Title: Solved and unsolved problems of time in quantum gravity

Date: Oct 02, 2008 09:00 AM

URL: http://pirsa.org/08100047

Abstract: I will identify six \'problems of time\' that arise in connection with quantum gravity and review the extent to which some of them can be regarded as solved, highlighting the very different aspects that they assume depending on one\'s starting point: Hamiltonian vs. path-integral, discrete vs continuous.

PoT 1. Canonical QG $\Rightarrow \Psi({}^3g)$ (or loop states ...)

$\Rightarrow$ the need to **recover time**

Unimodular aside

Unimodular grav yields $\Psi({}^3g, T)$ where $T = {}^4V$
(more precisely $\delta T = \int_\Sigma N\, dt\, d^3x$ [densitized lapse])

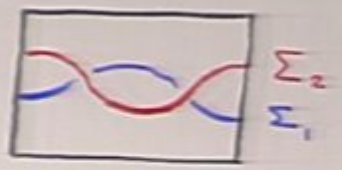
$i\partial\Psi/\partial T = \int \hat{H} N d^3x$

where can use any N such that $\int N d^3x = 1$
(all such N are equivalent by the surviving constraints: $\int N d^3x\, |\psi> = 0$ if $\int N d^3x = 0$)

This recovers a little bit of time,
but only one "finger" of the "many"

(It's all you need for Bianchi cosmos though!)

It doesn't let you, eg, ask about BH horizon,
since it doesn't yield a spacetime.
Also has trouble in $\sim$ flat context



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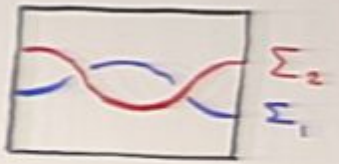


So PoT 1 is the most blatant problem of time.

But whence this frozen formalism anyway?

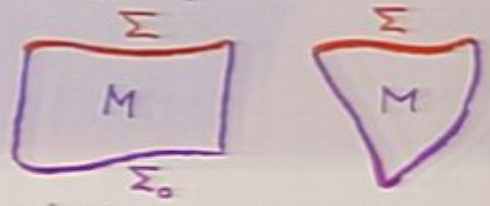
From Diff(^4M) !

Easy to understand in path $\int$:

It clearly doesn't matter where you put Σ

But $\widehat{H}$ "moves Σ around"

so $\delta\Psi = 0 \;\Rightarrow\; \widehat{H}\Psi = 0$



(To obtain unimodular formulation, we fix volume of M. This is invariant $\Rightarrow$ well defined. But it still leaves most of the slicing freedom.)

So in a more general sense, problems springing from Diff are also "PoTs" and we have ...

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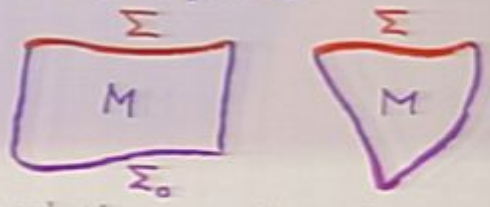

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PoT 2. Problems of principle springing from diffeomorphism invariance

A prime example:

How find variables (observables/beables) that are covariant (well defined)?

And how recognize their physical meaning?

Thus in canonical QG, $\widehat{O}$ ♮ constraints

Can find many (perhaps), but what do they mean?

Any operator in the "physical Hilbert space" is an observable, but . . . !

PoT 3. Technical problems flowing from diff-invariance

E.g. What is the measure-factor in the path integral?

Or the inner product in canonical QG?

Diff(M) is not compact ⇒ hard to divide out by Vol(Diff)

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PoT 4. Absence of Wick rotation (also an aspect?)

PoT 5. Problem of becoming: "Do things happen?"
(No unique slicing)

PoT 6. Problem of the "arrow of time"
(An opportunity for QG?)

