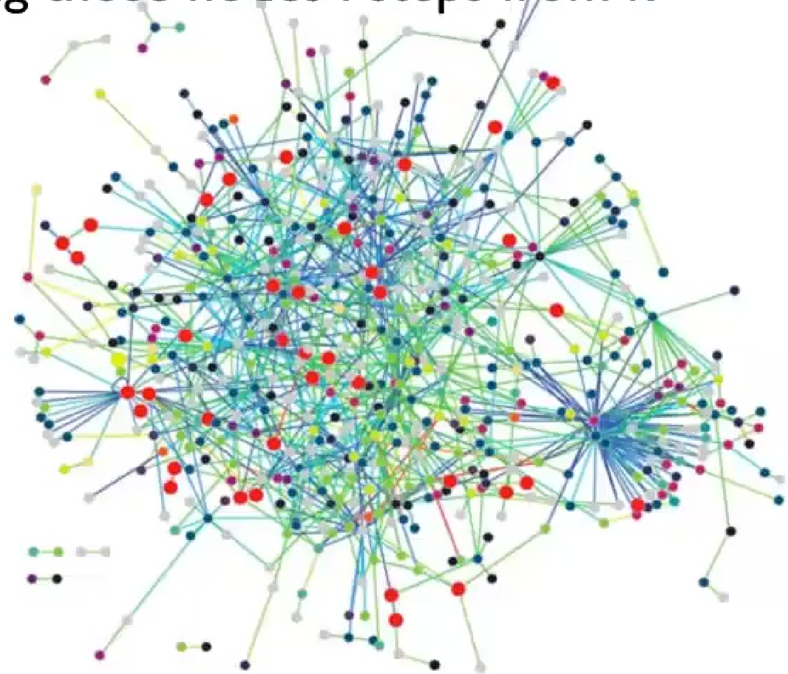
No uncertainty principle

Non-local, because Q is.

VARIETY

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)

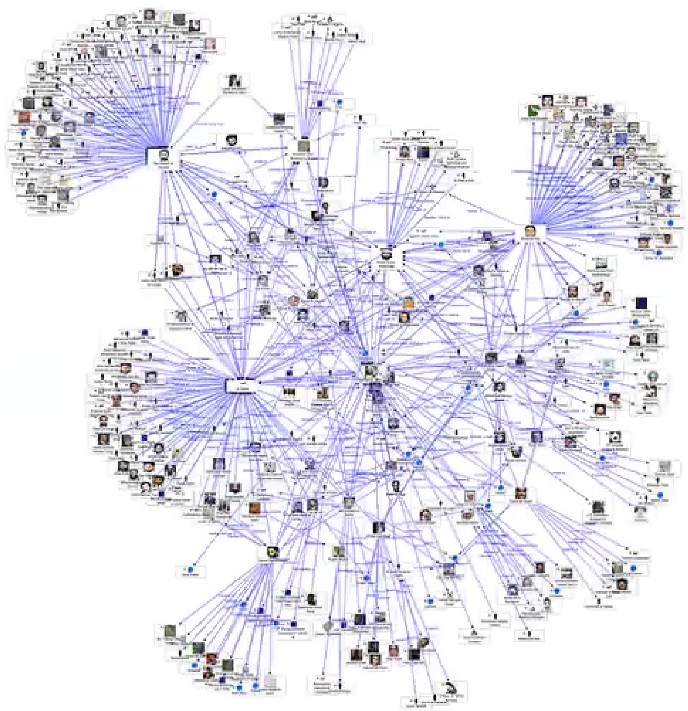
- The distinctiveness of the pair is

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

- The variety of G is

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

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



High variety

healthandsociety.columbia.edu

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

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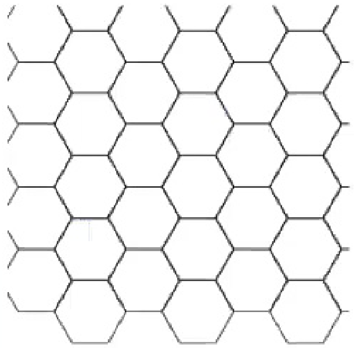
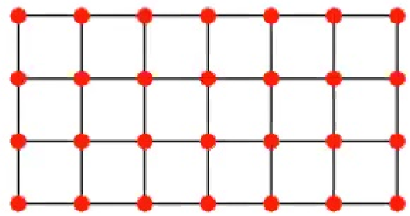
Low variety





