Title: Error free quantum gravity

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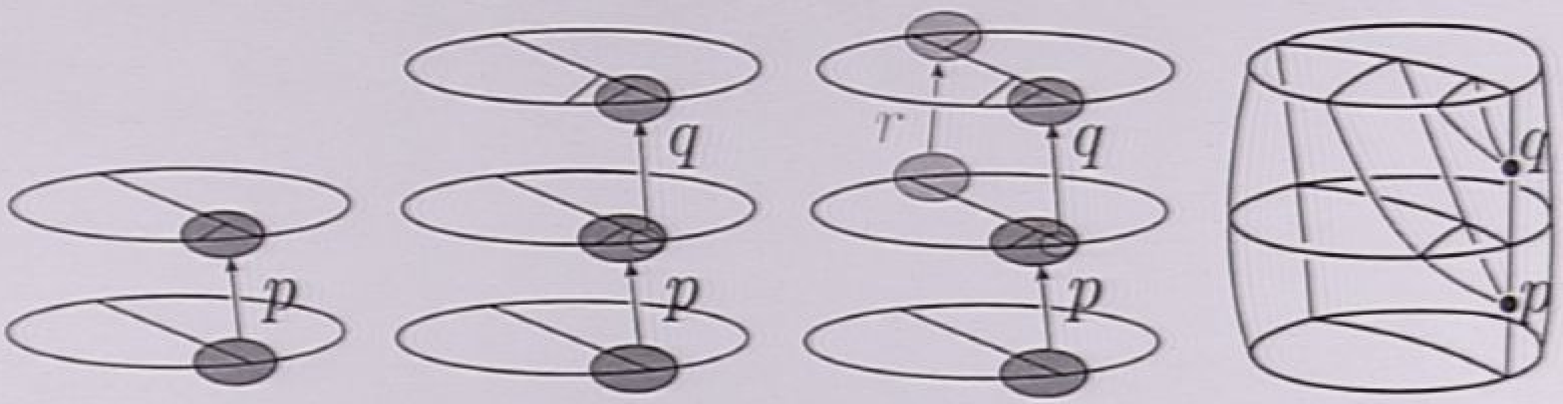
Abstract:

Evolution of spin networks generates a "spacetime network", or Spin Foam.



$$A(S_{\text{in}}, S_{\text{out}}) = \sum_{\Gamma} \sum_{\text{labels on }\Gamma} \prod_{f\in\Gamma} \dim j_f \prod_{v\in\Gamma} A_v(\{j\})$$

$$= \sum_{\text{histories}} \sum_{\text{labels}} \prod_{\text{events}} A(\text{event})$$

A spin foam Γ is a 2-dimensional complex with faces labeled by irreducible representations of the group and edges labeled by intertwiners.
Spacelike cuts through spin foams are spin networks.

$\sum_{\text{geometries}} \rightarrow$ dominant near-classical geometries $\rightarrow$ continuum approximation / limit

e.g. $\dashrightarrow^{?}$ weave states $\longrightarrow$

$\dashrightarrow^{?}$ coherent states $\longrightarrow$

$\dashrightarrow^{?}$ embeddable causal set $\longrightarrow$

$\longrightarrow$ typical CDT geometry $\longrightarrow$

Difficulties: – Define low-energy limit / ground state in a constrained system

– Coarse-grain a background-independent system (one must coarse-grain the observables, not the lattice)

II

STARTING FROM A QUANTUM THEORY,

THERE IS ONLY <u>ONE</u> SPACETIME

& IT CAN ONLY BE CLASSICAL

(NO SUPERPOSITION OF SPACETIMES)

with Olaf Dreyer

Wen: Photons are emergent

+

General Relativity : only events are physical

$\Longrightarrow$ Spacetime is the result of the interactions of the photons and it is also emergent

$$\boxed{\text{Fundamental pre-spacetime theory} \longrightarrow \text{emergent degrees of freedom} \longrightarrow \text{spacetime and gravity}}$$

eg.

