Title: A la recherche du temps perdu....in quantum gravity

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Abstract: Causal set quantum gravity is based on the marriage between the concept of causality as an organising principle more basic even than space or time and fundamental atomicity. Causal sets suggest novel possibilities for "dynamical laws" in which spacetime grows by the accumulation of new spacetime atoms, potentially realising within physics C.D. Broad's concept of a growing block universe
in which the past is real and the future is not. To do justice to relativity and general covariance, the atoms must accumulate in a partial order, exactly the order that the atoms have physically amongst themselves. That this is possible is demonstrated by the Rideout-Sorkin Classical Stochastic Growth models. This proof of concept -- of the compatibility of relativity and ``becoming" -- is, however, classical and is challenged by the global character of the physical world within a path integral framework for quantum theory. Out of the struggle to reconcile the global and local natures of the physical world may arise a quantal dynamics for causal sets.

A la recherche de temps perdu...
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Fay Dowker
Imperial College

Perimeter Institute May 2013

Time in classical relativity: something gained, something lost

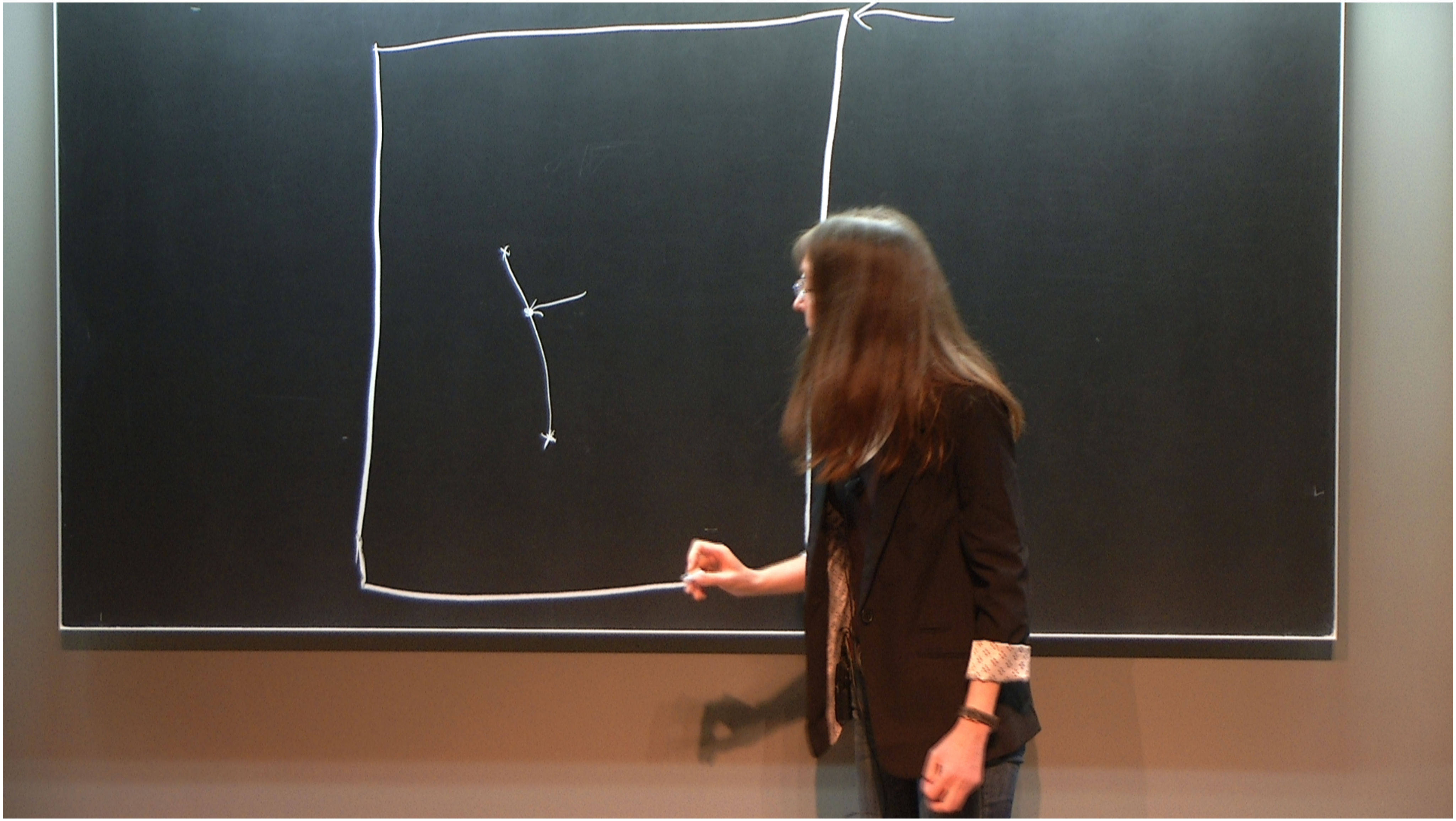
In pre-relativistic physics, time was "spatialised" as (merely) a fourth dimension.