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

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

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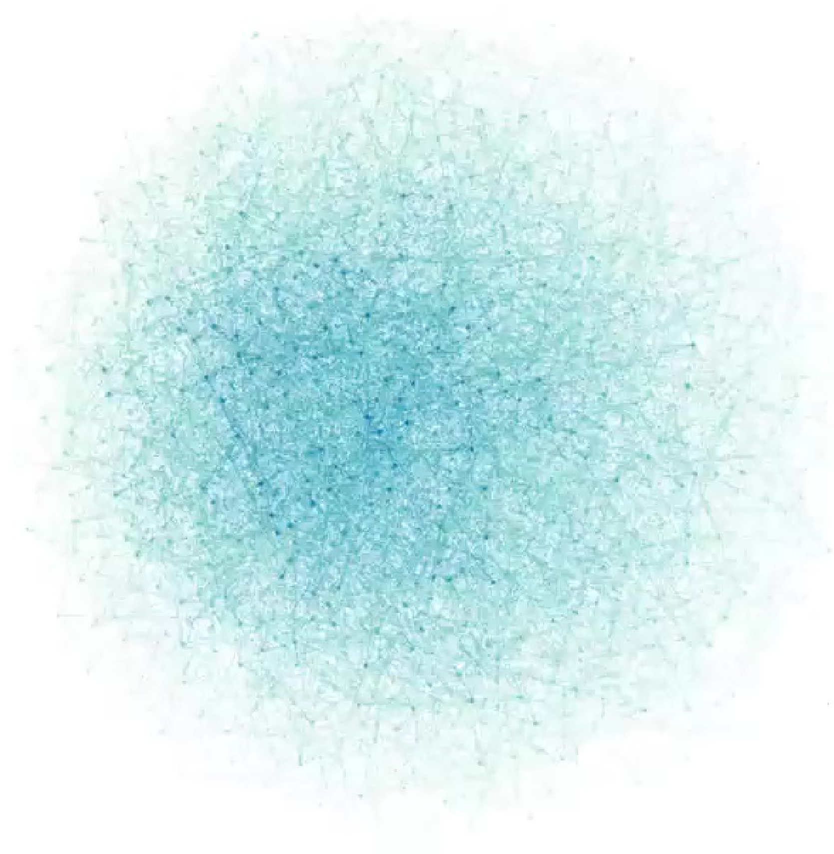
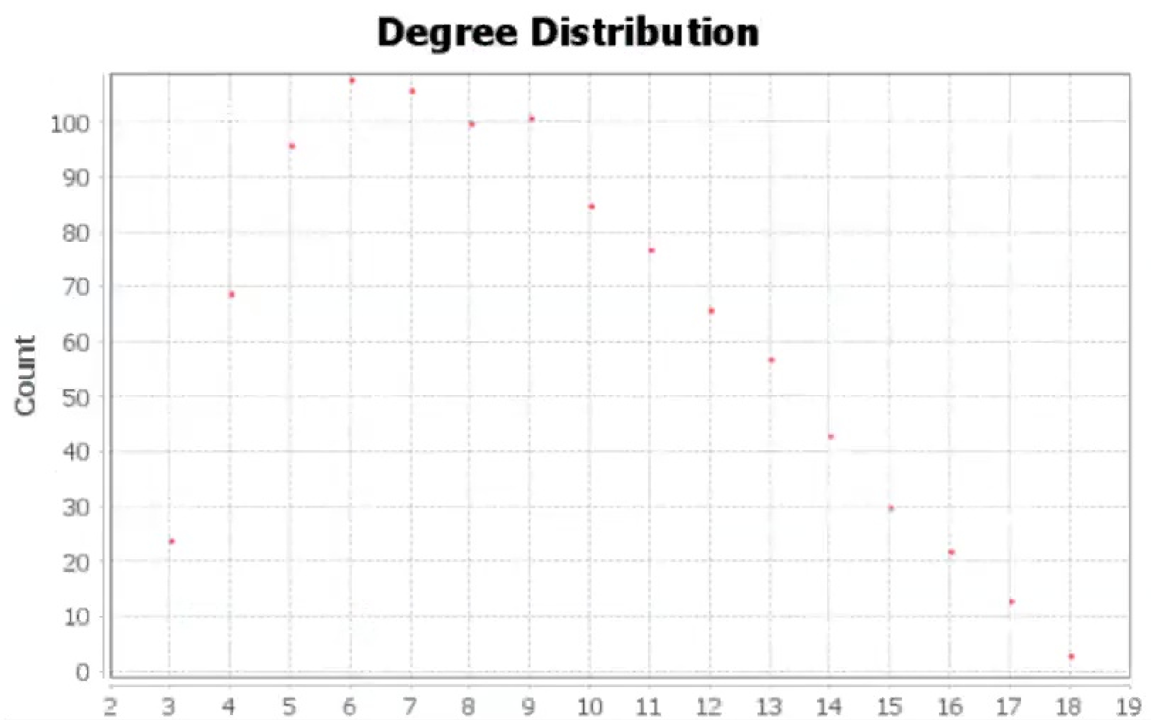
High variety

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



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

High variety



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

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

We posit that variety contributes to potential energy, while kinetic energy measures change in variety in time

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

ie the universe evolves so as to increase its variety.

