Lessons for quantum foundations from quantum gravity

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Quantum Gravity, the quest for unity

- Quantum Gravity is the name given to the putative theory that would provide a unified conceptual framework for all of physics. Thus it would encompass gravitational physics and our descriptions of "matter" and spacetime.

- We do not yet have a theory of Quantum Gravity. Nevertheless, looking ahead to what Quantum Gravity might be, and what it needs in order to come into being could throw light on quantum foundational issues (and vice versa).

- Scarcity of observational/experimental data directly relevant to Quantum Gravity has led to a wide range of different approaches..... how to find our way?

- Remarkably, we already know the answer to one Quantum Gravity question and there **is** a consensus that understanding this answer will play a major part in leading us to Quantum Gravity.

- I will describe what this is and explain what I believe it tells us.

The Laws of Black Hole Mechanics

Bardeen, Carter, Hawking 1973

κ is the **surface gravity** of the horizon of a stationary black hole, A is the surface area of the horizon

	Thermo	Black Hole
Zeroth Law	T is constant throughout system in **equilibrium**	κ is constant on horizon of **stationary** black hole
1st Law	$dE = TdS -$ work	$dM = \frac{1}{8\pi G}\kappa\, dA -$ work
2nd Law	$dS \geq 0$	$dA \geq 0$ Hawking's Area Theorem
3rd Law	T cannot be reduced to zero in a finite process	κ cannot be reduced to zero in a finite process

Already remarkable, but there was more to come

The Laws of Black Hole Thermodynamics

Bardeen, Carter, Hawking, Bekenstein, Gibbons, Perry

- A black hole has a temperature and an entropy

$$T_{BH} = \hbar \frac{\kappa}{2\pi}, \quad S_{BH} = \frac{1}{4} \frac{A}{l_p^2}$$

where κ is the surface gravity and $l_p^2 = G\hbar$

- The Zeroth Law: T_H is constant over the horizon of a stationary black hole

- The First Law: $dM = TdS - work$

- The Generalised Second Law: $dS_{BH} + dS_{ext} \geq 0$ **Bekenstein**

Black holes are the epitome of General Relativity (happy birthday GR by the way). It is striking that GR "knows" about quantum mechanics and thermodynamics:

The greatest unity yet achieved in physics

Seeking the Statistical Mechanics of BH Thermodynamics

- The BH entropy has a quantum gravitational value. Not only it is **finite** but its value sets a scale and suggests that spacetime itself is discrete

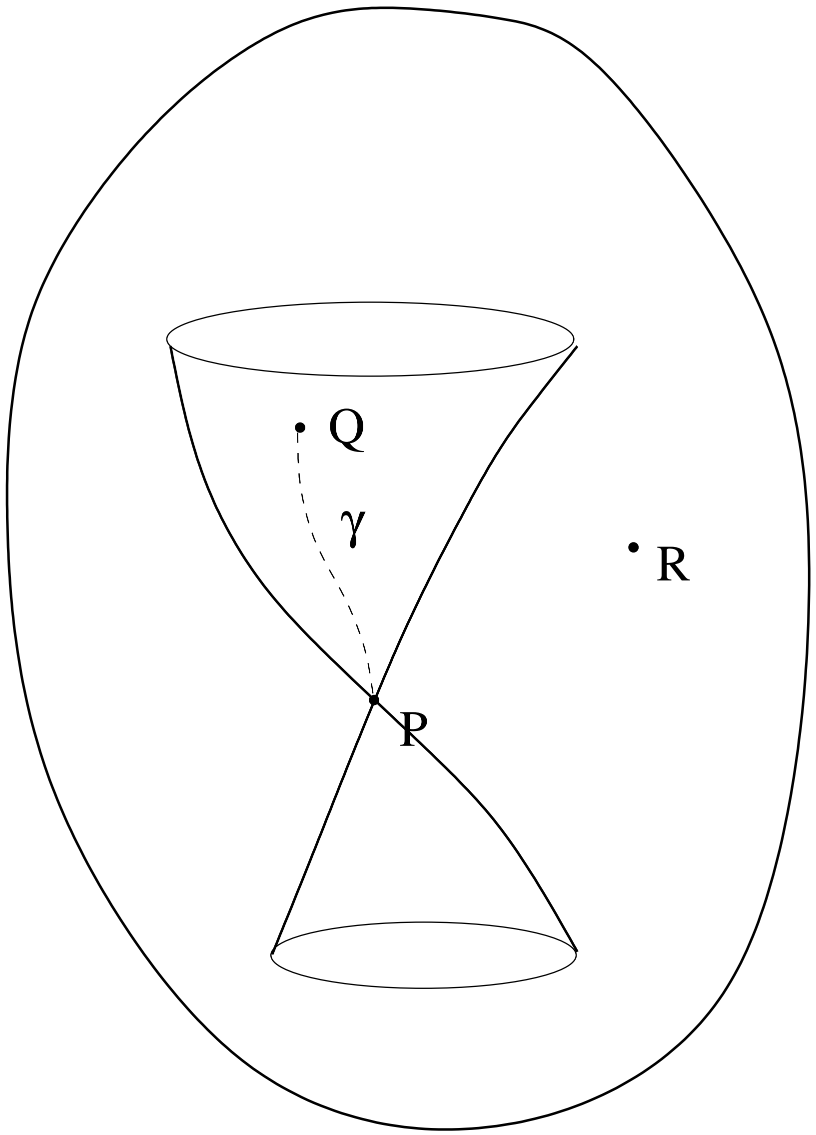
Entropy of BH is the number of Planck sized plaquettes tiling the horizon (up to factor of order one)