The revolution of Relativity banished the concept of global simultaneity as unphysical: there is no global "Now". Physical time, proper time elapses **locally** along worldlines. One reason that learning about Relativity is so emotionally satisfying is that this better scientific understanding **accords** with our experience (and intuition derived therefrom) that time is local. Relativity also restores to physics the distinction between time and space via the Lorentzian (- +++) metric signature.

So, something crucial about time has been recovered by relativistic physics.

However, General Relativity also shows that the physical world has a 4-dimensional character: it is a spacetime. Spacetime cannot be understood as the evolution in time of a physical, 3-dimensional entity.

So, there's no global Now & the physical world is a spacetime: a "block universe"?

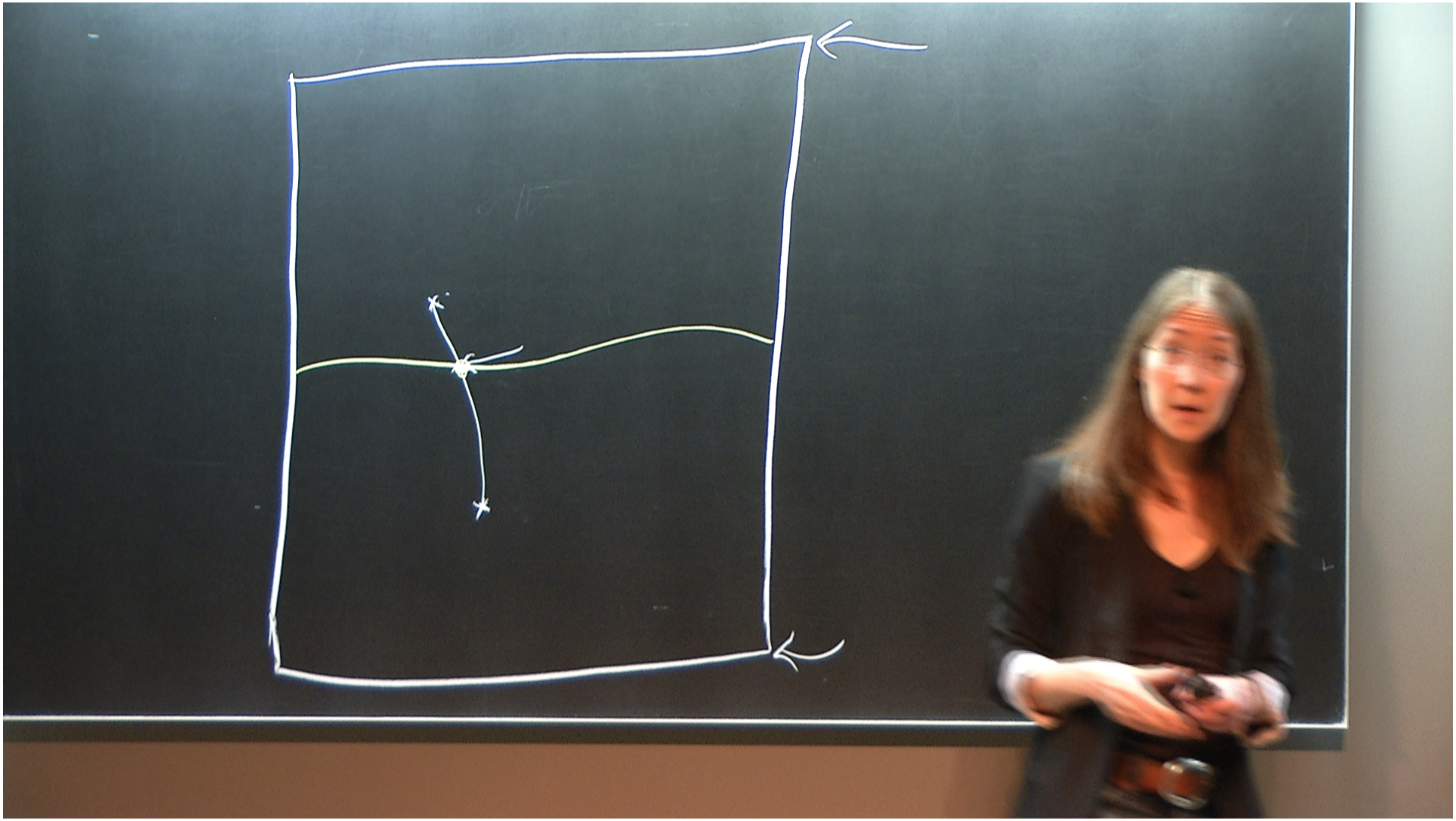


In search of the temporality lost in the Block

To do justice to the temporal nature of our perception whilst maintaining the spacetime nature of reality, a "growing block" seems natural **(Broad)**: the 4-dimensional spacetime in the past is real

> The Moving Finger writes; and, having writ,
> Moves on: nor all your Piety nor Wit
> Shall lure it back to cancel half a Line,
> Nor all your Tears wash out a Word of it
>
> Omar Khayyam (trans. Fitzgerald)

This requires a process of "becoming" that cannot be merely an unveiling of the block because that would introduce a physical, global time. Is this possible to realise within physics?



Quantum Gravity: we must be radical and yet conservative

The Quantum/Gravity boundary is where physics is at its least, and most unified.

In working towards quantum gravity, science will have to "make the leap to a new conception" **(Jacobson & Parentani)**. To arrive at a theory of quantum gravity we must make a creative leap, from a position that is grounded in current knowledge. Identifying that "grounded position" is itself a creative act: at any stage in the evolution to a new theory, there will be diverse views on which aspects of our current understanding will survive and which will turn out to be "excess baggage" **(Hartle)**.

The causal set approach claims that certain aspects of General Relativity and quantum theory will have direct counterparts in quantum gravity: the **spacetime causal order** from General Relativity and the **path integral** from quantum theory. It makes one main new hypothesis about the nature of the physical world: **fundamental discreteness of spacetime**.

Taken together, these three things form the bare bones conceptual basis of causal set theory: the spacetime causal order and atomicity furnish the kinematics and the path integral provides the framework for the quantum dynamics.

