Events are relative to a Lab: dissolving the debate on quantum switch experiments

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Abstract for QPL 2026 based on [1]

I. BACKGROUND AND MOTIVATION

Events and their localisation—what happens, where and when—are central to our understanding of the world, in both everyday life and science. They are closely tied to causality, which underpins a theory's explanatory power, since events serve as the relata of causal connections. In quantum theory, events are defined operationally through measurements and interventions, often relative to observers or agents, and causality in terms of information flow discernible by such agents. In contrast, general relativity treats events and causal relations as features of spacetime, independent of agents. This exposes a deep conceptual disparity between the two frameworks. Reconciling them is crucial for understanding both (1) quantum experiments in spacetime and relativistic quantum information tasks, and (2) quantum gravity, where spacetime itself becomes quantum and a classical background can no longer be assumed. The goal of this work is to develop a general notion of events and localisation without presupposing spacetime, one that bridges quantum and relativistic perspectives while being applicable for both (1) and (2).

A growing research area in quantum information where such notions are particularly central is in the study of protocols with indefinite causal order (ICO) of quantum operations [2–4]. The most prominent example is the quantum switch (QS), which has been linked to potential advantages for information processing. Sophisticated optical experiments in Minkowski spacetime [5–13] claim to implement the ICO of the QS, yet their interpretation remains debated [2, 6, 14–23] with diverging perspectives. One is a **coarse-grained perspective** [16, 22–24], where the QS and its realisations involve two operations (Alice and Bob) in indefinite order. Another is the **fine-grained perspective**, where by Alice and Bob's operations at different times yield a quantum circuit with definite, acyclic causal order, compatible with relativistic causality. Theoretical quantum gravitational realisations of QS have also been proposed [25], where spacetime geometry is in quantum superposition, raising the intriguing question of whether events, causality and ultimately information-processing possibilities in such exotic spacetimes differ fundamentally from those in optical QS type experiments in classical spacetime. Despite progress, the field remains divided on the physical and operational meaning of ICO, largely due to the absence of a general notion of events that consistently recovers both quantum information and relativistic perspectives under clear assumptions.

We propose such an approach, for defining events and localisation without assuming spacetime or a particular theory, but instead starting from operational assumptions: what information and degrees of freedom (d.o.f.) a laboratory can, in principle, access and act upon. The resolution [26, 27] of the Maxwell's demon paradox [28] shows that physical quantities like entropy are relative to what information an agent (demon vs macroscopic observer) can access and what d.o.f. they control. This motivates adopting relational, agent-dependent principles as the basis for defining events.

II. OVERVIEW OF CONTRIBUTIONS

Lab and relative events We introduce the operational notion of a Lab, and propose defining events relative to it. A Lab captures three essential choices encoding implicit assumptions in physical reasoning: (a) the level of detail at which a phenomenon is analysed; (b) reference degrees of freedom used to condition operations (e.g., turning on a laser when a clock reads 5pm, or sending a message when a spin is "up"); and (c) the allowed operations, including those possible in principle.

More concretely, a Lab A is specified by three items:

1. a *reference d.o.f.* R_A with a measurement $\mathcal{M}_{R_A} := \{\Pi_\lambda\}_{\lambda\in\Lambda}$ defined on it,
2. a *target d.o.f.* T_A
3. a *set of operations* $\mathcal{O}_A$ on R_A and T_A formed of conditioned operations: conditioned on the λ subspace of R_A, a corresponding operation O_A^λ acts on T_A.

The physical outcome labels $\mathcal{P}_A := \Lambda$ form the *reference information set*, giving a generalised notion of location. In standard quantum theory, these are controlled operations with R_A as control (in a basis given by $\mathcal{M}_{R_A}$). Each $O_A \in \mathcal{O}_A$ is then an event relative to the Lab A. Our notion of reference differs from reference frames, particularly quantum reference frames [29–35]. For example, a quantum spin can act as a reference d.o.f. when used as the control of a CNOT gate—distinct from its role as a quantum reference frame for other spins.

Relative measurability and localisation. We introduce the concept of *relative measurability* of the reference and define *localisation* of events relative to a Lab, and then apply them in the example of the quantum switch. This requires initial conditions $\mathcal{I}_A$ on R_A, T_A, and possibly an external *environment* E_A. Relative measurability captures that for the given initial conditions $\mathcal{I}_A$, $O_A \circ \mathcal{M}_{R_A}$ and O_A (where $\circ$ denotes sequential composition of operations) have the same effect on T_A and E_A (i.e. when R_A is discarded), for all $O_A \in \mathcal{O}_A$. This is sensitive to correlations between the reference of a Lab and its objects of study: if R_A is entangled with T_A or E_A, measuring R_A can disturb them and thus violate relative measurability.

