DEFINITE vs SUPERPOSED CAUSAL ORDERS and QUANTUM GRAVITY

Marko Vojinović*, in collaboration with Nikola Paunković†

*Institute of Physics, University of Belgrade, Serbia
†Instituto de Telecomunicacõoes and Departamento de Matemática,
Instituto Superior Técnico, Universidade de Lisboa, Portugal

based on arXiv:1905.09682

TOPICS

- Introduction
- Graphs, quantum circuits, spacetime and causality
- Quantum switch: 4-event, 3-event and 2-event versions
- An observable which distinguishes between them
- Implications for the relational view of physics
- Conclusions

INTRODUCTION

What is an "event"?

- in *relativity*, an **event** is a point on a spacetime manifold $\mathcal{M}$ (m-event)
- in *information theory*, an **event** is an interaction between a physical system and an instrument, represented by a gate in a circuit diagram $\mathcal{C}$ (c-event)

What is "causal order"?

- in *relativity*, **causal order**, $\prec_{\mathcal{M}}$, is a relation of partial order defined by the light cone structure of a spacetime manifold $\mathcal{M}$
- in *information theory*, **"causal" order**, $\prec_{\mathcal{C}}$ is a relation of partial order defined by oriented links between gates in a circuit diagram $\mathcal{C}$

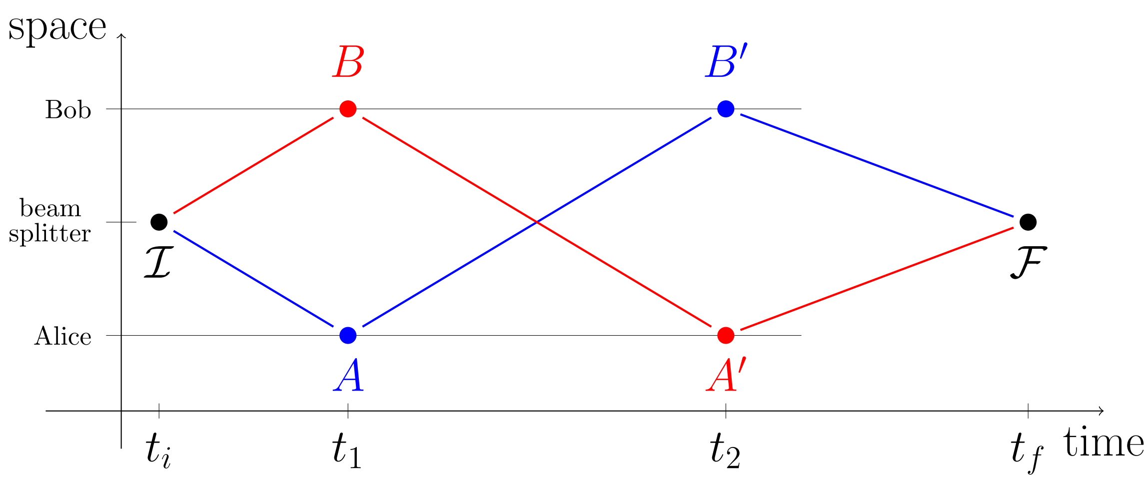
The morale of this lecture is to demonstrate that these notions are both observable and inequivalent.

$\Rightarrow$ The usage of the terms **event** and **causal order** by experts from different communities is **overloaded**, and one should be careful what one is talking about.