Entropy of a box of gas is equal to the number of molecules (up to factor of order one)

- Less heuristic: the black hole entropy will include the "entanglement entropy" of quantum fields in spacetime and without a **physical short distance cutoff** that entanglement entropy is infinite **(Sorkin)**

- There's nothing locally special about BH horizons are discrete. If horizons are discrete, so must spacetime itself be.

Causal Structure (light cone structure) is central to black hole thermodynamics



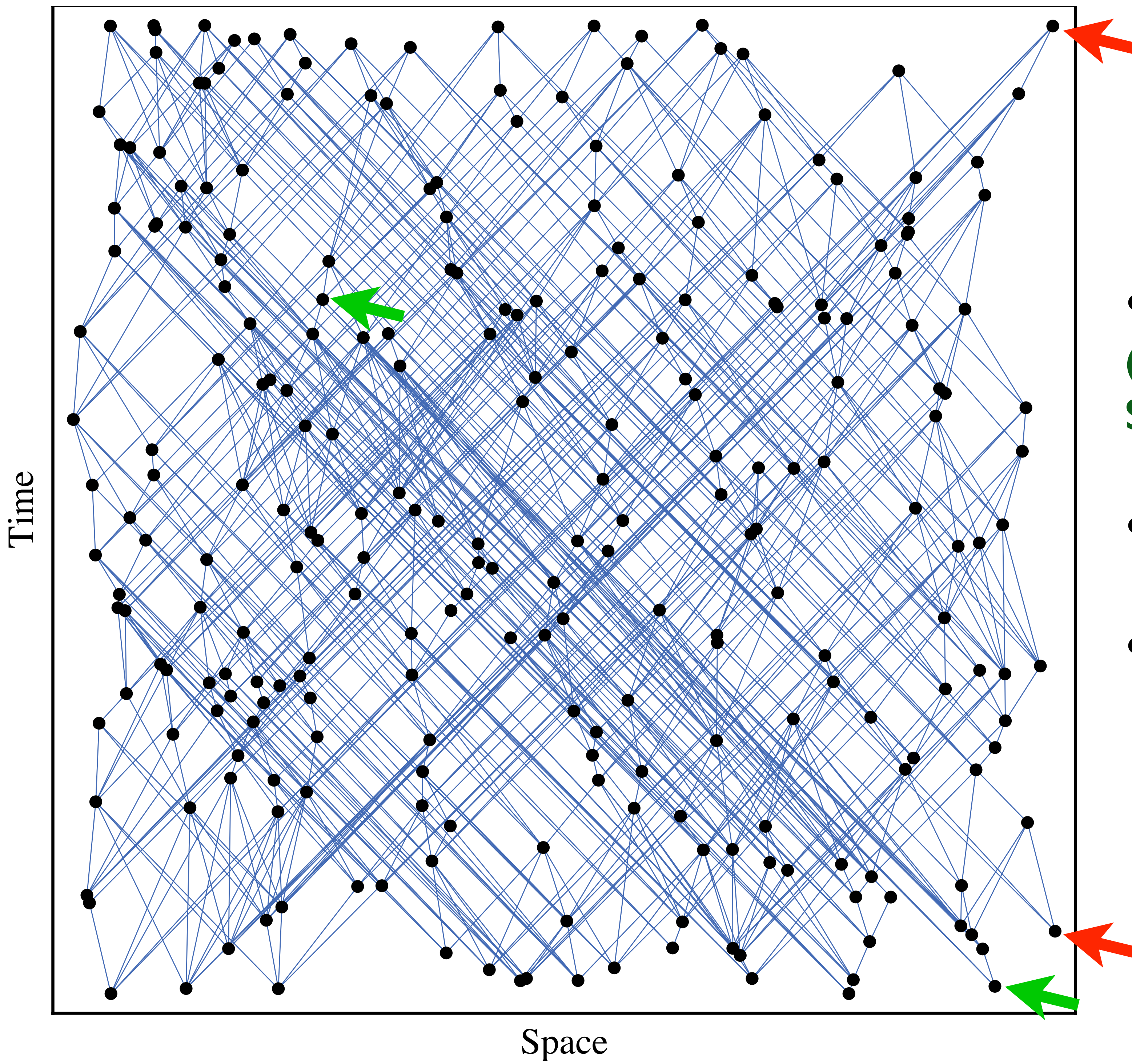
A black hole horizon is the boundary of the causal past of any "eternal" worldline. Black hole thermodynamics is intimately tied to the causal nature of the horizon