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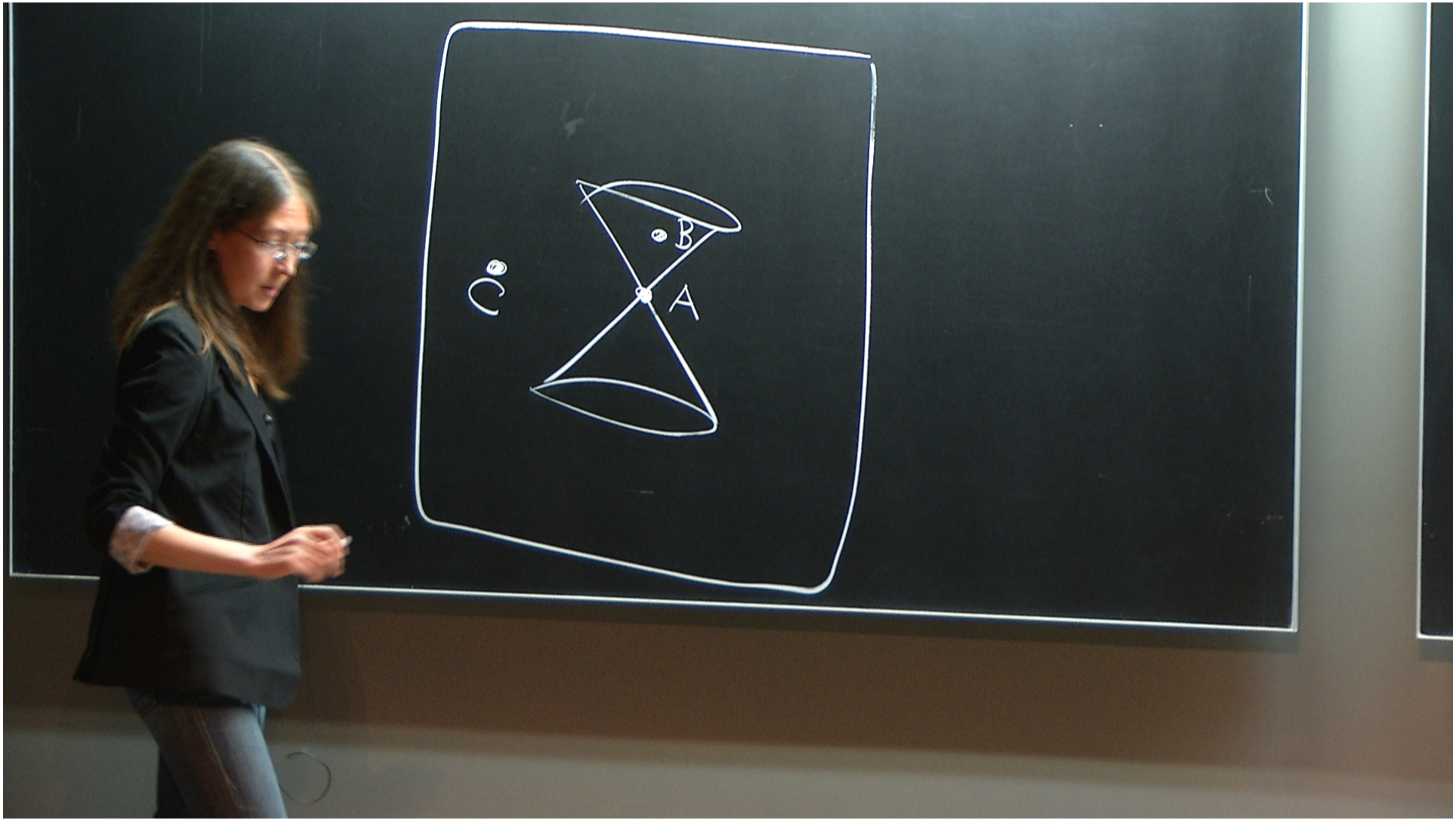
Causal structure at the heart of General Relativity

Spacetime in General Relativity has a causal order. That causal order is fundamental to understanding General Relativity.

The epitome of the theory is a Black Hole and our understanding is in 4-dimensional, spacetime, causal terms. For example, Hawking's area theorem (the classical limit of the second law of black hole thermodynamics) is proved using global causal analysis -- it cannot be understood in terms of three dimensional physical entities. Indeed there is compelling evidence that the Laws of Black Hole Thermodynamics are a special case of unified "Laws of Causal Horizon Thermodynamics" **(Jacobson&Parentani)** including deSitter and Rindler horizons.

This causal order **unifies within itself** the topology (inc. dimension), differentiable structure, 9/10 of the metric, and the causal structure of a Lorentzian manifold **(Robb, Alexandrov, Zeeman, Penrose, Hawking, Malament)**

Spacetime in General Relativity almost **is** a causal order.



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Causal sets: the marriage of causality and atomicity

The missing tenth of the geometry, not given by causal order, is local physical **scale.**

To account for spacetime as we know it, need to provide causal order and physical scale. Discreteness does the job because we can **count** (c.f. psychological awareness of "duration")

Order + Number = Geometry

Now, it is widely expected that the differentiable Lorentzian manifold structure of spacetime will break down at the Planck scale. Fundamental spacetime atomicity is perhaps the simplest way to realise this expectation. It happens to be **exactly** what is necessary if one is drawn to conceive of spacetime as "pure causal order". A causal set is a discrete causal order:

"Not a marriage of convenience but the uniting of soul mates"

