

New type of closed timelike curves from quantum gravity

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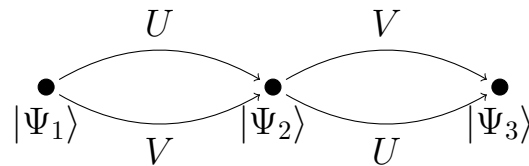
QUANTUM SWITCH PROTOCOL

Introduced by the quantum information community [Chiribella et al, 2013], it describes a hypothetical quantum protocol “without a definite causal structure”:

- an example of a higher order quantum operation,
- Alice and Bob perform operations U and V on a particle in initial state $|P\rangle$,
- the order of these operations is coupled to another quantum system (the Control), which is a qubit, so that

$$U_{\text{switch}} = |0\rangle_C \langle 0| \otimes UV + |1\rangle_C \langle 1| \otimes VU,$$

The concept of a “higher order quantum operation” comes from category theory, motivating the idea that one should have full quantum control not only over *physical systems*, but also over the *operations* on physical systems:



QUANTUM SWITCH PROTOCOL

In principle, one can use U_{switch} to arrange a quantum superposition of the order of operations A and B :

- start from the initial total state $|\Psi_i\rangle = |C\rangle \otimes |P\rangle$, with $|C\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$,
- apply the switch operation to obtain the final state

$$|\Psi_f\rangle = \frac{1}{\sqrt{2}}|0\rangle \otimes UV|P\rangle + \frac{1}{\sqrt{2}}|1\rangle \otimes VU|P\rangle,$$

- project the control in the superposed basis $|\pm\rangle = \frac{1}{\sqrt{2}}(|0\rangle \pm |1\rangle)$,
- depending on the outcome for the control being $+$ or $-$, the particle will end up in the state

$$\frac{1}{2}(UV + VU)|P\rangle \quad \text{or} \quad \frac{1}{2}(UV - VU)|P\rangle,$$

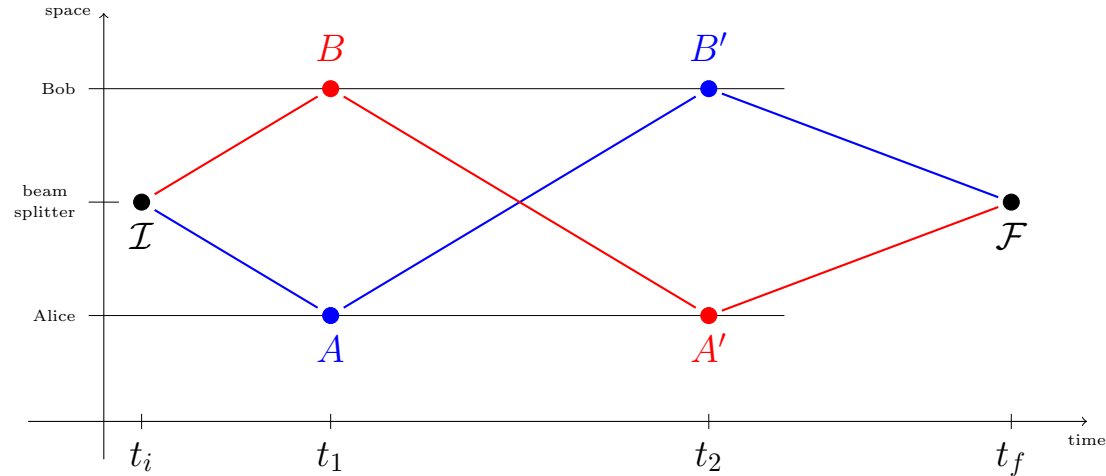
- both resulting states represent a quantum superposition of the order of operations U and V .

OPTICAL SWITCH

Can one implement this in experiment? Under certain additional assumptions, sure!

- experiments in quantum optics [Procopio et al, 2015; Rubino et al, 2017; Rubino et al, 2022],
- particle \rightarrow a polarized photon,
- the control \rightarrow photon trajectory,
- operations U and $V \rightarrow$ rotations of the polarization.

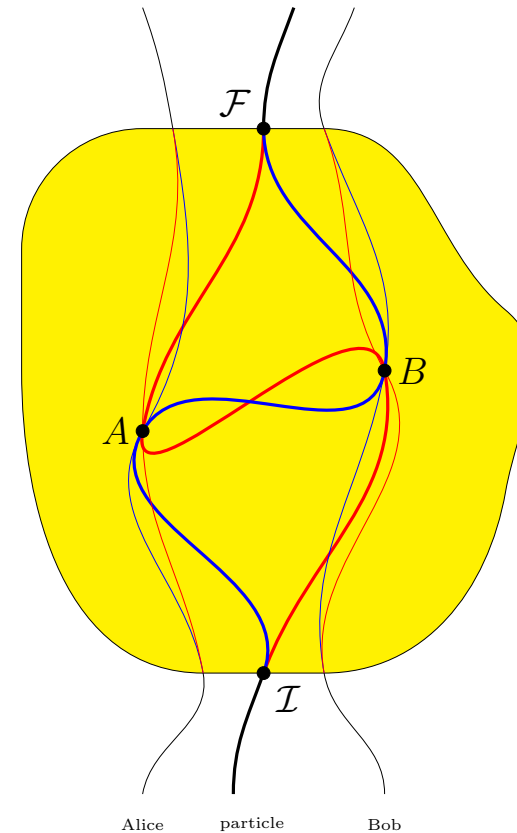
Such experimental realization is called the “optical switch”. A spacetime diagram of the process:



GRAVITATIONAL SWITCH

Can one obtain a genuine superposition of causal orders, i.e., no definite causal structure? Under certain additional assumptions, sure!

