

New Forks in the Road on the Way to Quantum Gravity Dedicated to Rafael Sorkin

Fay Dowker

Theoretical Physics Group
Imperial College London
Puzzles in the Quantum Gravity Landscape
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Rafael's 1997 "Forks" paper

"Forks in the Road, on the Way to Quantum Gravity", International Journal of Theoretical Physics, Vol. 36, No. 12, 1997 and Rafael's Perimeter Institute website (he often updated his paper versions on there).

- Rafael's 1997 paper is the text of a talk given at the symposium on Directions in General Relativity, University of Maryland, in May **1993** in honour of Dieter Brill and Charlie Misner.
- Because of our chutzpah and the sheer scope of our ambition—to create a unified framework for all of known fundamental physics—there is not one clear road to quantum gravity. There are many knotty decisions to make along the way.
- However,

When you come to a fork in the road, take it.
Yogi Berra

- When a task is hard, diversity of approach is a strength. As a community we can follow Yogi Berra's advice. But it is also important to challenge each other's choices.

The 1997 Forks, verbatim

- Is the signature of the spacetime metric Lorentzian or Euclidean (or both)?
- Should we allow degeneracies in the metric or closed timelike curves (or possibly both)?
- Should we fix the 4-volume in the gravitational Sum-over-histories or extend the sum over all 4-volumes, as is normally assumed?
- Is the deep structure of spacetime discrete or continuous?
- Which feature of spacetime is most basic, its causal order, its metric or its topology (or perhaps even the algebra of functions on spacetime)?
- Is topology dynamical or is it absolute?
- Is the entropy of a black hole outside or inside its horizon?
- What really exists, the history or the wave-function?
- Should we approach the "quantization" of gravity via the sum-over-histories or via canonical quantization?
- Is probability absolute/unconditional or relative/conditional (do quantum probabilities make sense?)
- Is the cosmological constant, Λ , approximately or exactly zero?

Rafael's 1997 answers

- Is the signature of the spacetime metric **Lorentzian** or Euclidean (or both)?
- Should we allow **degeneracies** in the metric or closed timelike curves (or possibly both)?
- Should we **fix the 4-volume** in the gravitational Sum-over-histories or extend the sum over all 4-volumes, as is normally assumed?
- Is the deep structure of spacetime **discrete** or continuous?
- Which feature of spacetime is most basic, **its causal order**, its metric or its topology (or perhaps even the algebra of functions on spacetime)?
- Is topology **dynamical** or is it absolute?
- Is the entropy of a black hole **outside** or inside its horizon? [Toward a Proof of Entropy Increase in the Presence of Quantum Black Holes 1986, Ten Theses on Black Hole Entropy 2005]
- What really exists, **the history** or the wave-function?
- Should we approach the "quantization" of gravity via **the sum-over-histories** or via canonical quantization?
- Is probability absolute/unconditional or **relative/conditional** (do quantum probabilities make sense?)
- Is the cosmological constant, Λ , **approximately** or exactly zero? 

A Selection of New Forks

- Is there a phenomenologically relevant mesoscale between the Higgs scale and the Planck scale or is there no new physics all the way down (up)? [Does locality fail at intermediate length-scales? (2006)]
- Does time pass or is the world an unchanging block? [Relativity theory does not imply that the future already exists: A Counterexample (2007)]
- In the path integral interpretation, is the world a single history, a co-event or something else? [Quantum Dynamics without the Wave Function (2007)]
- Is logic for physics fixed or dynamical? [An exercise in “anhomomorphic logic” (2007)]

Identify other forks in the landscape!

Time

Does it pass?

[Relativity theory does not imply that the future already exists: a counterexample (2007)]

- In Classical Sequential Growth models, the passage of time is the process of the asynchronous birth of causal set elements (spacetime atoms)
- The process is a physical element of the theory, in its own right
- It embodies the concept of Becoming (Bergson's concept of **durée**).
- There is no God's Eye View of the process.
- The lack of a God's Eye View throws light on (resolves?) the so-called Hard Problem of Consciousness (?)
- Can the concept of growth be extended to a **Quantum** Sequential Growth process?

There's a serious tension between the concept of process and the global nature of the path integral.

Sorkin's Quantum Measure Theory aka the path integral approach to quantum foundations

Axioms for Path Integral Quantum Theory = Quantum Measure Theory (Sorkin),
[closely related to Generalised Quantum Mechanics (Hartle)]

- A space of **histories** Ω
- A Boolean algebra $\mathfrak{A}$ of **events** (subsets of Ω)
- A Decoherence Functional $D(X, Y)$ a positive quadratic form on $\mathfrak{A}$ that is:
 1. Hermitian: $D(X, Y) = D(Y, X)^*$
 2. Linear: $D(X \cup Y, W) = D(X, W) + D(Y, W)$ when $X \cap Y = \emptyset$
 3. Normalised: $D(\Omega, \Omega) = 1$

$\mu(X) = D(X, X)$ is the **quantum measure** of event X .

In causal set quantum gravity, Ω is the set of all countable, past finite causal sets.

Interpretation

[Quantum Dynamics without the Wave Function (2007)]

- The World is an answering map or **co-event**

$$\phi : \mathfrak{A} \rightarrow \{0, 1\}.$$

Every event either happens or does not happen in the World.

- Classical logic if and only if ϕ is a homomorphism if and only if ϕ is equivalent to a single history.
- ϕ is preclusive: $\mu(A) = 0 \implies \phi(A) = 0$.
- Plus some other conditions (a “scheme”): **open problem**
- There are quantum systems – e.g. based on Kochen-Specker theorems – in which there is no ϕ that is preclusive and a homomorphism.
- Recovering classical physics (approximately) requires that if $\mathfrak{B}$ is the subalgebra of macro-events then $\phi|_{\mathfrak{B}}$ is a homomorphism (approximately).
- In one particular scheme, this can be proved if there are permanent records (Sorkin).

At the fork, take the co-event road.

Can time pass in a quantum system, can a co-event grow?

Evolving Realities for Quantum Measure Theory by Henry Wilkes,
arXiv:1809.10427

- Hard to compute the allowed co-events because, in a finite quantum system with n states, after t steps there are $N = n^t$ histories and $M = 2^N$ events and potentially 2^M co-events so the number of potentially allowed coevents is vast even for small n and small t .
- The scale of the computational challenge for quantum causal sets would be staggering.
- Seek a scheme that vastly cuts down the number of allowed co-events.
- Or find another interpretation not based on co-events (take another path at the fork).

May Rafael's memory be for a blessing

Rafael was a true scholar whose work was motivated by a profound confidence in the unity of physics. His contributions to physics were extraordinarily diverse and yet they form a coherent whole.

Rafael gave us Lorentzian Regge Calculus, the Kaluza-Klein monopole, a Quantitative Occam's Razor, Entanglement Entropy, Everpresent Lambda, Causal Set Quantum Gravity, Quantum Measure Theory, Impossible Measurements on Quantum Fields, Ten Theses on Black Hole Entropy and so much more.

He was a patient, kind and generous teacher and mentor. And funny too.

He will be greatly missed.