Quantum gates, timelike nonlocality and causality in quantum gravity

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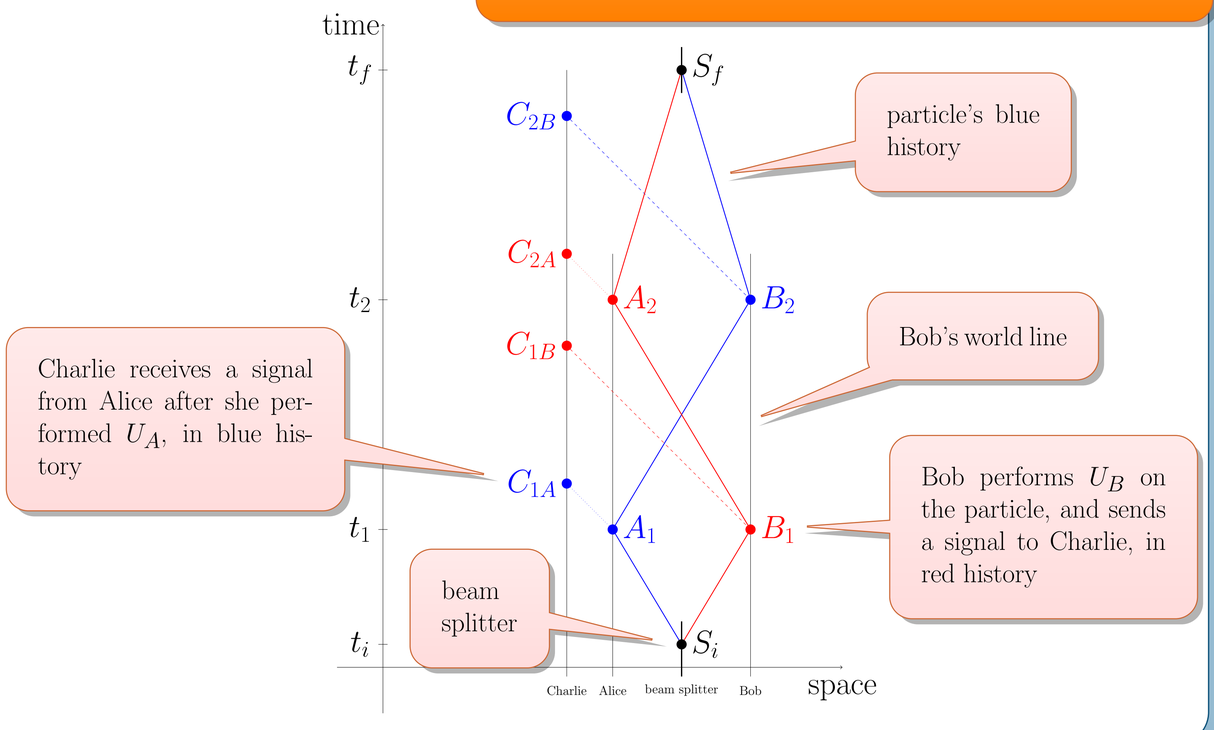
Abstract

We discuss the distinction between causal orders over sets of quantum gates and spacetime events, its implication to the understanding of quantum superpositions of causal orders in flat Minkowski spacetime, relationship to timelike nonlocality, and the realisation of the genuine superposition of causal orders within the framework of quantum gravity.

4-event diagram

The causal switch in flat Minkowski spacetime: each spacetime event corresponds to a spacetime-localized quantum gate, Charlie measures different elapsed times between Alice's and Bob's signals in two histories.