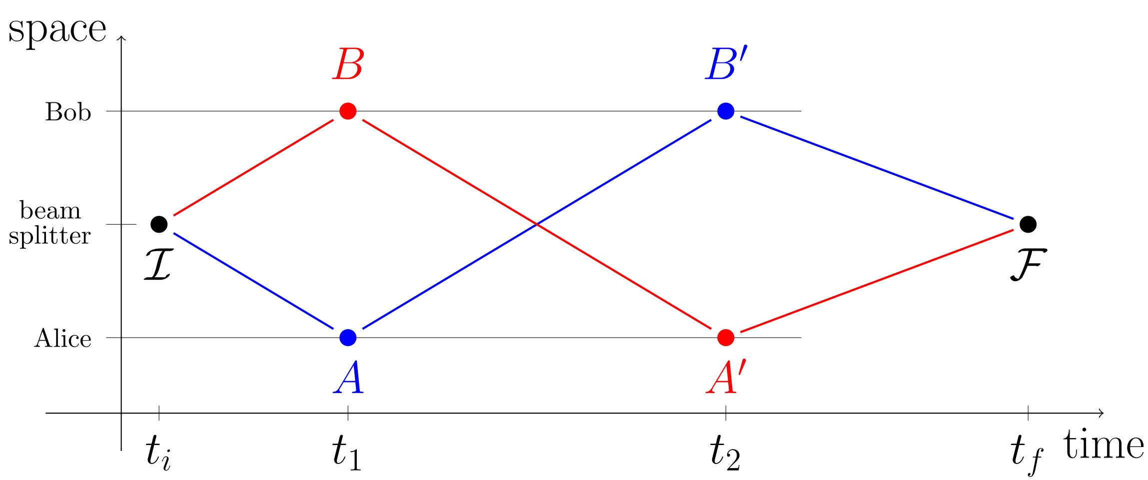
QUANTUM SWITCH

What is a *quantum switch* circuit?

- Informally, a **quantum switch** is a particular circuit in which the order of two operations, U and V, is not well-defined — the particle travelling through the circuit experiences a superposition of switched order of operations, UV and VU, coupled to the so-called **control system**.
- How to implement this in practice? Introduce the so-called 4**-event process**:



4-EVENT PROCESS

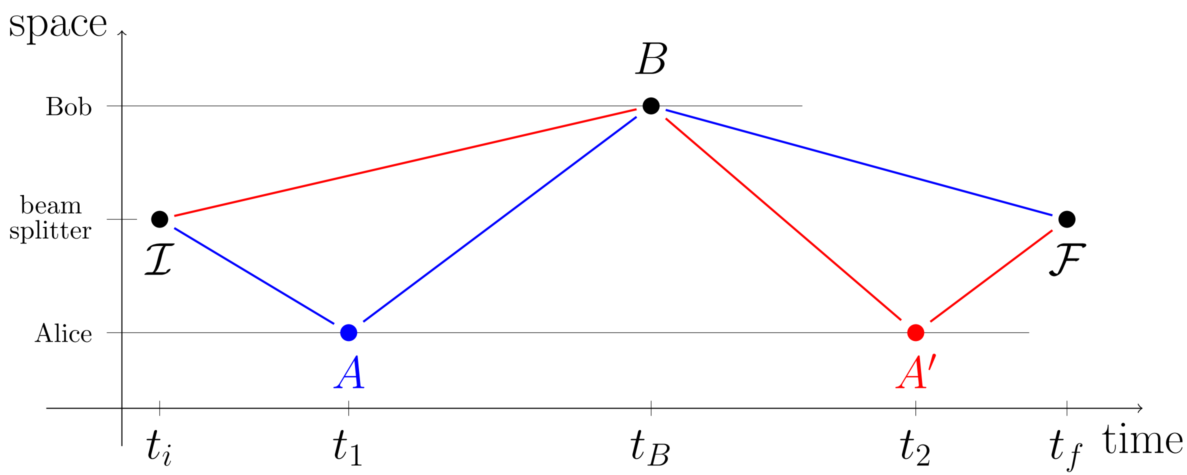


Properties of the 4-event process:

- it consists of 4 m-events (A, B, A' and B'), but only 2 c-events (operation U performed at either A or A', operation V at either B or B')
- the causal order of c-events is not well-defined — in the blue history $U \prec_{\mathcal{C}} V$, while in the red history $V \prec_{\mathcal{C}} U$, and these are in quantum superposition
- the causal order of m-events is well-defined — $A \prec_{\mathcal{M}} A', B'$, $\qquad B \prec_{\mathcal{M}} A', B'$

3-EVENT PROCESS

Can we do better, with less m-events? Identify m-events $B \equiv B'$, and thus introduce the 3-event process:



Properties of the 3-event diagram:

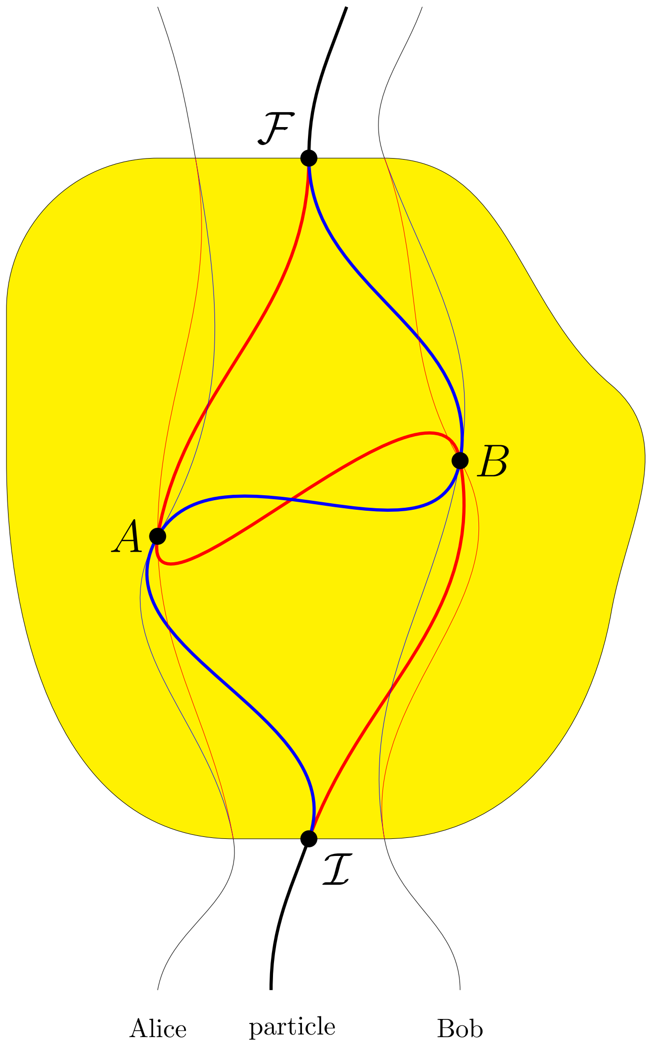
- 3 m-events (A, B, and A'), and 2 c-events (U at A or A', V at B)
- the causal order of c-events still in superposition of $U \prec_{\mathcal{C}} V$ and $V \prec_{\mathcal{C}} U$
- the causal order of m-events still well-defined — $A \prec_{\mathcal{M}} B \prec_{\mathcal{M}} A'$

2-EVENT PROCESS

Can we do better still, with only 2 m-events? Identify both $B \equiv B'$ and $A \equiv A'$?

- **not possible** on a classical spacetime manifold — requires either **superluminal** or **backwards-in-time** propagation of the particle!!
- arguably **possible** within the framework of **quantum gravity**, by creating a region with a quantum superposition of two graviational fields, each having its own spacetime causal structure
- called the **gravitational switch**, it contains precisely 2 m-events and 2 c-events
- the causal order of c-events is in superposition of $U \prec_{\mathcal{C}} V$ and $V \prec_{\mathcal{C}} U$
- the causal order of m-events is also in a superposition of $A \prec_{\mathcal{M}}^{(g)} B$ and $B \prec_{\mathcal{M}}^{(\tilde{g})} A$, since gravitational configurations $g_{\mu\nu}$ and $\tilde{g}_{\mu\nu}$ are in superposition

THE GRAVITATIONAL SWITCH



OBSERVABILITY OF M-EVENTS

Can one operationally distinguish m-event A from A' and B from B'?

- Discussion in L. M. Procopio et al, *Nature Communications* **6**, 7913 (2015):

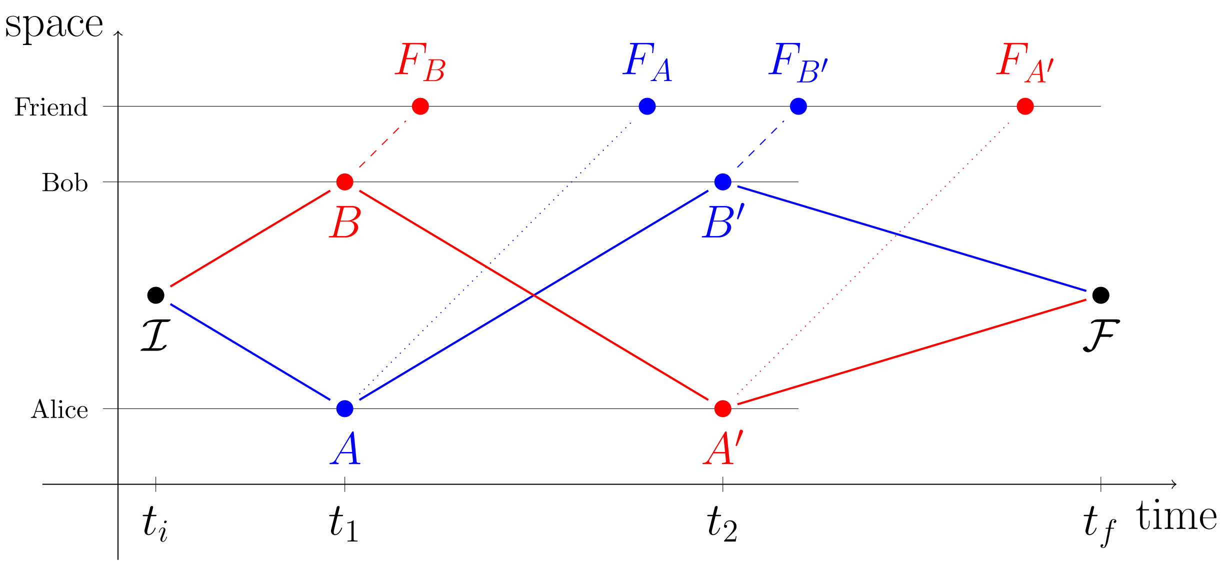
"Traditionally, space-time events are defined with respect to some coordinate system, which describes a given underlying space-time. [Then] one can say that there are two different times at which each photon can undergo the corresponding operation. In this perspective, one would describe the experiment in terms of **four space-time events** [...], **whose causal order is determined** by the underlying classical space-time. Note, however, that **any attempt to physically distinguish the two times** at which a photon can pass through a gate **would reveal which-way information and thus destroy the interference**. The results of the experiment confirm that such information is not available anywhere and that the interpretation of the experiment in terms of **four, causally-ordered events cannot be given an operational meaning.**"