Three roads to "quantization"

What is a quantum theory? (eg QFT)

(1) canonical: $[\widehat{q},\widehat{p}]=i\hbar,\quad \widehat{H}$

(QM as generalized Hamiltonian mechanics)

(2) path $\int$: $\int e^{iS(\gamma)}d\nu(\gamma)$,

(QM as generalized stochastic process)

(3) "algebraic/qft": $g_{ab}(x)\to\widehat{g}_{ab}(x)$

operator Einstein eqs.

$[\widehat{g}_{ab}(x),\widehat{g}_{cd}(y)]$ = Peierls bracket

(operationalist??)

Goldilocks:

(1) has too little time

(3) has too much (but all gauge!) no top change

(2) is "just right"

Consider sum-over-histories QG — continuum version
(eg CDTs, $\sim$ safety(?))

PoT 1: absent! nothing to recover
Could stop lecture here!

PoT 2: ameliorated, maybe soluble
($\exists$ many "observables", enough?)

PoT 3: some good ideas, many problems

(Cute illustration of some of these conceptual issues: paper with Sudarsky on large fluctuations in entropy; related issues: how define S? need ρ?)

The path $\int$ answer to What is a quantum theory?
is incomplete. We lack a free-standing path $\int$ theory.

Usually people write the path-integral as $\int_{\Sigma_0}^{\Sigma_1} e^{iS(\gamma)}$
and think of it as a propagator for ψ
and base its interpretation on ψ.

We need to free the path integral from ψ
(cf decoherent histories, q-measure μ).

We need to answer **What is a quantal reality?**
and to do so without presupposing a background causal structure (see anhomomorphic coevents).

What is the continuum decoherence functional for gravity even formally?! question rarely posed

But I want to devote the rest of this talk to some of the remaining PoTs in the context of sequential growth dynamics for causets.

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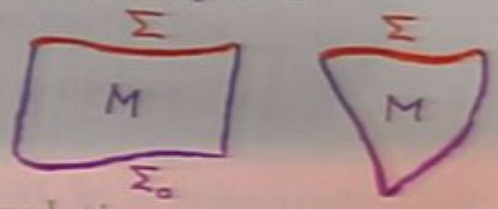

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Causal sets (causets)

discreteness helps cure ∞s.

"explains" why metric (and why $(-+++)$).

causets carry on "tradition of causality"