Spin/string networks $\longrightarrow$ excitations $\longrightarrow$ interactions of excitations define a SINGLE causal set

$\parallel$

$\boxed{\text{spacetime with Einstein's eq}^{\text{ns}}}$

Q1: Fundamental pre-spacetime theory?

In solid state physics lattices are *in* spacetime.

A: One can reformulate the solid state construction to a manifestly background-independent form (as long as there are no spatial symmetries and modulo the time in the fundamental Hamiltonian).

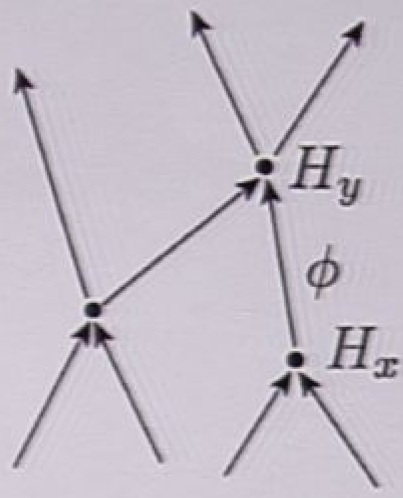
A dynamical quantum system is a Quantum Information Processing System

Unnecessary references to geometry can be eliminated using the language of quantum information processing.
Low energy limit: what we see is what nature encoded

What is an encoded system and when do we have a flat spacetime?
Can we find the class of microscopic dynamics that has the desired low energy properties?

Note: To recover QFT in the low energy limit, we need to coarse-grain $\times 10^{20}$ and be left with a unitary theory.

The quantum information processing system



ϕ is a quantum channel:

linear $\phi : \mathcal{B}(H_x) \to \mathcal{B}(H_y)$ such that

$id_k \otimes \phi : M_k \otimes \mathcal{B}(H_x) \to M_k \otimes \mathcal{B}(H_y)$

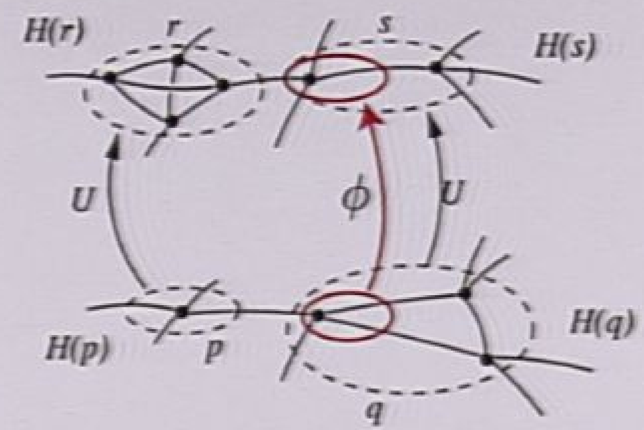
is positive for all $k \geq 1$ and trace-preserving.

Operator-sum representation of CP maps: Choi&Kraus

For every CP map ϕ, there is a set of operators $\{E_a\} \subseteq \mathcal{B}(H_1, H_2)$ such that

$$\phi(\rho) = \sum_a E_a \rho E_a^\dagger \quad \text{for all} \quad \rho \in \mathcal{B}(H_1)$$

