Title: What does the Path Integral imply for Quantizing Time?

Speakers: Kenneth Wharton

Collection: Quantizing Time

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Abstract: "Even though path-integral formulations of quantum theory are thought to be equivalent to state-based approaches, path-integrals are rarely used to motivate answers to foundational questions. This talk will summarize a number of implications concerning time and time-symmetry which result from the path-integral viewpoint. Such a perspective sheds serious doubt on dynamical collapse theories, and also pushes against efforts to extend configuration space to include multiple time dimensions. A recently-developed map between all possible two-qubit entangled states and spacetime-based path-integrals sheds further doubt on any need to extend spacetime to a large ontological configuration space.

(References include arXiv:2103.02425, 1512.00740, 1103.2492 .)"

What does the Path Integral imply for “quantizing time”?

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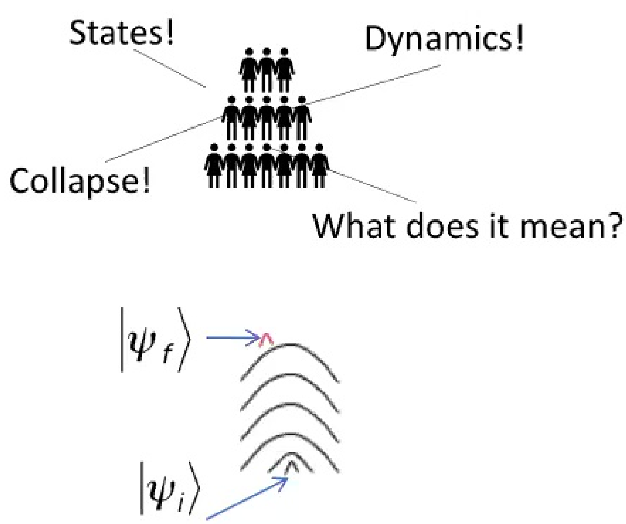
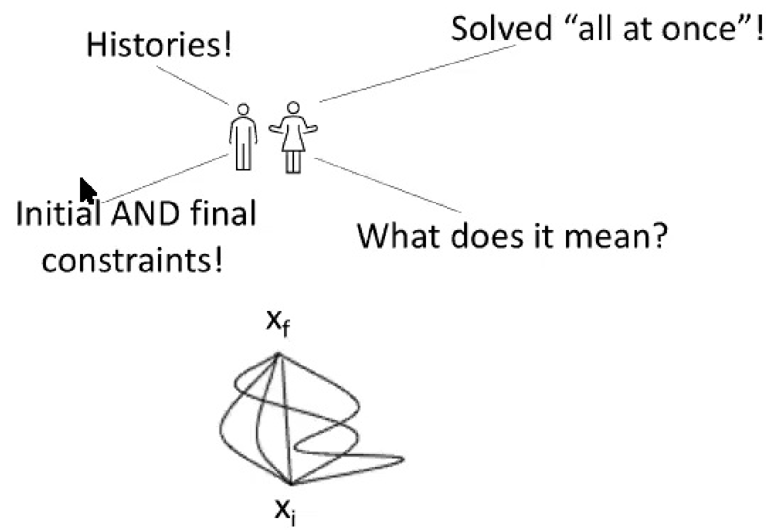
Few physicists look to path integrals for interpretational questions of QM/QFT.





Path Integrals are best fit for Spacetime Issues

- Spacelike Foliations are irrelevant – histories vs. states
- Time-Symmetries far more evident
- Classical action well-defined in curved spacetime

So why is the path integral neglected?

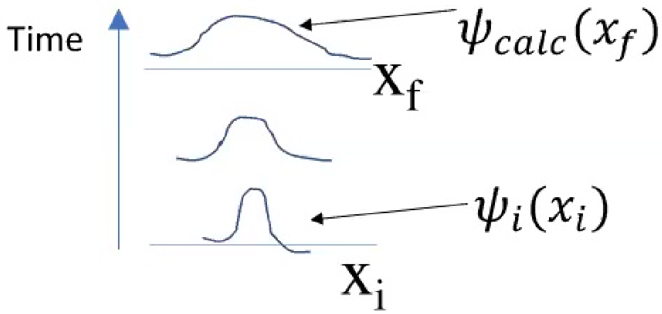
- "Equivalent" to canonical QM/QFT ?
- No clear way to analyze entanglement ?
- Counter-intuitive "all at once" analysis ? (vs. Universe as a Computer)

Quick Outline:

1) Propagators vs. Full Path Integrals (Dynamics vs. "all at once")
2) New Toolbox for Path Integral account of entangled states
3) Application: The role of temporal order in Entanglement Swapping