Order + Number = Geometry

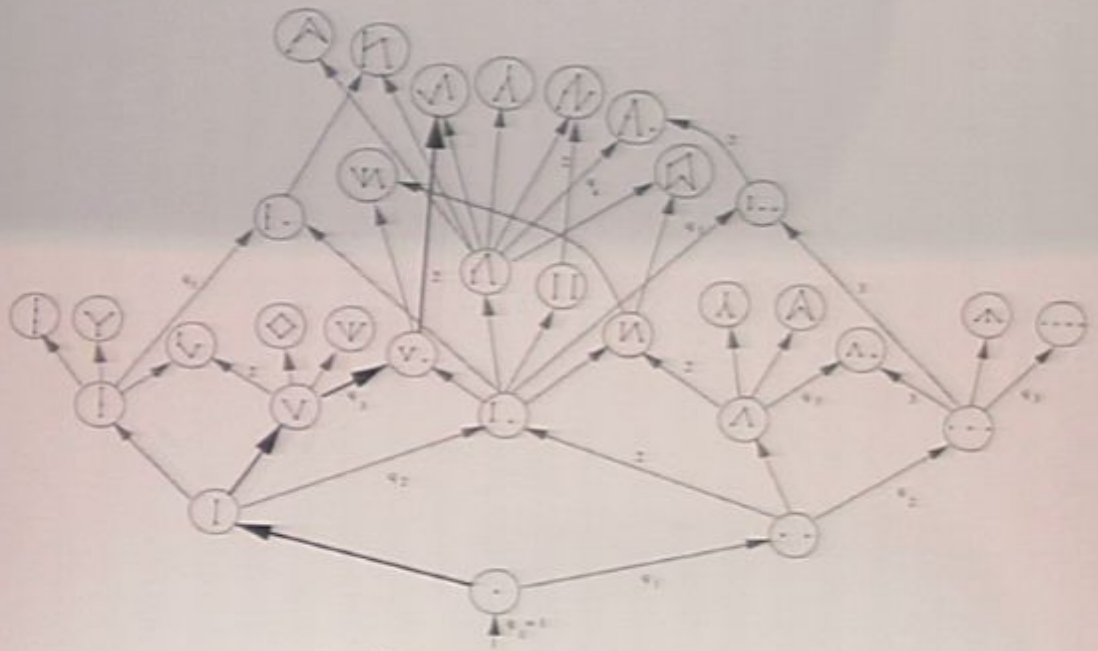
def: causet = past-finite partial order

The dynamics of sequential growth

We still lack QSG but have CSG

It partly reproduces manifold

It serves as laboratory for problems of time

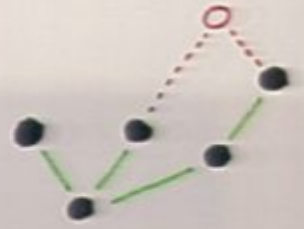


The poset of finite causal sets

The CSG models (a classical dynamics)

Random walk through "poscau"

The transition probabilities



$$Prob = \frac{\lambda(\varpi, m)}{\lambda(n, 0)}$$

$prob = p^2(1-p)$

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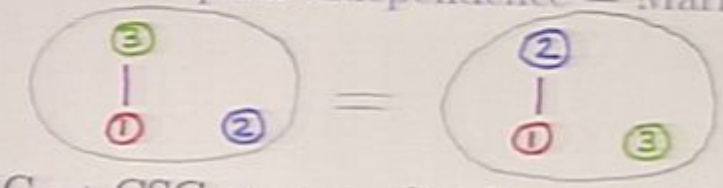
The meaning of general covariance (GC)

label invariance = path independence = Markov



(GC + BC → CSG as generalized percolation)

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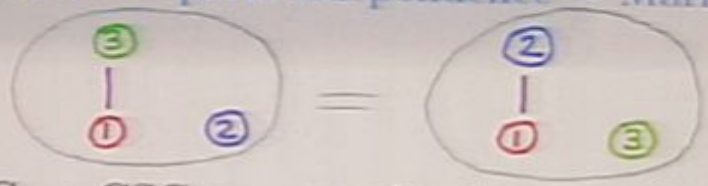

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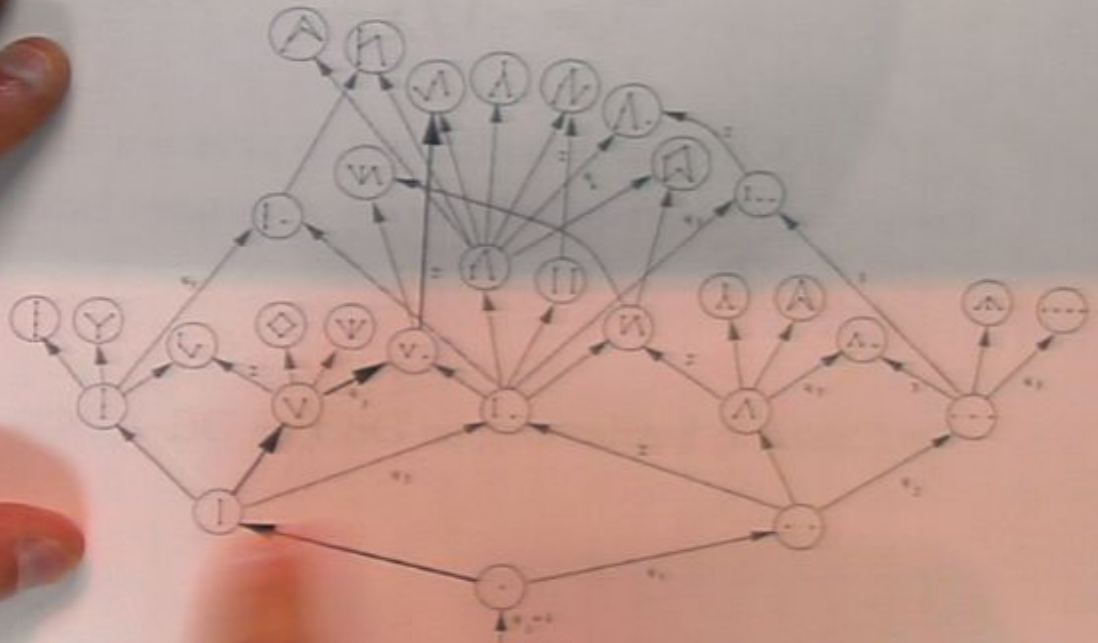