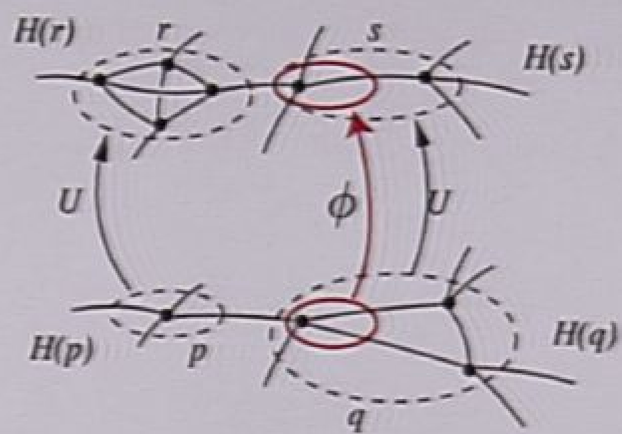
Special case of a QIP: quantum geometry



$$A_{s_i \to s_f} = \sum_{\Gamma : s_i \to s_f} \prod_{e \in \Gamma} \phi_e$$

$\Gamma =$ causal set, spin foam complex
$H_x =$ intertwiner spaces

Special case of a QIP: string networks



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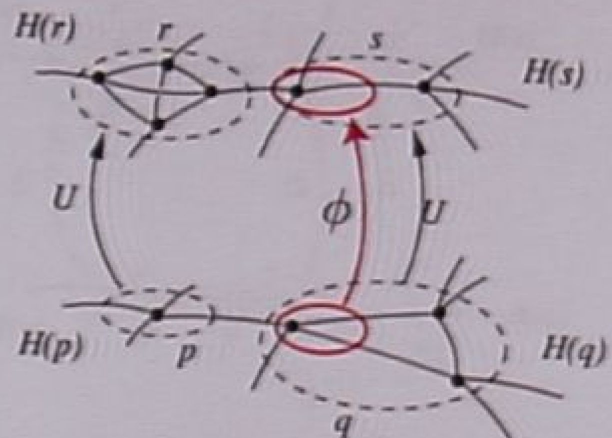

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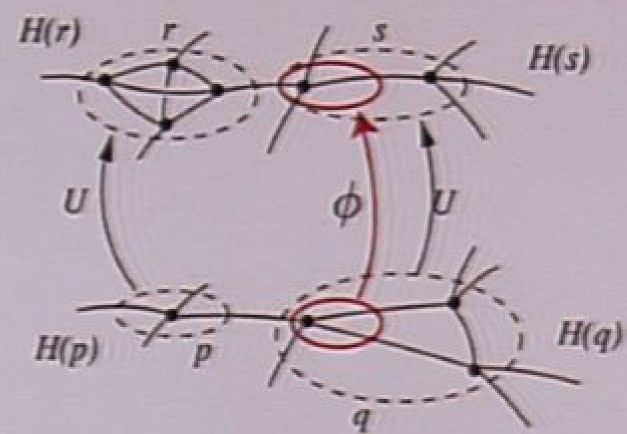