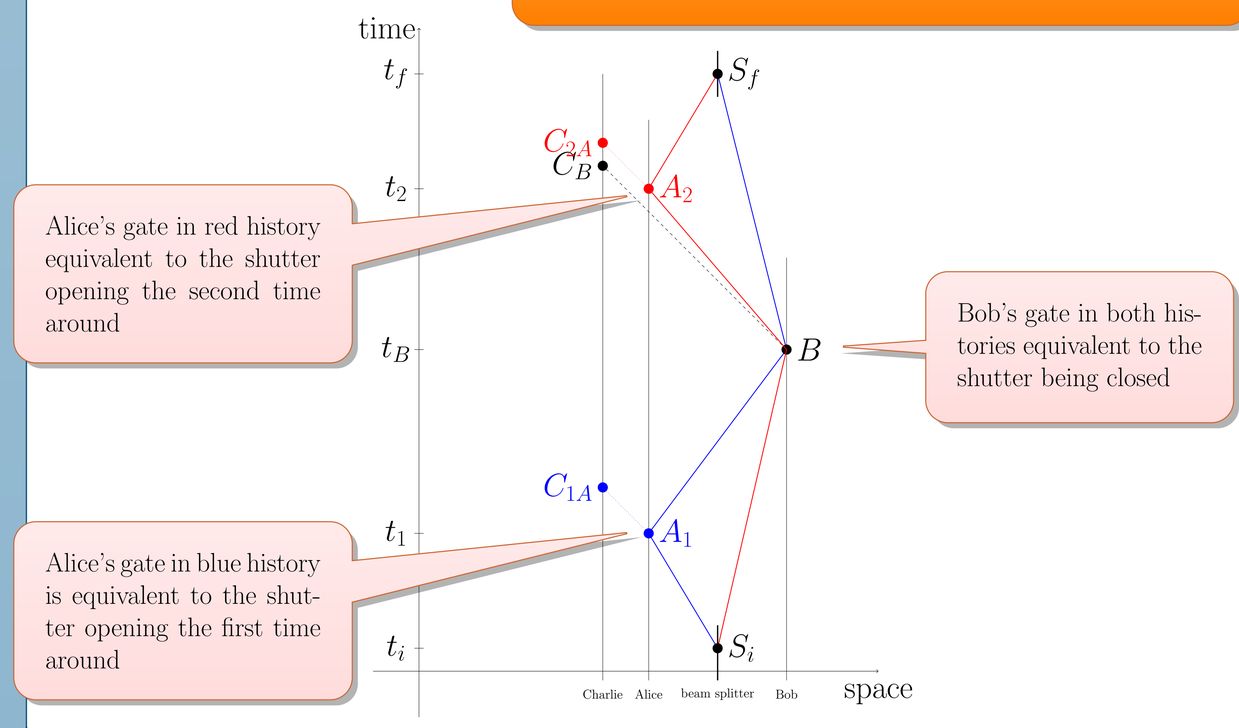


⟸ Spacetime-localized quantum gates

Causality of quantum gates means that there exists a relation of partial order among gates in a quantum circuit [1, 2]. On the other hand, causality in spacetime means that there exists a relation of partial order among events in Minkowski spacetime. Since a quantum circuit is made of physical objects that live in spacetime, the ordered set of gates must be *embeddable* into spacetime. This implies that the activity of any single quantum gate corresponds to a single event in spacetime, and if the same gate can be active at more than one instant in time, it corresponds to *multiple* spacetime-localized gates [3].

3-event diagram

Slightly modified causal switch in flat Minkowski spacetime: Bob has only one spacetime-localized quantum gate, Alice's two gates correspond to the shutter being open in the timelike double slit experiment.

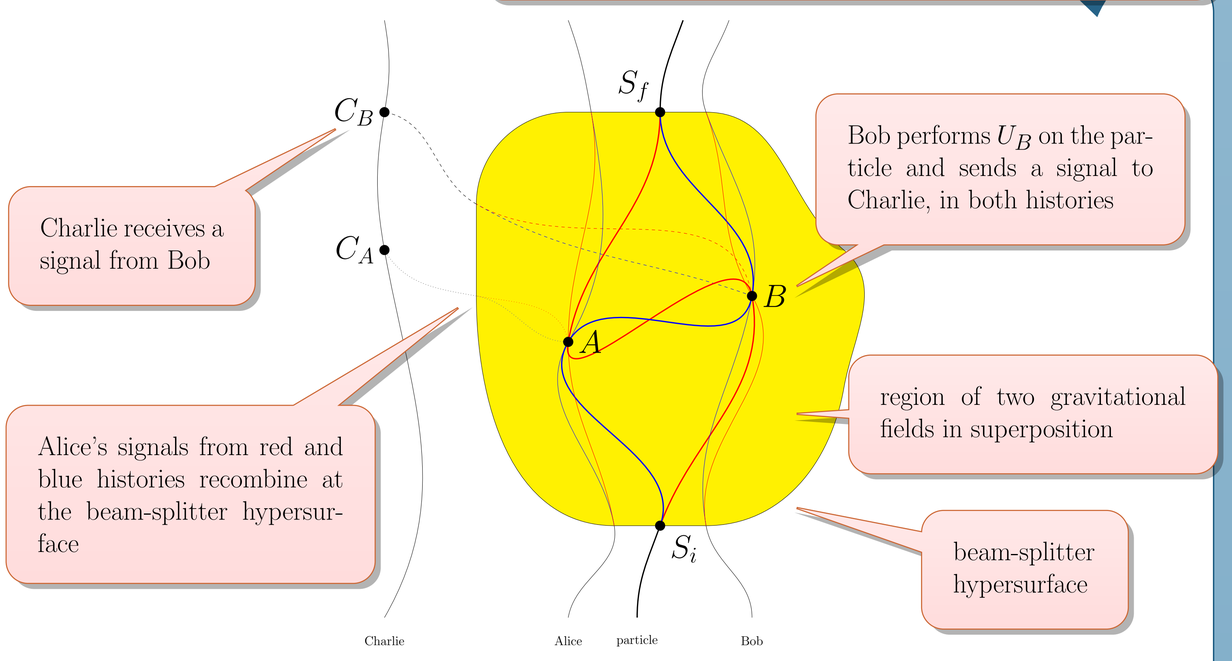


Timelike double-slit experiment ⟹

The 3-event causal switch in flat Minkowski spacetime turns out to be equivalent to the timelike double-slit experiment, in which a shutter opens and closes twice in a row, while a particle goes through the shutter "twice" and interferes with itself afterwards [4].

2-event diagram

The causal switch in quantum gravity: there are only two spacetime-localized quantum gates, Charlie always measures identical elapsed time between Alice's and Bob's signals.



⟸ Gravitational causal switch

In contrast to the flat-space case, where the causal switch has to be constructed from four (or at least three) gates, in the context of *quantum gravity* one can actually consider a superposition of two different spacetimes with two different causal order relations [5]. This enables one to discuss the genuine two-gate causal switch. An external observer (Charlie) can distinguish between the four-gate and two-gate switches by having Alice and Bob emit photons to Charlie when they perform their respective operations U_A and U_B on the particle. Charlie measures the proper time between the arrivals of the two photons on a subansamble, and obtains two different randomly distributed answers for the flat causal switch, versus only one answer for the quantum-gravitational causal switch [3].

References

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Conclusions

- Distinguishing between causal orders over sets of quantum gates and spacetime events is crucial for the proper understanding of causality in flat, curved and quantum spacetimes.
- The equivalence between the 3-event causal switch and the timelike double-slit suggests that experiments with the causal switch in flat spacetime [6, 7] demonstrate the known effect of timelike nonlocality, rather than the superposition of causal orders.
- In the context of quantum gravity, one can construct a *genuine* 2-event causal switch by superposing two different spacetime causal structures. Such quantum-gravitational causal switch can be observably distinguished from its 3- or 4-event counterparts in flat Minkowski spacetime.

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