Quantum gates, timelike nonlocality and causality in quantum gravity

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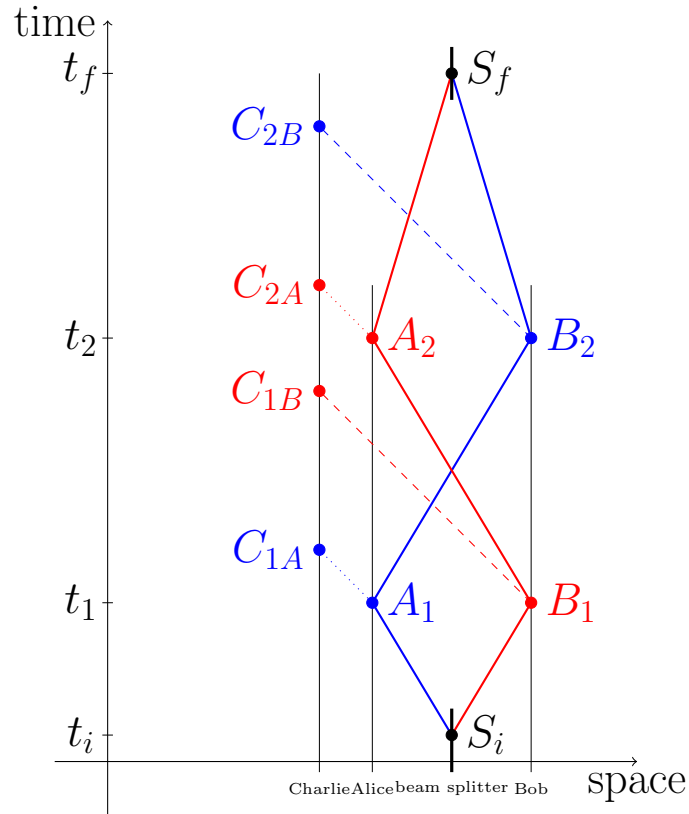
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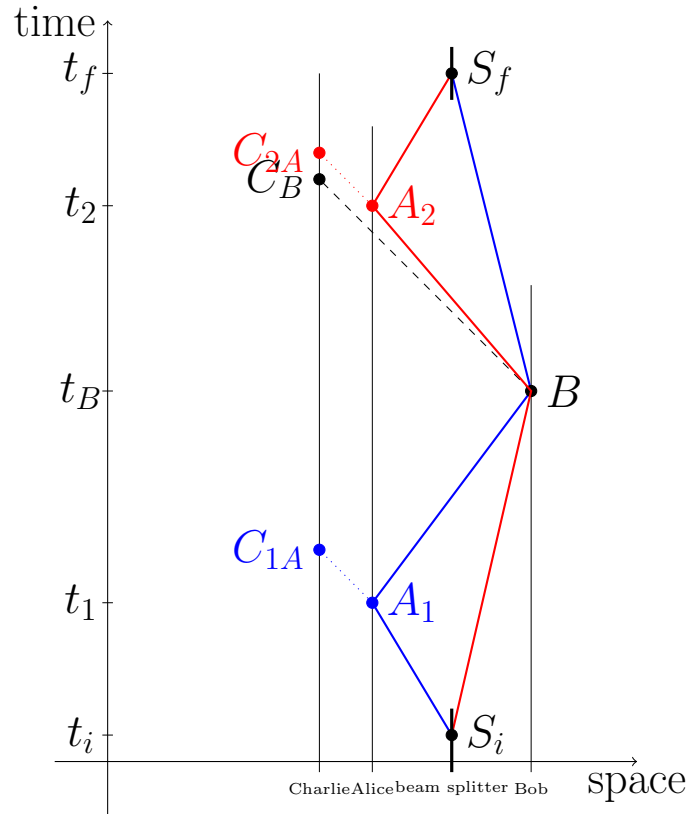# The causal switch in flat Minkowski spacetime

- A relation of partial order among gates in a quantum circuit [1, 2]: $(\mathcal{G}, \prec_{\mathcal{G}})$

- A relation of partial order among events in Minkowski spacetime: $(\mathcal{M}, \prec_{\mathcal{M}})$

$\Rightarrow$ $(\mathcal{G}, \prec_{\mathcal{G}})$ must be *embeddable* into $(\mathcal{M}, \prec_{\mathcal{M}})$

$\Rightarrow$ 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].

Timelike double-slit experiment

- Alice's gate in blue history $\Leftrightarrow$ shutter open at t_1

- Bob's gate in both histories $\Leftrightarrow$ shutter closed at t_B

- Alice's gate in red history $\Leftrightarrow$ shutter open at t_2

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

Gravitational causal switch
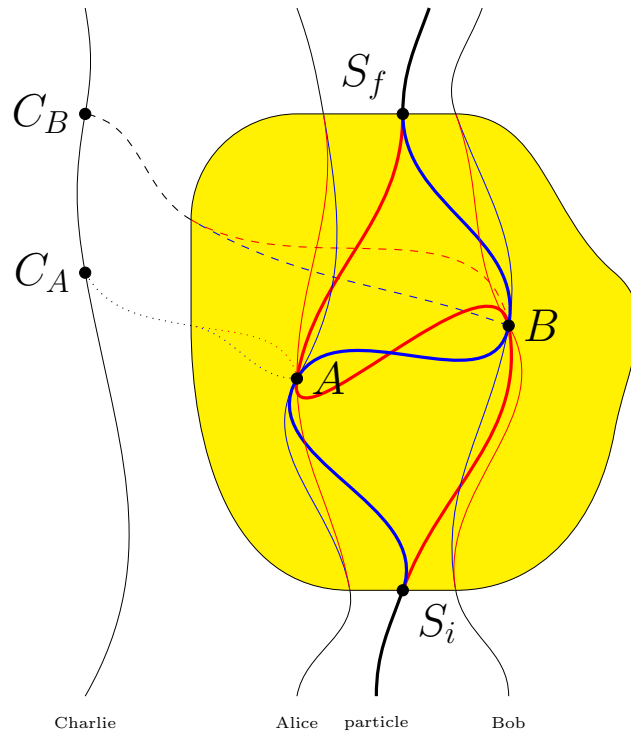
- *Quantum gravity*: superposition [5] of $(\mathcal{M}, \prec_{\mathcal{M}}^{\text{red}})$ and $(\mathcal{M}, \prec_{\mathcal{M}}^{\text{blue}})$

- A *genuine* two-event (bipartite, two-gate) causal switch

- Alice and Bob signal to Charlie with photons

$\Rightarrow$ Charlie measures the proper time between the arrivals of the two photons on a subansamble, and can distinguish between the flat-space causal switch and the quantum-gravitational causal switch [3].

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.

Bibliography

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THANK YOU!