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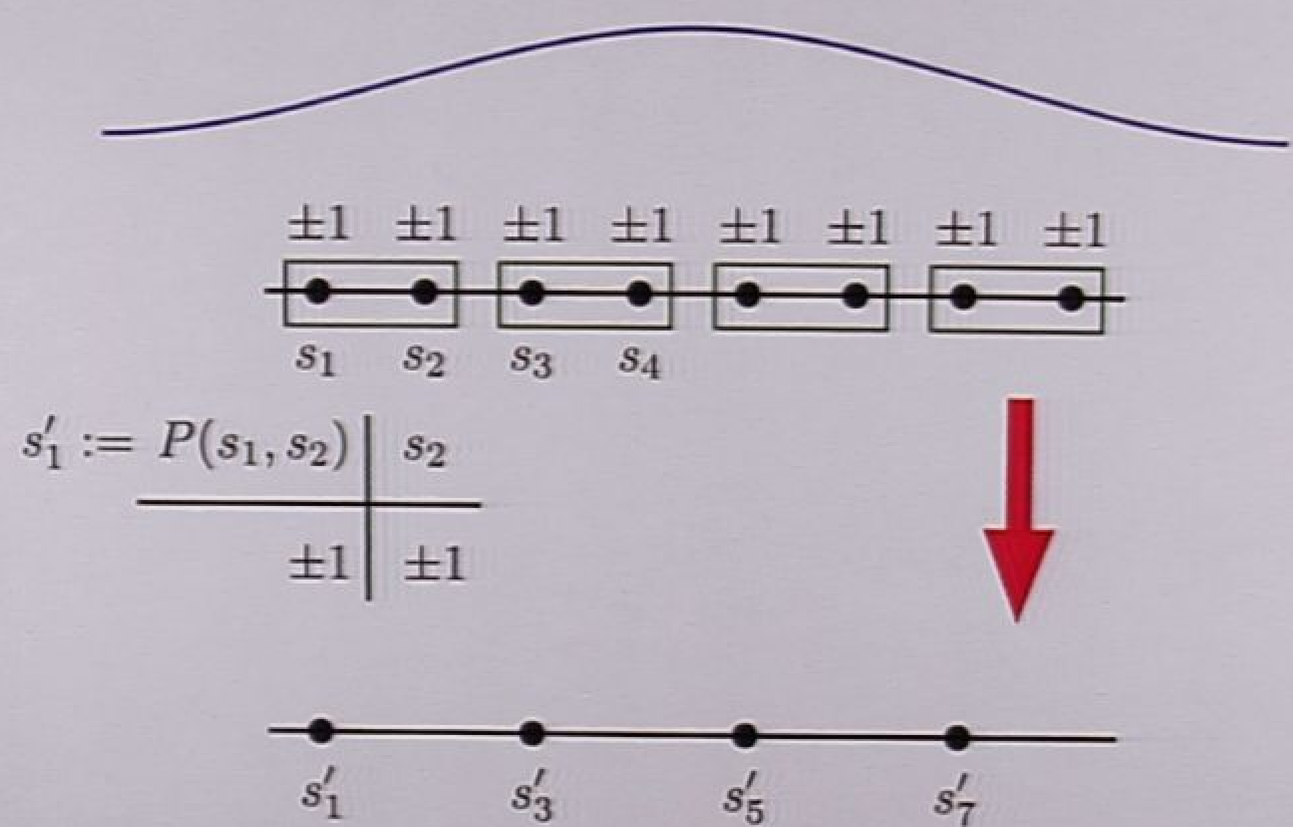
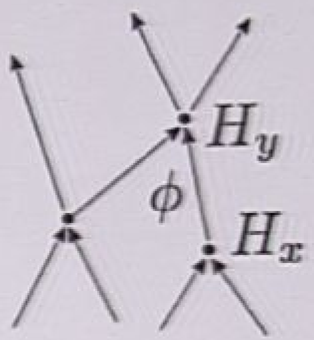
Low energy physics as error correction/encoding



w/ D. Poulin

What is an appropriate notion of low-energy limit for a QIP?



$\longrightarrow$

low energy limit

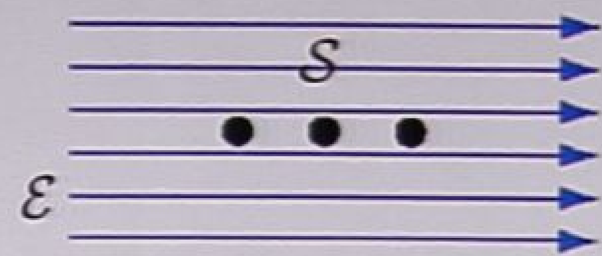
$l_{\text{Planck}} = 10^{-35} m$

$QFT \sim 10^{-15} m$

We need to coarse-grain $\times 10^{20}$ and remain unitary.

What we see is what nature encoded.