Localisation tells us when an event O_A for a Lab A is localised at some "location" $\lambda \in \mathcal{P}_A$ relative to that Lab, and initial conditions $\mathcal{I}_A$: this is the case when for the given $\mathcal{I}_A$, $\Pi_\lambda \circ O_A \circ \Pi_\lambda$ and O_A have the same effect on T_A and E_A.

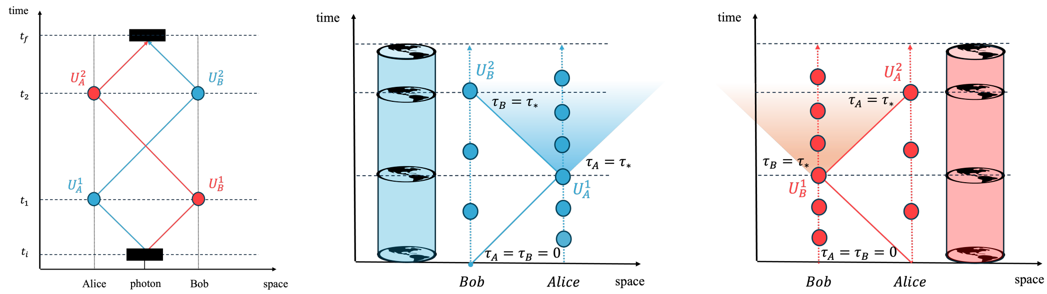
In quantum information protocols, E_A corresponds to parts of the protocol external to Lab A, making the above concepts inherently dependent not only on the Lab but also on the context of the surrounding protocol. Moreover, these definitions recover standard concepts in quantum and relativity theories under specific choices of Labs e.g., crossing of worldlines or subsystem locality.

Dissolving the debate on quantum switch experiments. The quantum switch [2] is an abstract protocol that involves a control and target system, and performs a quantum controlled superposition of the order of Alice and Bob's quantum operations on the target. In Fig. 1, we illustrate two realisations of QS in distinct physical regimes (a) QS_{CT}: QS where agents follow a classical trajectory in a classical (Minkowski) space-time. This is the case if we take Alice and Bob to be classical experimenters performing a table-top quantum experiment such as the optical QS [6, 7]. (b) QS_G the quantum gravitational QS [25] where spacetime geometry is in a linear quantum superposition.

First we take the optical quantum switch analysed from the view of the Labs of classical experimenters i.e., QS_{CT}. The coarse vs fine-grained perspectives are recovered under distinct instantiation of the Labs and their choice of reference R_A and target d.o.f T_A, and set $\mathcal{O}_A$ of operations on them.

- **Lab for fine-grained optical QS:** R_A includes physical references (e.g. rods and clocks) tied to the background spacetime, T_A includes the photon and the vacuum (zero-photon mode), while $\mathcal{O}_A$ allows to operate on T_A depending on the spacetime location given by R_A. For such Labs, the optical QS admits a definite causal order explanation, in terms of fine-grained events which are localised relative to R_A (e.g., Alice's operation localised at time t_1).
- **Lab for coarse-grained optical QS:** R_A is a single element (eg, target label) that does not include any spacetime information, T_A is the photon (vacuum not included), $\mathcal{O}_A$ are effectively operations only on T_A as the reference is a single element that simply identifies the target subsystem. For such Labs, the optical QS does not admit any definite causal order explanation as above.

This yields our first conclusion that *events, their localisation and causal order are relative to a Lab. Even for the same physical experiment, there can exist different choices of Labs from which it is*



(a) QS_{CT} (b) QS_G

FIG. 1: (a) QS_{CT}: Alice and Bob each follow a classical trajectory (black dotted lines) in the classical background spacetime, the target system is in a superposition of trajectories (red and blue solid lines). This corresponds to the space-time diagram of a typical QS_O experiment [6].(b) QS_G [25]: a superposition of the two spacetime geometries drawn separately in the left/right diagrams, obtained by superposing the corresponding mass configurations. Alice and Bob follow different trajectories in the two branches (red and blue dotted lines), so does the target (red and blue solid lines).

analysed. This dissolves the debate by showing that the different conclusions on ICO in the optical experiments stem from distinct assumptions on what constitutes the Lab.