The Propagator

(unitary dynamics for states)

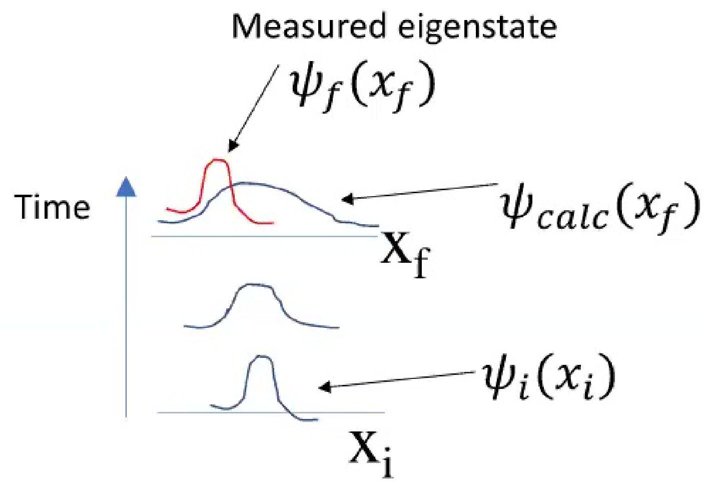


$$\psi_{calc}(x_f) \approx \int \psi_i(x_i) \left[\sum exp(iS/\hbar) \right] dx_i$$

Sum over all x_i to x_f paths

The Path Integral

(testable probabilities)



$$P(\psi_i, \psi_f) \approx \left| \int \psi_{calc}(x_f) \; \psi_f^*(x_f) \, dx_f \right|^2$$

Explicitly Time-Symmetric Single-Particle Probabilities

$$P(\psi_i,\psi_f) \approx \left| \iint \int \psi_i(x_i)\ \psi_f^*(x_f) \left[\sum exp(iS/\hbar) \right] dx_i dx_f \right|^2$$

The Single-Particle Path Integral

Sum over all x_i to x_f paths

- Can turn joint probabilities into conditional probabilities with usual “fixing” of ψ_i
- Symmetry only results when combining Dynamics + Born rule into one expression.
  - Separating out the usual dynamics breaks this path integral symmetry!
- Unobserved ψ_{calc} has disappeared! (Why demand integration in some particular order?)
- No need to integrate over paths with no support on measured ψ_f . (No sudden collapse)

Implications and References

- If ψ_{calc} isn't ontic, it is epistemic (state of knowledge, not reality)

- Spekkens, R.W., 2007. Evidence for the epistemic view of quantum states: A toy theory. *Physical Review A*, *75*(3), p.032110. arXiv:quant-ph/**0401052**

- Wharton, K., 2014. Quantum states as ordinary information. *Information*, *5*(1), pp.190-208. arXiv:**1403.2374**

- So what *is* going on? Can look to the full path integral for promising clues.

- Wharton, K., 2016. Towards a Realistic Parsing of the Feynman Path Integral. *Quanta*, *5*(1), pp.1-11. arXiv:**1512.00740**

- What about multiple particles / entanglement?

- Sinha, S. and Sorkin, R.D., 1991. A Sum-over-histories Account of an EPR (B) Experiment. *Foundations of Physics Letters*, *4*(4), pp.303-335.

- Wharton, K.B., Miller, D.J. and Price, H., 2011. Action duality: a constructive principle for quantum foundations. *Symmetry*, *3*(3), pp.524-540. arXiv: **1103.2492**

New result: Convert any two-qubit experiment into a Path Integral-friendly geometry!

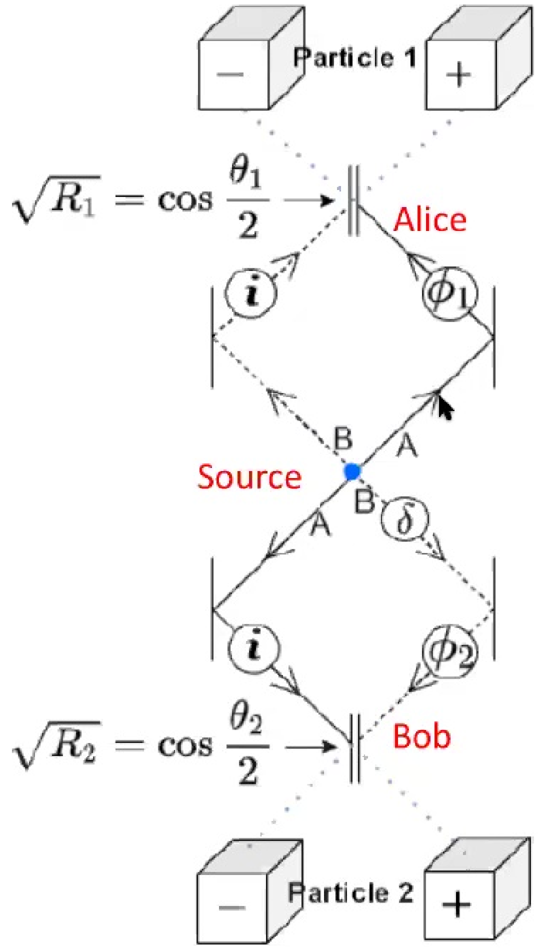
(Work with Narayani Tyagi; arXiv:**2103.02425)**