Example of quantum error correction



$$H^{\text{int}} = \sum_{\alpha} S_\alpha \otimes E_\alpha$$

$$S_\alpha = \sum_{i=1}^{3} \frac{\sigma_\alpha^i}{2}$$

$\alpha = x, y, z$

$su(2)$ rotations

Symmetric under S_3

$$\mathcal{H}_S = \mathbf{C}^2 \otimes \mathbf{C}^2 \otimes \mathbf{C}^2$$

$$\mathcal{H}_S \simeq \left(\mathcal{H}_{\frac{1}{2}} \otimes \mathbf{1}_2\right) \oplus \mathcal{H}_{\frac{3}{2}}$$

Evolution acts identically on the two $\mathcal{H}_{\frac{1}{2}}$.
I can choose basis $|s_z, \lambda\rangle, s_z = \pm\frac{1}{2}, \lambda = 0, 1$

noisy protected

Noiseless subsystem

$$\boxed{\begin{gathered}\mathcal{H}_S \simeq \left(\mathcal{H}_{\frac{1}{2}} \otimes \mathcal{H}_{\text{NS}}\right) \oplus \mathcal{H}_{\frac{3}{2}} \\ S_\alpha \simeq \sigma_{(\alpha)} \otimes \mathbf{1}_{\text{NS}}\end{gathered}}$$

$\mathcal{H}_{\text{NS}}$ behaves as a "free particle" (coherent degree of freedom).

Zanardi &Rasetti
Knill, Laflamme &Viola
Holbrook, Kribs & Laflamme

Noiseless Subsystems

Let ϕ be a channel on H and $H = (H^A \otimes H^B) \oplus K$. B is *noiseless* for ϕ if

$$\forall \sigma^A, \forall \sigma^B, \exists \tau^A : \phi(\sigma^A \otimes \sigma^B) = \tau^A \otimes \sigma^B$$

B is conserved under evolution, evolves unitarily. It is a propagating coherent degree of freedom.

In quantum computing, $\phi = \{E_a\}$ are the errors (noise). Noiseless subsystems is the fundamental passive technique for error correction.

For us, $\phi = \{E_a\}$ is simply the microscopic Planckian evolution.

Possible way for flat space from noiseless subsystems:

Group (Poincaré)-invariant Noiseless Subsystems

$$\forall \sigma^A, \forall \sigma^B, \exists \tau^A : \quad \phi(\sigma^A \otimes \sigma^B) = \underbrace{\mathcal{U}(\tau^A)}_{\text{generate desired transformations}} \otimes \sigma^B$$

Q1: Fundamental pre-spacetime theory?

In solid state physics lattices are in spacetime.

A: One can reformulate the solid state construction to a manifestly background-independent form (as long as there are no spatial symmetries and modulo the time in the fundamental Hamiltonian).

Q2: Why Einstein's equations, why 4D smooth geometry?

NOTE: These questions are also open for the quantum geometry theories. Here at least we have only one spacetime.

CONSTRUCTION: Use excitations and their interactions to define both geometry and $T_{\mu\nu}$.

CONJECTURE: If you do this consistently, the geometry and $T_{\mu\nu}$ will not be independent but will satisfy Einstein's equations as identities.

cf Lloyd

Q3: Is this Background Independent?

<u>Definition</u>: A quantum theory of gravity is <u>background independent</u> if its basic quantities and concepts do not presuppose the existence of a given background metric.

$\Rightarrow$ Microscopic theory is trivially BI.

Have to show that the emergent physics is BI wrt the internally defined relational geometry.

Q4: What about the time in the fundamental Hamiltonian?

Potential problem: it could lead to a preferred reference frame or experimental conflict.

Advantage: Meaningful ground state.

Noiseless Subsystems

$$N_\alpha |ab\rangle = \sum_{b'} M^{\alpha}_{bb'} |ab'\rangle$$

when M are 1-d, $\underline{\underline{N_\alpha}} |ab\rangle = \underbrace{p^{\alpha}_{b}}_{\text{phases}} |ab\rangle$ STA

Constraints:

In $\mathcal{H}_{kin}$ $[C_a, C_b] = f_{ab}^{c} C_c$

Physical states $C_a |\psi\rangle_{phys} = 0$ defines $\mathcal{H}_p$

Dirac observables $[D, C_a] = 0$

CONSTRAINTS AS STABILIZERS:

If $C_a|\psi\rangle = 0$, then $\underbrace{(\mathbb{1} + \lambda C_a)}_{N_a} |\psi\rangle = |\psi\rangle$.