Distinction between optical and gravitational switches. Secondly, we compare the optical and quantum gravitational QS. While earlier work [36] suggested no difference between them in terms of events, localisation and causality, a careful specification of Labs reveals finer distinctions. Consider the fine-grained optical QS (QS_O) and the gravitational QS (QS_G), where Alice and Bob's Labs in QS_G include their proper time and relative spatial distance to the mass (or equivalently, acceleration) as references. In both cases, unlike the coarse-grained QS, agents can coherently perform different operations depending on the order—for example, Alice may apply U_A^1 if she acts before Bob and U_A^2 if after. However, the key distinctions are

- In QS_O the spacetime references are relatively measurable, while in QS_G they are not. This is because in QS_G the distance/acceleration reference is entangled with the QS control, whereas in QS_O the reference clock in a physical laboratory is independent of the photonic experiment taking place on its table-top.
- Operationally, the relative measurability entails that Alice and Bob in QS_O can use their references to intervene independently at distinct locations (e.g., rotating a wave plate at t_1 and again at t_2), thereby localising fine-grained events. In QS_G, by contrast, they cannot intervene independently relative to their references, and their events remain non-localised.
- As a consequence, for these choice of Labs, QS_O can be fine-grained into a sequence of localised events with definite causal order, but not QS_G.

III. OUTLOOK

Our work emphasizes that events and causal order between them, depends on the choice of Lab, even within a fixed physical experiment. This motivates reexamining the resource-theoretic understanding of ICO in physical protocols in space-time, given that the notion of ICO is not preserved under distinct choices of Labs. Further the distinctions we found between the optical and gravitational QS do not arise from quantum gravity effects, but from whether a Lab's reference is entangled with the system under study. Relative measurability can detect this, and it would be interesting to systematically link it to measures of correlations and non-classicality. Moreover, so far it is only known classical-spacetime realisations of QS admit a fine-grained definite-order explanation for some choice of Labs. Under what conditions and in which regimes can such explanations be guaranteed? Addressing this may also clarify how definite information-theoretic causal order emerges in the absence of a background spacetime.

[1] V. Vilasini, Lin-Qing Chen, Liuhang Ye, and Renato Renner. Events and their localisation are relative to a lab, 2025. https://arxiv.org/abs/2505.21797.

[2] Giulio Chiribella, Giacomo Mauro D'Ariano, Paolo Perinotti, and Benoit Valiron. Quantum computations without definite causal structure. *Physical Review A*, 88(2):022318, 2013. https://journals.aps.org/pra/abstract/10.1103/PhysRevA.88.022318.

[3] Ognyan Oreshkov, Fabio Costa, and Časlav Brukner. Quantum correlations with no causal order. *Nature communications*, 3(1):1092, 2012. https://www.nature.com/articles/ncomms2076.

[4] Mateus Araújo, Cyril Branciard, Fabio Costa, Adrien Feix, Christina Giarmatzi, and Časlav Brukner. Witnessing causal nonseparability. *New Journal of Physics*, 17(10):102001, 2015. https://iopscience.iop.org/article/10.1088/1367-2630/17/10/102001.

[5] Mateus Araújo, Fabio Costa, and Časlav Brukner. Computational advantage from quantum-controlled ordering of gates. *Physical Review Letters*, 113(25), 2014. http://dx.doi.org/10.1103/PhysRevLett.113.250402.

[6] Lorenzo M Procopio, Amir Moqanaki, Mateus Araújo, Fabio Costa, Irati Alonso Calafell, Emma G Dowd, Deny R Hamel, Lee A Rozema, Časlav Brukner, and Philip Walther. Experimental superposition of orders of quantum gates. *Nature communications*, 6(1):7913, 2015. https://www.nature.com/articles/ncomms8913.

[7] Giulia Rubino, Lee A. Rozema, Adrien Feix, Mateus Araújo, Jonas M. Zeuner, Lorenzo M. Procopio, Časlav Brukner, and Philip Walther. Experimental verification of an indefinite causal order. *Science Advances*, 3(3), 2017. http://advances.sciencemag.org/content/3/3/e1602589.

[8] K. Goswami, C. Giarmatzi, M. Kewming, F. Costa, C. Branciard, J. Romero, and A.G. White. Indefinite causal order in a quantum switch. *Physical Review Letters*, 121(9), 2018. http://dx.doi.org/10.1103/PhysRevLett.121.090503.

[9] Kejin Wei, Nora Tischler, Si-Ran Zhao, Yu-Huai Li, Juan Miguel Arrazola, Yang Liu, Weijun Zhang, Hao Li, Lixing You, Zhen Wang, and et al. Experimental quantum switching for exponentially superior quantum communication complexity. *Physical Review Letters*, 122(12), 2019. http://dx.doi.org/10.1103/PhysRevLett.122.120504.