(emphasis mine)

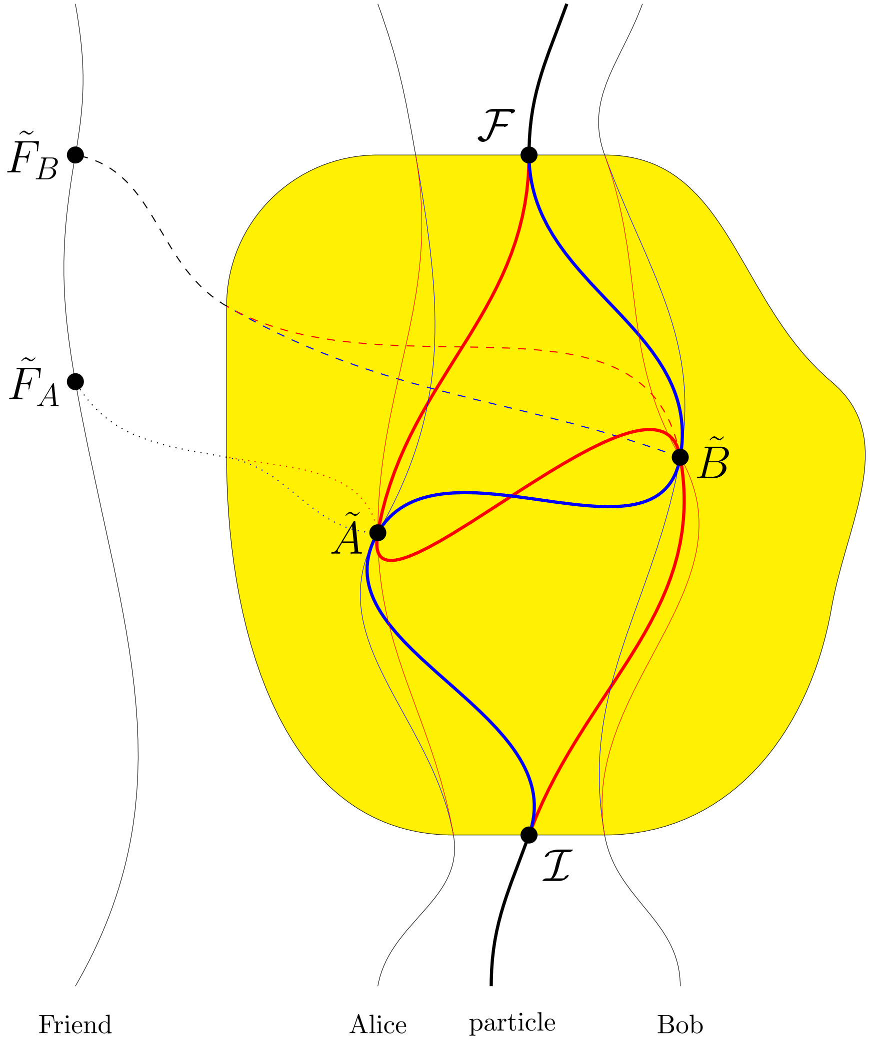
OBSERVABILITY OF M-EVENTS

Nevertheless, the answer is yes, m-events can indeed be distinguished!