T. Konopka

Noiseless Subsystems

$$N_\alpha |ab\rangle = \sum_{b'} M^\alpha_{bb'} |ab'\rangle$$

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If $C_a |\psi\rangle = 0$, then $\underbrace{(\mathbb{1} + \lambda C_a)}_{N_a} |\psi\rangle = |\psi\rangle$.

T. Konopka

Eg: 2d particle with $P_y = 0$.

$\mathcal{H}_{kin} = L^2(\mathbb{R}^2, dx) \ni |\psi\rangle = |p_x, p_y\rangle$

Constraint $\quad P_y |p_x, p_y\rangle = 0 \quad \rightarrow \mathcal{H}_{phys} \ni |p_x, 0\rangle$

Rewrite $\quad P_y|\psi\rangle = 0 \quad$ as $\quad (\mathbb{1} + P_y \lambda)|\psi\rangle = |\psi\rangle \quad \forall \lambda$

$N_\lambda := \mathbb{1} + P_y \lambda$ is stabilizer on physical states

i.e. constrained system $\equiv$ 2d particle coupled to environment

$$H_I = \sum_\lambda (\mathbb{1} + P_y \lambda) \otimes B_\lambda = P_y \otimes \tilde{B}$$

$\rightarrow U_I(t) = e^{i P_y \otimes B t} \quad$ identity on $P_y|\psi\rangle = 0$.

Evolution = A system follows a path in configuration space

Symmetry = Only certain paths in the configuration space are selected

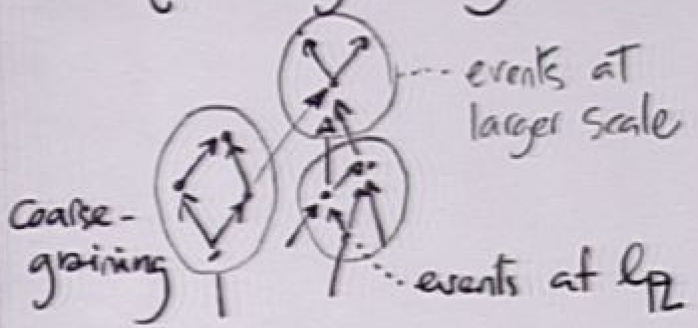
Constraints = A mechanism that implements a restriction of the allowed paths in config. space

Noiselessness = parts of quantum systems are unchanged by interactions with the environment

Q5: What is the significance of the underlying theory?

Coarse-graining vs phase transitions

In quantum geometry theories:



Wen: photons are topological excitations

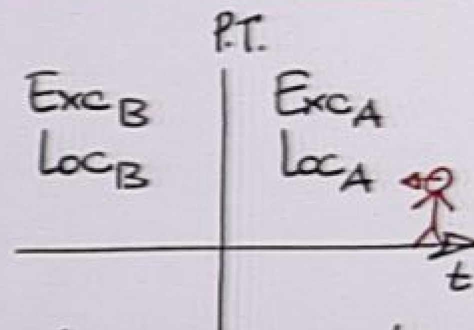
Noiseless subsystems: the effective subsystem lives in the entire fundamental system.

$\Downarrow$

① No role for l_{PL}.

② Observable consequences/remnants of the phase transition.
Potential for QG effects at large scale

e.g. horizon problem



We see correlations we cannot explain with Loc_A.

③ O.D.: pre-spacetime → excitations → spacetime
Can remove problems that can be traced to s/t being fundamental, e.g. Λ.

Q6: Doesn't string theory do what you want?

No, String theory is not background independent.

But matrix models are close to the present proposal.

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