Step 1: Rotate Coordinates of generic 2-qubit state into a Schmidt Basis:

$$|\psi\rangle = A\,|0\rangle \otimes |1\rangle + Be^{i\delta}\,|1\rangle \otimes |0\rangle = \begin{pmatrix} 0 \\ A \\ B\,e^{i\delta} \\ 0 \end{pmatrix}$$

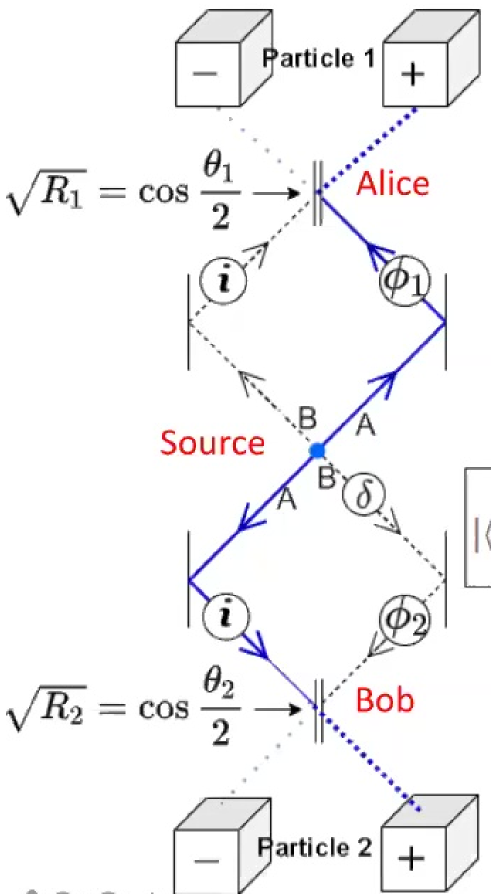
Step 2: Convert to which-way entanglement: Imagine two-photon source that emits photons in opposite directions, w/ different probabilities.
(If measured directly, one direction is found with probability A^2, another is found with probability B^2.)

Step 3: Implement controllable parameters (basis choice, etc) with adjustable phase plates and beamsplitters.



$$\mathcal{E}^{A}_{++} = A\left(e^{i\phi_1}\, i\cos\frac{\theta_1}{2}\right)\left(i\sin\frac{\theta_2}{2}\right)$$

$$\mathcal{E}^{B}_{++} = B\left(i\sin\frac{\theta_1}{2}\right)\left(e^{i\delta}\, e^{i\phi_2}\, i\cos\frac{\theta_2}{2}\right)$$

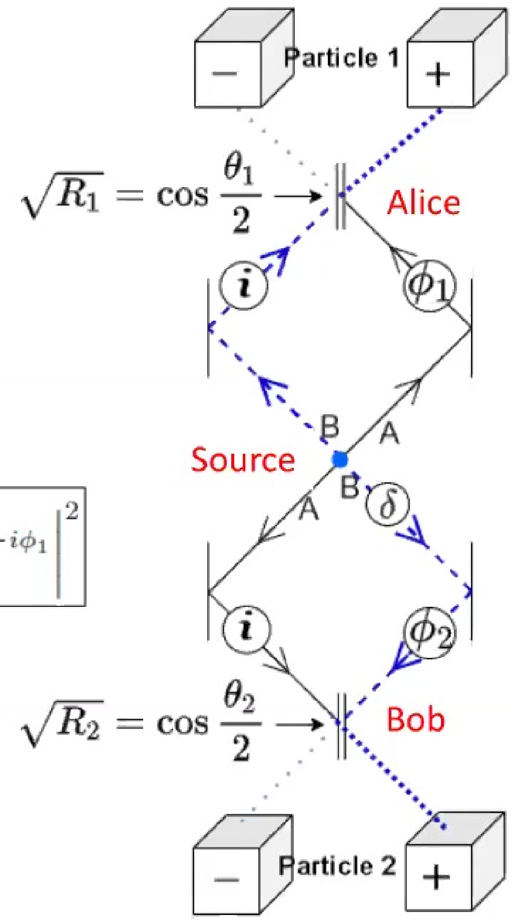


$$Prob(+\,+) = |\mathcal{E}^{A}_{++} + \mathcal{E}^{B}_{++}|^2$$

Always Matches Conventional QM Calculations!