- Gravitational field \rightarrow local light cone structure.
- Superpositions of gravitational fields \rightarrow superpositions of causalities!
- \implies **Gravitational switch!!**
[Zych et al, 2019; Paunković, MV, 2020].



CTC CONSTRUCTION

The gravitational switch can be applied to implement closed timelike curves, in a novel way:

$$|G_I\rangle|\Psi_I\rangle \xrightarrow{U_1} \alpha_I|G_B\rangle|\Psi_I\rangle + \beta_I|G_R\rangle|\Psi_I\rangle.$$

$$\alpha_I|G_B\rangle|\Psi_I\rangle + \lambda_B\beta_B|G''_R\rangle V|\Psi_B\rangle \xrightarrow{U_2} \lambda_A|G_A\rangle|\Psi_A\rangle.$$

$$\lambda_A|G_A\rangle|\Psi_A\rangle \xrightarrow{U_3} \lambda_A|G_A\rangle U|\Psi_A\rangle,$$

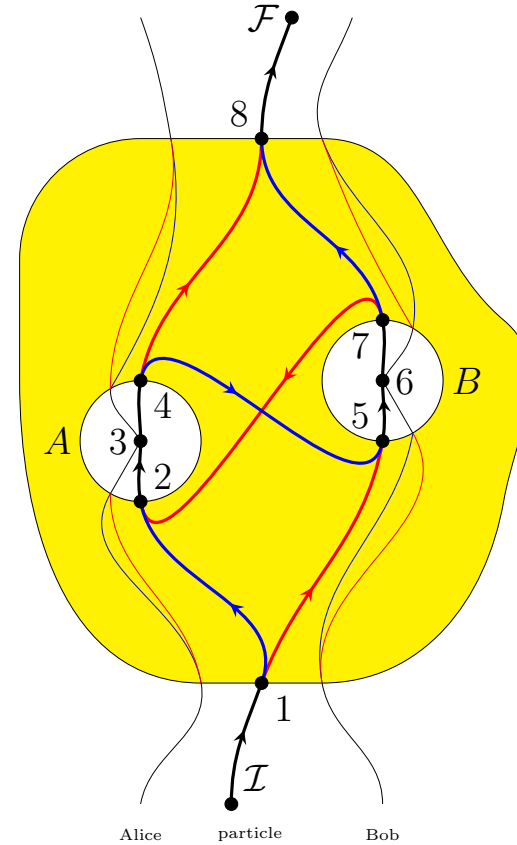
$$\lambda_A|G_A\rangle U|\Psi_A\rangle \xrightarrow{U_4} \lambda_A\left(\alpha_A|G'_B\rangle + \beta_A|G'_R\rangle\right)U|\Psi_A\rangle.$$

$$\beta_I|G_R\rangle|\Psi_I\rangle + \lambda_A\alpha_A|G'_B\rangle U|\Psi_A\rangle \xrightarrow{U_5} \lambda_B|G_B\rangle|\Psi_B\rangle.$$

$$\lambda_B|G_B\rangle|\Psi_B\rangle \xrightarrow{U_6} \lambda_B|G_B\rangle V|\Psi_B\rangle,$$

$$\lambda_B|G_B\rangle V|\Psi_B\rangle \xrightarrow{U_7} \lambda_B\left(\alpha_B|G''_B\rangle + \beta_B|G''_R\rangle\right)V|\Psi_B\rangle,$$

$$\lambda_A\beta_A|G'_R\rangle U|\Psi_A\rangle + \lambda_B\alpha_B|G''_B\rangle V|\Psi_B\rangle \xrightarrow{U_8} |G_O\rangle|\Psi_O\rangle.$$



CTC CONSTRUCTION

The gravitational switch can be applied to implement closed timelike curves, in a novel way:

$$\begin{aligned}
 |G_I\rangle|\Psi_I\rangle &\xrightarrow{U_1} \alpha_I|G_B\rangle|\Psi_I\rangle + \beta_I|G_R\rangle|\Psi_I\rangle. \\
 \alpha_I|G_B\rangle|\Psi_I\rangle + \lambda_B\beta_B|G''_R\rangle V|\Psi_B\rangle &\xrightarrow{U_2} \lambda_A|G_A\rangle|\Psi_A\rangle. \\
 \lambda_A|G_A\rangle|\Psi_A\rangle &\xrightarrow{U_3} \lambda_A|G_A\rangle U|\Psi_A\rangle, \\
 \lambda_A|G_A\rangle U|\Psi_A\rangle &\xrightarrow{U_4} \lambda_A\left(\alpha_A|G'_B\rangle + \beta_A|G'_R\rangle\right)U|\Psi_A\rangle. \\
 \beta_I|G_R\rangle|\Psi_I\rangle + \lambda_A\alpha_A|G'_B\rangle U|\Psi_A\rangle &\xrightarrow{U_5} \lambda_B|G_B\rangle|\Psi_B\rangle. \\
 \lambda_B|G_B\rangle|\Psi_B\rangle &\xrightarrow{U_6} \lambda_B|G_B\rangle V|\Psi_B\rangle, \\
 \lambda_B|G_B\rangle V|\Psi_B\rangle &\xrightarrow{U_7} \lambda_B\left(\alpha_B|G''_B\rangle + \beta_B|G''_R\rangle\right)V|\Psi_B\rangle, \\
 \lambda_A\beta_A|G'_R\rangle U|\Psi_A\rangle + \lambda_B\alpha_B|G''_B\rangle V|\Psi_B\rangle &\xrightarrow{U_8} |G_O\rangle|\Psi_O\rangle.
 \end{aligned}$$

A so-called *trivial solution* exists:

$$\begin{aligned}
 U &= V = I, \\
 |\Psi_A\rangle &= |\Psi_B\rangle = |\Psi_O\rangle = |\Psi_I\rangle, \\
 U_4 &= U_2^{-1}, \quad U_7 = U_5^{-1}, \quad U_8 = U_1^{-1}, \\
 |G'_R\rangle &= |G''_R\rangle = |G_R\rangle, \quad |G'_B\rangle = |G''_B\rangle = |G_B\rangle, \\
 |G_B\rangle &= \alpha^{-1}U_1|G_I\rangle - \alpha^{-1}\beta|G_R\rangle, \\
 |G_A\rangle &= U_2U_1|G_I\rangle, \\
 |G_B\rangle &= U_5U_1|G_I\rangle, \\
 |G_O\rangle &= |G_I\rangle, \\
 |\lambda_A| &= |\lambda_B| = 1, \quad \beta = \sqrt{1 - \alpha^2}, \\
 |G_I\rangle, |G_R\rangle, \alpha, U_1, U_2, U_5, |\Psi_I\rangle &\text{ are arbitrary.}
 \end{aligned}$$

The trivial solution is important since it demonstrates the self-consistency of the system, and that the set of solutions is nonempty.

CTC CONSTRUCTION

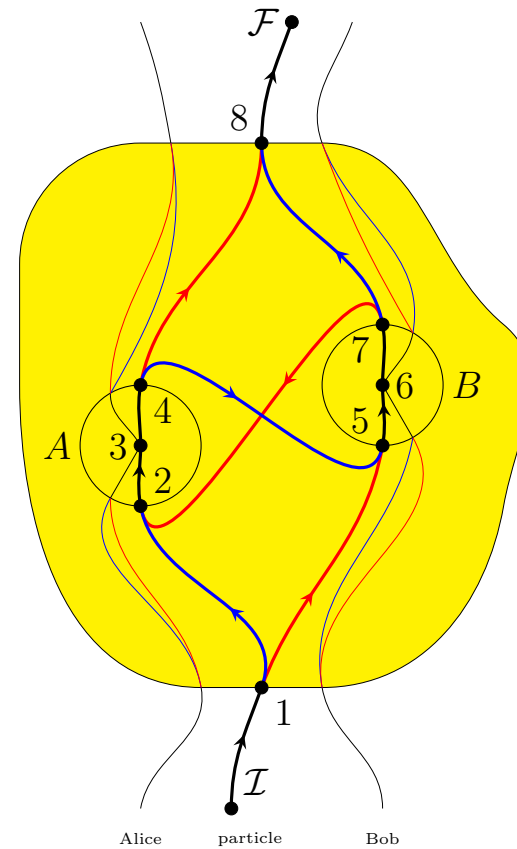
Even more general configurations of the gravitational switch have CTC solutions, including nontrivial ones:

- Three classes of nontrivial solutions found, depending on several parameters.
- General structure — one part of the solution describes the particle entering and exiting the yellow blob, and the other part describes the particle cycling within a closed loop

$$2 \rightarrow 3 \rightarrow 4 \rightarrow 5 \rightarrow 6 \rightarrow 7 \rightarrow 2.$$

- Rough structure of the implicit solution:

$$\left(1 + c_1 UV\right) |\Psi\rangle = \left[c_2 U + c_3 UV + c_4 UVU\right] |\Psi_I\rangle,$$
$$c_1, c_2, c_3, c_4 \in \mathbb{C}.$$



CONCLUSIONS

- Quantum information community came up with an interesting toy example process — the quantum switch.
- The implementation of the switch can be done in the context of quantum gravity — the gravitational switch.
- The ideas behind the gravitational switch can be modified and utilized to construct various CTC solutions.
- The CTC solutions do not require exotic topology, but exist in ordinary globally hyperbolic spacetimes.
- Arguably, it is easier to put gravity into a quantum superposition than to change spacetime topology...

Research is ongoing!

THANK YOU!