To hold fast to the unity already uncovered in BH Thermodynamics, postulate that causal order is more fundamental than any other spacetime structure.

Causal order marries atomicity

- Moreover, the causal order encodes the geometry of a continuum spacetime up to a local scale factor. The causal order **unifies** within itself topology, differentiable structure, causal structure and 9/10 metric **(Robb, Penrose, Kronheimer, Zeeman, Hawking, Malament).**
- Adding the spacetime volume measure provides the missing metric information: Order + Volume = Geometry
- In a discrete manifold, you get that information for free because you can **count** elements **(Riemann)**
- Order + Number = Geometry **(Sorkin)**
- A Lorentzian spacetime can be encoded in a **discrete partial order** or **causal set** **('tHooft; Myrheim; Bombelli, Lee, Meyer & Sorkin)**
- The discrete entity — the causal set — is the fundamental description and the continuum is an approximation.

A discrete order (causal set) for 2-d Minkowski space



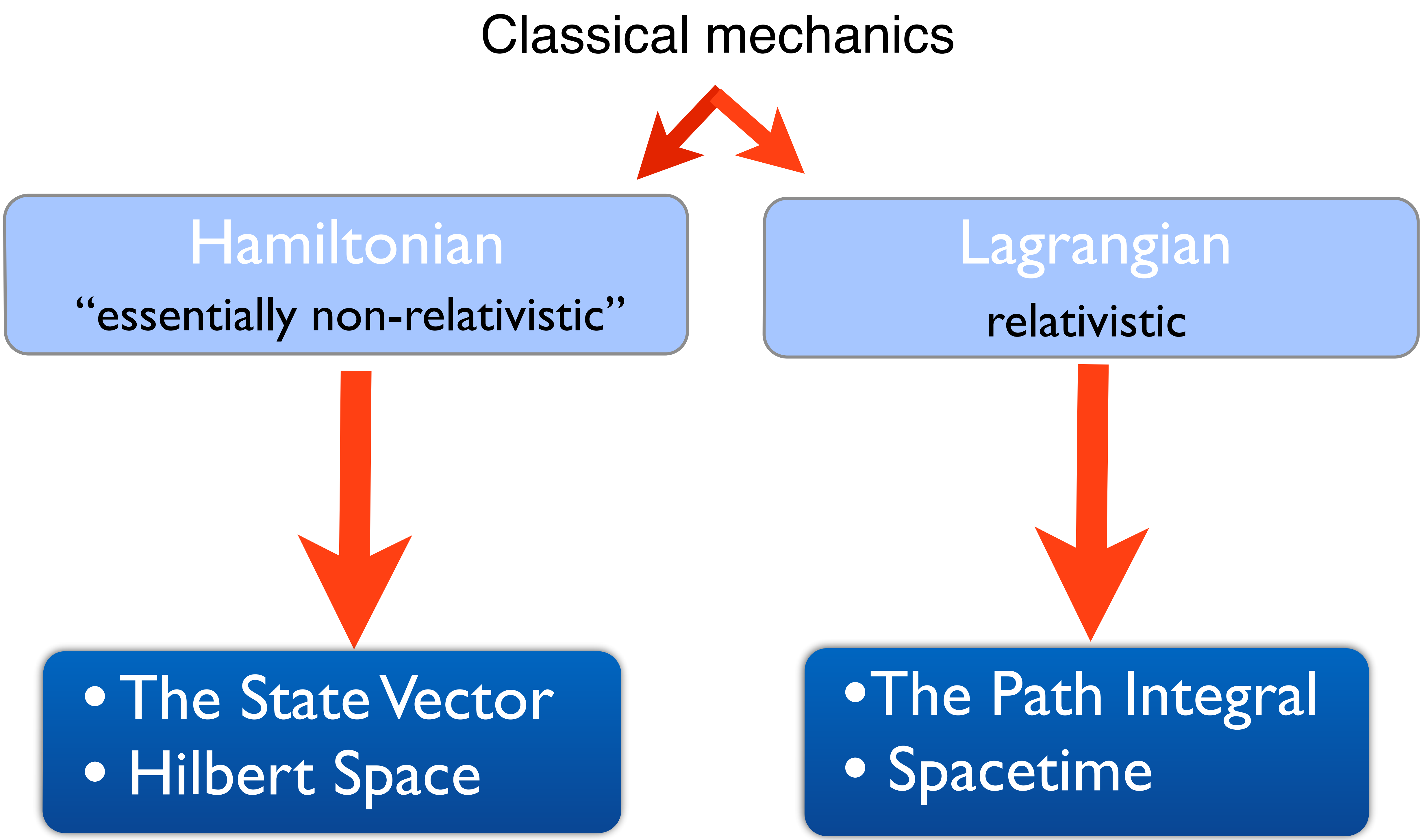
- Lorentz invariant **(Bombelli, Henson, Sorkin)**
- Number~Volume
- 10^{240}