$$|\langle + + |\psi\rangle|^2 = \left| A\cos\frac{\theta_1}{2}\,\sin\frac{\theta_2}{2}\,e^{-i\phi_2} + B\,e^{i\delta}\sin\frac{\theta_1}{2}\,\cos\frac{\theta_2}{2}\,e^{-i\phi_1}\right|^2$$

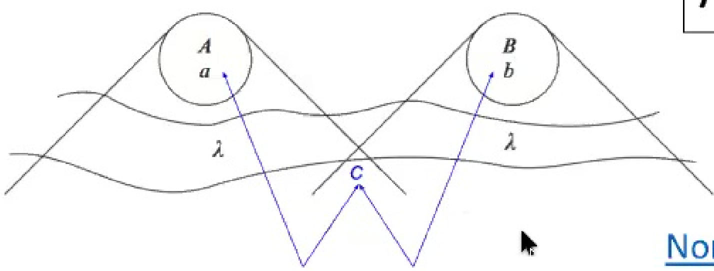
New Paper also shows how to implement some 3-qubit states (GHZ)



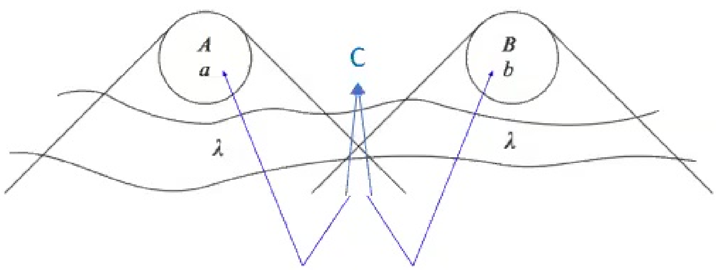
Features of Path Integral Entanglement

- All histories live in spacetime, on usual lightlike-trajectories.
  -- No evidence of usual QM configuration space
- No unusual connection between Alice and Bob's wings of experiment.
- Alice and Bob's local settings can influence the amplitude of each entire history.
- No "Collapse" in the relevant histories
- Path Integral works the same regardless of Alice-Bob measurement order (regardless of reference frame!).
  - See "Feynman Integral Symmetry Hypothesis" (FISH), in Wharton, Miller, Price (2011); arXiv: **1103.2492**

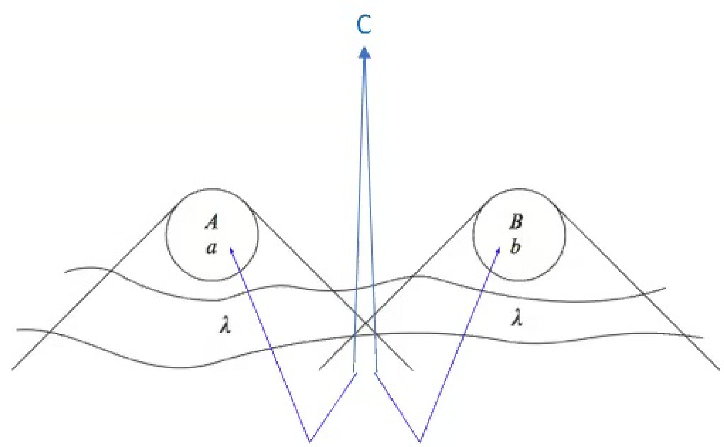
Application: Entanglement Swapping



[Nonlocality via Entanglement-Swapping--a Bridge Too Far?](#)
Huw Price and Ken Wharton - arXiv:**2101.05370**.



(New unpublished work with Raylor Liu extends
Path integral framework to arbitrary two-qubit
measurements -- such as at point C. Email for details.)



Many think this is not "True" entanglement
between A+B, despite same correlations.
– Just "postselection"?

FISH + Path Integral framework Concludes:
All three of these work exactly the same way!

Take-Home Messages

- A good way to examine your biases is to consider alternate viewpoints of the same phenomena.
- You can now translate all your favorite entanglement experiments into path integrals: Tyagi and Wharton (2021), arXiv:**2103.02425**
- While analyzing dynamics, don't ignore the eventual measurement! (Don't mistake your lack of knowledge about the future for evidence that the future doesn't matter.)
- There's lots of low-hanging fruit to be discovered in the field of "all-at-once" quantum foundations!