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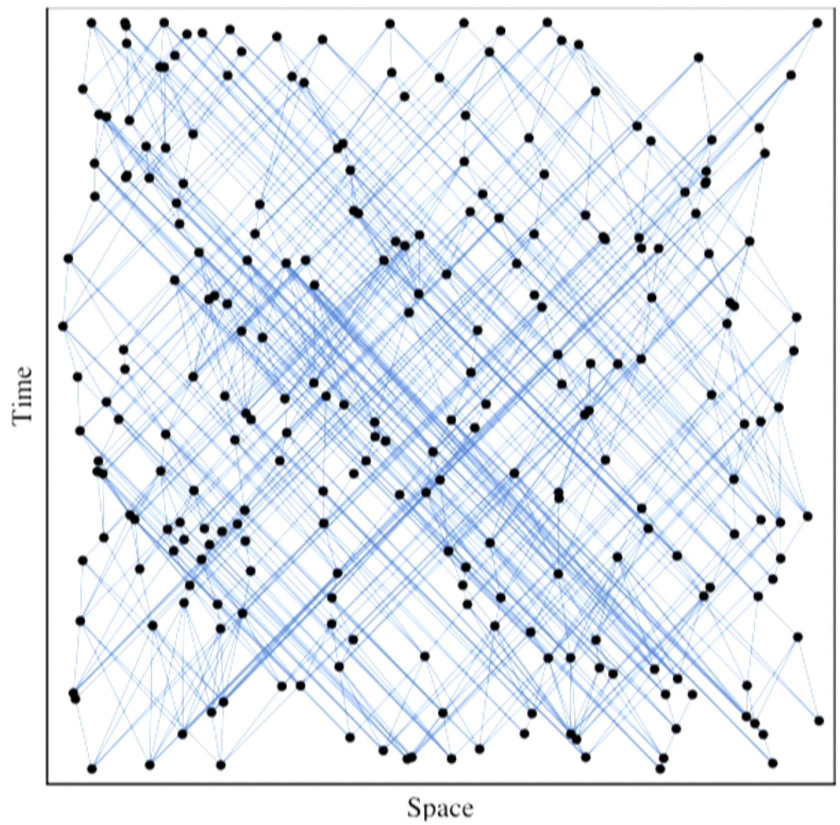
A causal set that is well approximated by 2d Minkowski space



- Hasse
- dimension
- Lorentz inv
- nonlocal
- relational
- austere
- no background

On Planckian scales, this is what Minkowski space is (like)
Not just Minkowski, any Lorentzian manifold

A Causal Set is a discrete order

A causal set (or causet) is a set, C, with a binary relation, $\preccurlyeq$, referred to as "precedes," which satisfies:

* Transitivity: if $x \preccurlyeq y$ and $y \preccurlyeq z$ then $x \preccurlyeq z$, $\forall x, y, z \in C$;
* Acyclicity: if $x \preccurlyeq y$ and $y \preccurlyeq x$ then $x = y$, $\forall x, y \in C$;
* Local finiteness: for any ordered pair of elements x and z of C, the cardinality of the set $\{y \mid x \preccurlyeq y \preccurlyeq z\}$ is finite

The first two axioms say that C is a **partial order**. The third axiom is what makes the set **discrete**. The elements of C are the atoms of spacetime

The deep structure of spacetime is a causal set

At macroscopic scales, the order $\preccurlyeq$ gives rise to the spacetime causal order and the number of elements gives the spacetime Volume: Number $\approx$ Volume

('tHooft; Myrheim; Bombelli, Lee, Meyer, Sorkin)

Causal set quantum gravity

- A quantum theory of causal sets will be based on the path integral: there is no apparent sense to be made of a "canonical" quantum theory of causal sets.
- Basing Quantum Theory fundamentally on the path integral requires new work but for now, all that is needed is the notion that
- Path integral Quantum Theory is a species of generalised stochastic process: Quantum Mechanics is a generalisation of Brownian motion or a random walk.

Therefore, as a warm up for quantum causal set theory, it makes sense to construct classical stochastic models for causal sets: random causal sets......there's a vast array of possibilities for probability distributions.....how to choose something that has some chance of being physically relevant as a "law of motion" for a discrete spacetime?

The notion of **becoming** played a heuristic role in the discovery of an interesting class of models.

Classical sequential growth models (Rideout&Sorkin)

- A random process of continual births of new spacetime atoms.
- No atom is born to the past (below) any already existing atom, otherwise any order of birth is possible.
- We want the two runs to be different representations of the same physics: the only thing physical about the birth order should be the order relation of the causal set that results -- the rest is pure "gauge". How to capture this mathematically?