- On Planckian scales, this is what 2-d Minkowski space is (like)
- There are causal sets corresponding to each continuum spacetime

Causal Set Quantum Gravity?

- How do we build a quantum theory of causal sets?
- Dirac: “Quantum mechanics was built up on a foundation of analogy with the Hamiltonian theory of classical mechanics”
- But a discrete, relativistic entity like a causal set is inimical to any Hamiltonian formulation
- Dirac: “There is an alternative [..] provided by the Lagrangian. [..T]here are reasons for believing that the Lagrangian one is the more fundamental”
- And that leads to?
- Dirac: The Path Integral

Dirac's Choice for quantum mechanics



For causal sets the path integral is the only option

$$\text{“} \quad \mu(A) = \left| \sum_{\mathcal{C} \in A} e^{iS(\mathcal{C})} \right|^2 \quad \text{”}$$

- Ready made "quick and dirty" interpretation: classical behaviour results if non-classical causal sets destructively interfere
- For unity's sake choose the path integral as the foundational basis for all quantum theories
- Questions: What **is** the interpretational framework that would make concrete and precise the quick and dirty interpretation? What is the nature of the physical world in a sum-over-histories quantum theory?
- There are two path integral based interpretational schemes in the literature: Hartle's generalised quantum mechanics and Sorkin's quantum measure theory.
- Both deal directly with (spacetime) **events:** Quantum mechanics is a generalised stochastic process, a variety of Brownian motion with a "quantal measure"

(Causal Set) Quantum Gravity is non-unitary

- Black hole evaporation indicates that quantum gravity is non-unitary **(Hawking)**
- Recent "firewall" results on black holes reinforce this view. Unitarity can be maintained only by giving up on semiclassical physics.
- There are other reasons more specific to discrete theories and to causal sets that indicate that quantum causal set theory will necessarily be non-unitary
- This non-unitarity is to be welcomed: Sorkin has given a fascinating proof of the semiclassical generalised second law is based on the non-unitary autonomous evolution of the quantum state exterior to the black hole horizon

Summary and further remarks

- Seeking Stat Mech for black holes leads to atomic causal order: causal sets
- Causal Set quantum gravity requires a path integral (sum-over-histories) framework and motivates thinking of the path integral as the foundation for all quantum theories.
- Path integral quantum theory deals with events in spacetime. The wave function is merely a summary of enough of the past to be able to make future predictions. It has no fundamental, ontological status and neither is it epistemic: "psi-ontic or psi-epistemic" is false dichotomy.
- Causal set quantum gravity will be nonunitary.
- The primal struggle between "local" and "global" aspects of physics shows up with a vengeance: the Path Integral is fundamentally global. But the physical world is "local enough" for us to conceive of what is going on in this room without consideration of the rest of the universe. Can this be achieved in path integral quantum theory?