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THE ACTION

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$$Z[\Gamma] = \prod_{J|>K\in\Gamma} \int dp_a^K{}_J \prod_I \delta(\mathcal{P}_a^I) e^{-\imath\mathcal{H}(P)}$$

$$\mathcal{H} = gT + g'U$$

Kinetic energy

Potential energy

$$\frac{g'}{g^2} = \frac{\hbar^2}{8m} Z_V$$

$$\mathcal{W}_a^I = \sum_{K \in \mathbf{Past(I)}} \frac{p_{aK}^I}{|p_{aK}^I|^w}$$

View from event, I consists of momentum passed to I from k in the immediate past.

$$\mathcal{D}(I, J) = (\mathcal{W}_I - \mathcal{W}_J)^2$$

Difference of two views I and J.

$$T = (\sum_{I|>J} \left(\sum_{I>K} p_{aK}^I - \sum_{J>L} p_{aL}^J \right)^2$$

Kinetic energy, summed over all causal pairs.

$$\mathcal{U} = \mathrm{U}_{<>} = \sum_{I<>J} \left(\sum_{I>K} \frac{p_{aK}^I}{|p_{aK}^I|^2} - \sum_{J>L} \frac{p_{aL}^J}{|p_{aL}^J|^2} \right)^2$$

Potential energy, summed over all causal pairs.

$$\boxed{\mathcal{H} = gT + g'\mathcal{U}}$$

The delta functions of the energy-momentum constraints are exponentiated, inventing a lagrange multiplier for each one, the z^a_I

$$Z = \prod_J^K \int dp^K_{a\ J} \prod_I \int dz^a_I \; e^{\imath(-\sum_I z^a_I \mathcal{P}^I_a + gT + g'\mathcal{U})}$$

Lagrange multiplier: z

Effective action

$$S^{eff} = -\sum_I z^a_I \mathcal{P}^I_a + gT + g'\mathcal{U}$$

Stationary phase approximation

$$p^J_{aK} = \frac{1}{gn^2_{pre}}(z^a_J - z^a_K) - \frac{g'}{gn^2_{pre}} \mathcal{T}^{ab}(\mathcal{W}^J_b - \mathcal{W}^K_b)$$

$$\dot{z}^a \approx p^a g n_c^2 + \dots$$

$$\delta p_a = \delta p^T_a + \delta p^L_a$$

Transverse projection in momentum space

$$\mathcal{T}_{ac} = [\delta_{ac} - \frac{p^L_{aK} p^L_{cK}}{|p^L_{aK}|^2}],$$

Probability distribution function: pdf = ρ (z)

$$< \mathcal{A} >= \frac{1}{N}\sum_{K=1}^{N}\mathcal{A}(z_K) \to \int_a^R d^d z\rho(z)\mathcal{A}(z) \qquad \int_{\mathcal{C}} \rho = 1$$

$$\begin{aligned} < \mathcal{A}(z_I^a) > &= \frac{1}{Z}\prod_J^K \int dp_a^K{}_J \prod_I \int dz_I^a \mathcal{A}(z_I^a) e^{\imath S^{eff}} \\ &= \frac{1}{Z}\prod_I \int dz_I^a \mathcal{A}(z_I^a) \prod_J^K \int dp_a^K{}_J e^{\imath S^{eff}} \end{aligned}$$

ρ***(z)*** ***Normalized density function on emergent space of z's.***

Coarse graining = averaging over small scale dof= RG
Average over micro def to make room for simple probabilities over MDF.

We split p into transverse and longitudinal: we integrate over the transverse fluctuations The longitudinal are the gradients of phases.

$$\partial_a S = p_a^{L}$$

$$Z = \prod_J^K \int dp_a^K{}_J \prod_I \int dz_I^a \, e^{\imath(-\sum_I z_I^a \mathcal{P}_a^I + gT + g'\mathcal{U})}$$

$$Z(\rho, S) = \int d\rho dS e^{\imath \mathcal{S}^{cg}}.$$

$$\mathcal{S}^{cg}(\rho(z), S(z)) = \int dt \int_{\mathcal{C}} \rho(z,t) \left[\dot{S} + g n_{pre}^2 g^{ab} (\partial_a S(z,t))(\partial_b S(z,t) + \frac{g'}{g^2} \mathcal{U}(z) \right]$$

$$U^{eff} = \frac{g'}{g^2} \sum_{I<>J} \left(\sum_{K \in \mathbf{Past(I)}} \frac{z_I^a - z_K^a}{|z_I^a - z_K^a|^2} - \sum_{N \in \mathbf{Past(J)}} \frac{z_J^a - z_N^a}{|z_J^a - z_N^a|^2} \right)^2 + C + \mathcal{O}(g'^2)$$