- While individual spacetime points are not observable due to diff-invariance of the spacetime manifold, **their mutual distinctiveness** is a property of topology (so-called Hausdorff separability), and is thus diff-invariant.
- Introduce a third party, Friend, and have Alice and Bob send photons to Friend whenever they interact with the particle:



OBSERVABILITY OF M-EVENTS



OBSERVABILITY OF M-EVENTS

What does Friend do?

- In the 4-event case, there are two possible states of two photons, $|F_{AB'}\rangle$ and $|F_{A'B}\rangle$, while in he 2-event case, there is only one such state, $|\tilde{F}_{AB}\rangle$.
- Friend measures a dichotomic photon non-demolition orthogonal observable

$$M = 1 \cdot (P_< + P_>) + 0 \cdot P_= \,,$$

where $P_<$, $P_>$ and $P_=$ are projectors onto the three photon states, respectively.

- **In the** 2**-event case**, the total state of the particle and photons is $\frac{1}{\sqrt{2}}\left(|R\rangle + |B\rangle\right)|\tilde{F}_{AB}\rangle$, and **Friend obtains result** 0 for M without disturbing the superposition of the particle.
- **In the** 4**-event case**, the total state of the particle and photons is

$$\frac{1}{\sqrt{2}}\Big(|R\rangle|F_{A'B}\rangle + |B\rangle|F_{AB'}\rangle\Big) \equiv \frac{1}{2\sqrt{2}}\Big[\Big(|R\rangle + |B\rangle\Big)\Big(|F_{A'B}\rangle + |F_{AB'}\rangle\Big) + \Big(|R\rangle - |B\rangle\Big)\Big(|F_{A'B}\rangle - |F_{AB'}\rangle\Big)\Big].$$

OBSERVABILITY OF M-EVENTS

What does Friend do?

- **In the** 4**-event case**, the total state of the particle and photons is

$$\frac{1}{\sqrt{2}}\Big(|R\rangle|F_{A'B}\rangle + |B\rangle|F_{AB'}\rangle\Big) \equiv \frac{1}{2\sqrt{2}}\Big[\Big(|R\rangle + |B\rangle\Big)\Big(|F_{A'B}\rangle + |F_{AB'}\rangle\Big) + \Big(|R\rangle - |B\rangle\Big)\Big(|F_{A'B}\rangle - |F_{AB'}\rangle\Big)\Big].$$

- **Friend obtains result** 1 for M, and subsequently performs **quantum erasing** by an additional measurement of the photons in the basis

$$|\pm\rangle \equiv \frac{1}{\sqrt{2}}\left(|F_{A'B}\rangle \pm |F_{AB'}\rangle\right) ,$$

thus projecting the particle back into a superposed state $\frac{1}{\sqrt{2}}\left(|R\rangle \pm |B\rangle\right)$. Knowing the outcomes of the measurement of M and of $|\pm\rangle\langle\pm|$, Friend can postselect the $+$ state for the particle, ultimately not disturbing the superposition.

COMMENTS ON RELATIONALISM

What can we learn from the observable that is measured by Friend?

- The c-events can be counted by Alice and Bob, and in each of the discussed set-ups there are precisely 2 c-events.
- The outcome of the observable M allows Friend to count the m-events, and their number is generically different from the number of c-events.

$\Rightarrow$ Contrary to the statement by Procopio et al, one actually **can give an operational meaning to m-events**, and to the corresponding relation of causal order induced by the spacetime metric, without revealing which-way information.

Spacetime causality cannot be substituted with the order of gate operations in a quantum circuit.
Quantum superpositions of causal orders can be discussed only in the context of quantum gravity (if at all).

COMMENTS ON RELATIONALISM

What are the consequences for the relational approach to spacetime and to physics?

- One must be very careful when applying relational ideas to the notion of spacetime!
- While individual m-events cannot be observed directly due to diff-invariance, various properties that involve them can be observed — mutual distinguishability of m-events and causal structure of the spacetime metric are **invariants**, and can be observable!
- **When building a relational description of the world, the manifold structure of spacetime cannot be ignored** — its number of dimensions ($D = 4$), its topology and its causal structure are **observables**, and any theoretical model has to either

  (a) **postulate** their values (ontological, non-relational spacetime manifold), or

  (b) **derive** their values from "simpler" relational first principles (emergent spacetime).

So far, no theoretical model ever succeded in implementing (b).

THANK YOU!