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Discrete General Covariance

- General Covariance in general relativity means that **coordinates** on spacetime are unphysical.
- The analogue here is **label invariance** or birth order invariance.
- The probabilities of the two ways of arriving at the same causet should be equal.
- That condition and a local causality condition (called Bell causality) severely restrict the models.

- A Classical Sequential Growth model, specified by a sequence of positive real numbers

$$t_0 = 1, t_1, t_2, t_3, \ldots$$

- The class contains some fascinating models, with suggestive properties
- In one class, without fine tuning the t's (couplings), the causet that grows takes the form of a universe that grows to a certain size, collapses to a single point, re-expands, collapses, re-expands....... infinitely often, getting larger and lasting longer in each successive epoch **(Brightwell, Martin, O'Connor, Sorkin)**

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Physics is dynamic, mathematics is static

- The growth model is as close as it seems to be possible to come to capturing the notion of asynchronous becoming. But......

- I can **show** you **in real time** the model process. But once it is said, written down, communicated in words and equations, the description becomes static.
- Even the "showing" doesn't work for sequential growth because any given active demonstration of the growth introduces the unphysical "pure gauge" total order of the appearance of the elements.
- Resort to metaphor.....

- Causal set elements **are born**.

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Quantum causal sets: will "becoming" be lost again?

- CSG models are not **quantum** gravity.
- Two strategies for discovering Quantum Causet Dynamics

$$Z(N) = \sum_{\text{all } \mathcal{C}} e^{iS(\mathcal{C})}$$

We have proposals for causet actions in any dimension **(Dionigi Benincasa, FD, Lisa Glaser)**

We can start to do Monte Carlo simulations **(Sumati Surya)**

A quick and dirty interpretation of the path integral/sum: which configurations dominate? Are they manifold-like?

Quantum Sequential Growth

Replace probabilities by amplitudes in the model

Find the quantum analogue of Bell causality and solve for QSG.... Here causal set workers join forces with quantum information workers: what is the quantum analogue of local causality that will give us the Tsirelson, rather than Bell, inequalities?

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Quantum growth models

- Growth of **what** exactly?
- Seeking a model for quantum causal sets in which the physical world grows is thus entwined with the quantum foundational question: what **is** the physical world in a quantum theory? And how do we make predictions about it?
- Look again to theory of stochastic processes: "quantum mechanics is Brownian motion on acid"

Classical stochastic

$$\mu(\text{EVENT}) = \sum_{\gamma \text{ in EVENT}} p(\gamma)$$

If $\mu(\text{EVENT}) = 0$ then EVENT does not happen

Quantum stochastic

$$\mu(\text{EVENT}) = \left| \sum_{\gamma \text{ in EVENT}} a(\gamma) \right|^2$$

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Becoming can be a guide

If $\mu(\mathrm{EVENT}) = 0$ then EVENT does not happen

- In Brownian motion, the physical world is a single trajectory (history)
- In Quantum Mechanics, it cannot be a single history if the rule above holds: many proofs based on famous quantum antinomies, for example the Kochen Specker Theorem **(FD & Yousef Ghazi-Tabatabai)** and the GHZ state **(Dionigi Benincasa, Michel Buck & FD)**
- Seek a description of the physical world as close as possible to a single history -- a "generalised history"
- Can that generalised history have a growing character like the walker in a random walk taking steps, or the causet in a CSG?
- Here, again, growth is a heuristic in motivating directions of investigation

- Work in progress **(FD, Stan Gudder, Rafael Sorkin, Sumati Surya, Petros Wallden, Fern Watson)**

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Summary

- Relativity sets up a challenge to the notion of becoming because it tells us there is no such thing as a global physical present moment. And moreover the physical world in GR is a spacetime: it has a 4-dimensional character
- Causal set quantum gravity takes the structure at the heart of GR, the causal structure of spacetime and completes it by making it atomic.
- The atomicity provides new possibilities for laws of motion for spacetime: laws of growth
- The absence of a globally defined time is compatible with a physical process of becoming: in Classical Sequential Growth things happen, they just happen in a partial order
- It remains to be seen if this is possible in a quantum world
- Putting the struggle to work: maybe the requirement that a growing world find a place in quantum theory will guide us towards the correct quantum dynamics for causal sets.