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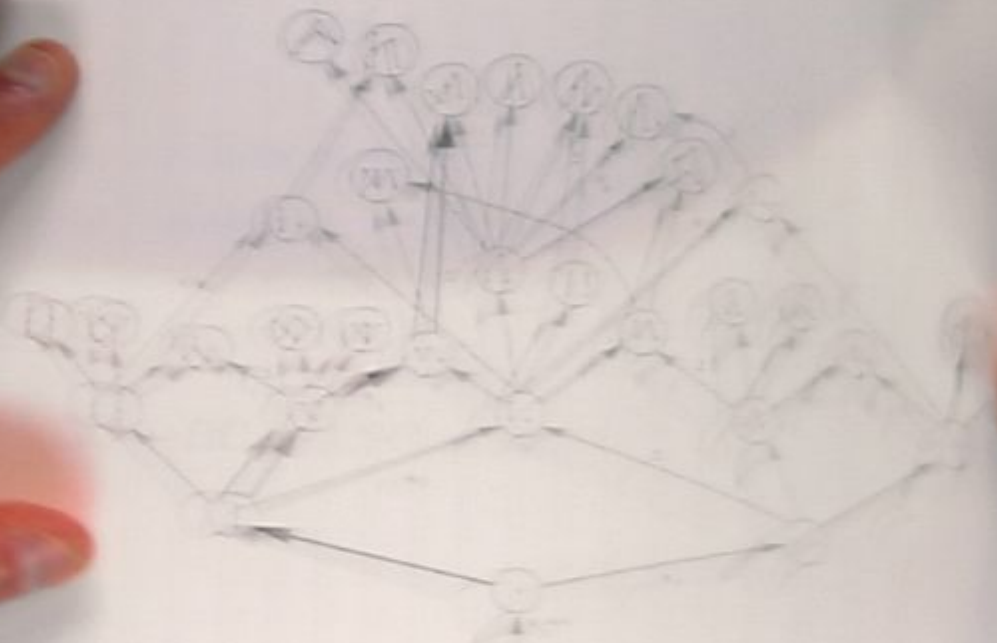

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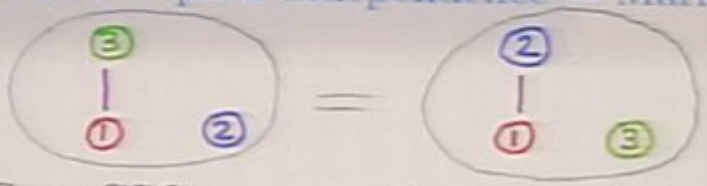

(GC + BC → CSG as generalized percolation)

How CSG solves PoT 3: Well $\int \to \sum$!

How CSG solves PoT 6 (does it?): renders it not a meaningful question (also most CSG break T-reversal)

How CSG solves PoT 2:

history space and event algebra ("alg of observables")

the labeled event-algebra $\widetilde{\mathfrak{A}}$, $\widetilde{\Omega}$

the covariant event-algebra $\mathfrak{A}$, Ω

stems and stem events (stem predicates)

THEOREM: The stem-events S generate $\mathfrak{A}$ modulo sets of $\mu = 0$

Every question in $\mathfrak{A}$ is made from $S_1, S_2, S_3 \ldots$ via $\vee, \wedge, \sim$

REMARK In principle could do same for continuum

REMARK Resolution is mainly kinematic $\Rightarrow$ should go through also for QSG

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Time passing = birth of elements of causet

and yet general covariance is respected

You might call this **asynchronous becoming**

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