$p_a = \delta S$

$$S^{II} = \sum_I z_I^a \mathcal{P}_a^I + \mathcal{Q}_{causal} + \mathcal{Q}_{acausal}$$

$$= \int_{\mathcal{C}} \rho(\dot{S} - \frac{1}{2m}(p_a)^2 - \mathcal{U}_{Bohm})$$

$$\frac{g'}{g^2} = \frac{\hbar^2}{8m} Z_V$$

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Putting everything together:

$$S = \int dt \int d^d z \rho(z) \left[\dot{S} + \frac{(\partial_a S)^2}{2m} + \frac{\hbar^2}{8m}(\frac{1}{\rho}\partial_a \rho)^2 + U + O(\frac{1}{r}) + O(\frac{1}{N}) \right]$$

Equations of motion:

quantum potential

$$\dot{\rho}(x^a) = \partial_a(\rho \frac{1}{m} g^{ab} \partial_b S(x^a))$$

$$-\dot{S} = \frac{1}{2m} g^{ab} (\frac{\partial S}{\partial x_{a\alpha}})(\frac{\partial S}{\partial x_{b\alpha}}) - \frac{\hbar^2}{2m} \frac{\nabla^2 \sqrt{\rho}}{\sqrt{\rho}} + U$$

These are the real and imaginary parts of the Schroedinger equation:

$$\Psi(x,t) = \sqrt{\rho} e^{\frac{\imath}{\hbar} S}$$

$$\imath\hbar \frac{d\Psi}{dt} = \left(-\frac{\hbar^2}{2m} \nabla^2 + U \right) \Psi$$

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The kinetic energy gives the HJ equations

The momentum is cyclic so there is an HJ function st in ensemble averages:

$$p_a(s) = \partial_a S(x(s), s), \qquad \dot{p}_a(w) = \partial_a(\rho(w)\dot{S}(w))$$

The ensemble average of the kinetic energy is an action the for HJ eq.

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

Add to this the < variety > gives an action for the Schrodinger eq. .

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

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

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.

$$\imath\hbar\frac{d\psi}{dt} = \left[-\frac{\hbar^2}{2m}\nabla^2 + U \right]\psi$$

$$\psi = \sqrt{\rho} e^{\frac{\imath}{\hbar}S} e^{-\imath mc^2 s}$$

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

By following the expansion we find a non-linear correction to the Schrodinger equation.

$$\imath\hbar\frac{d\Psi}{dt} = \left(-\frac{\hbar^2}{2m}\nabla^2 + U + \Delta U^Q(\bar{\Psi}\Psi)\right)\Psi$$

Where

$$\Delta U^Q = \frac{r'^2}{N^{\frac{2}{d}}}\frac{d}{d+2}\frac{\hbar^2}{2m}\left[\frac{\nabla^4\rho}{\rho} - 2\frac{(\nabla^2\rho)^2}{\rho^2} - 2\frac{(\nabla^a\rho)(\nabla_a\nabla^2\rho)}{\rho^2}\right]$$

N=size of the ensemble
r' = infrared cutoff

Note that probability is conserved.

EMERGENCE OF SPACETIME FROM ENERGETIC CAUSAL SETS

The adjacent possible (to do)

- ✓ Build the special relativist version, using the Celestial Spheres
- ✓ Incorporate general relativity by adding dynamical connections,
- ✓ to conservation laws.
- ✓ Do a QFT version a la amplitude computations.

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The adjacent possible (to do)

- ✓ Build the special relativist version, using the Celestial Spheres
- ✓ Incorporate general relativity by adding dynamical connections,
- ✓ to conservation laws.
- ✓ Do a QFT version a la amplitude computations.
- ✓ Explore deformations of momentum space.
- ✓ Spacetime is emergent from the causal structure these transfers generate (dual Noether theorem)

Summary

- ✓ The universe consists of views of the causal pasts of present events
- ✓ Systems with similar views interact; this replaces locality
- ✓ These interact through a potential that acts to increase the diversity of views, called the variety
- ✓ Events are causally connected by transfers of energy-momentum
- ✓ Spacetime is emergent from the causal structure these transfers generate (dual Noether theorem)
- ✓ Similar views group into real ensembles which interact strongly
- ✓ These non-local interactions generate Bohm's quantum potential, and hence explain and complete quantum mechanics
- ✓ Large systems have no near copies; this solves the measurement problem