[10] Yu Guo, Xiao-Min Hu, Zhi-Bo Hou, Huan Cao, Jin-Ming Cui, Bi-Heng Liu, Yun-Feng Huang, Chuan-Feng Li, Guang-Can Guo, and Giulio Chiribella. Experimental transmission of quantum information using a superposition of causal orders. *Physical Review Letters*, 124(3), 2020. http://dx.doi.org/10.1103/PhysRevLett.124.030502.

[11] K. Goswami and J. Romero. Experiments on quantum causality. *AVS Quantum Science*, 2(3):037101, 2020. http://dx.doi.org/10.1116/5.0010747.

[12] Márcio M. Taddei, Jaime Cariñe, Daniel Martínez, Tania García, Nayda Guerrero, Alastair A. Abbott, Mateus Araújo, Cyril Branciard, Esteban S. Gómez, Stephen P. Walborn, and et al. Computational advantage from the quantum superposition of multiple temporal orders of photonic gates. *PRX Quantum*, 2(1), 2021. http://dx.doi.org/10.1103/PRXQuantum.2.010320.

[13] Giulia Rubino, Lee A. Rozema, Daniel Ebler, Hlér Kristjánsson, Sina Salek, Philippe Allard Guérin, Alastair A. Abbott, Cyril Branciard, Časlav Brukner, Giulio Chiribella, and et al. Experimental quantum communication enhancement by superposing trajectories. *Physical Review Research*, 3(1), 2021. http://dx.doi.org/10.1103/PhysRevResearch.3.013093.

[14] Christopher Portmann, Christian Matt, Ueli Maurer, Renato Renner, and Bjorn Tackmann. Causal Boxes: Quantum Information-Processing Systems Closed under Composition. *IEEE Transactions on Information Theory*, 63(5):3277–3305, 2017. http://ieeexplore.ieee.org/document/7867830/.

[15] V. Vilasini. Causality in quantum theory (and beyond). Masters Thesis, ETH Zürich, 2017. https://foundations.ethz.ch/wp-content/uploads/2019/07/vilasini_master_thesis-v2.pdf.

[16] Ognyan Oreshkov. Time-delocalized quantum subsystems and operations: on the existence of processes with indefinite causal structure in quantum mechanics. *Quantum*, 3:206, 2019. https://doi.org/10.22331/q-2019-12-02-206.

[17] Nikola Paunković and Marko Vojinović. Causal orders, quantum circuits and spacetime: distinguishing between definite and superposed causal orders. *Quantum*, 4:275, 2020. http://dx.doi.org/10.22331/q-2020-05-28-275.

[18] V. Vilasini and Renato Renner. Embedding cyclic information-theoretic structures in acyclic space-times: No-go results for indefinite causality. *Phys. Rev. A*, 110:022227, 2024. https://link.aps.org/doi/10.1103/PhysRevA.110.022227.

[19] V. Vilasini and Renato Renner. Fundamental limits for realizing quantum processes in spacetime. *Phys. Rev. Lett.*, 133:080201, 2024. https://link.aps.org/doi/10.1103/PhysRevLett.133.080201.

[20] Nick Ormrod, Augustin Vanrietvelde, and Jonathan Barrett. Causal structure in the presence of sectorial constraints, with application to the quantum switch. *Quantum*, 7:1028, 2023. http://dx.doi.org/10.22331/q-2023-06-01-1028.

[21] David Felce, Nicetu Tibau Vidal, Vlatko Vedral, and Eduardo O. Dias. Indefinite causal orders from superpositions in time. *Physical Review A*, 105(6), 2022. http://dx.doi.org/10.1103/PhysRevA.105.062216.

[22] Anne-Catherine de la Hamette, Viktoria Kabel, Marios Christodoulou, and Časlav Brukner. Quantum diffeomorphisms cannot make indefinite causal order definite. 2022. https://arxiv.org/abs/2211.15685.

[23] Viktoria Kabel, Anne-Catherine de la Hamette, Luca Apadula, Carlo Cepollaro, Henrique Gomes, Jeremy Butterfield, and Časlav Brukner. Quantum coordinates, localisation of events, and the quantum hole argument. *Commun. Phys.*, 8(1):185, 2025. https://www.nature.com/articles/s42005-025-02084-3.

[24] Anne-Catherine de la Hamette, Viktoria Kabel, and Časlav Brukner. What an event is not: unravelling the identity of events in quantum theory and gravity, 2024. https://arxiv.org/abs/2404.00159.

[25] Magdalena Zych, Fabio Costa, Igor Pikovski, and Časlav Brukner. Bell's theorem for temporal order. *Nature communications*, 10(1):3772, 2019. https://www.nature.com/articles/s41467-019-11579-x.

[26] R. Landauer. Irreversibility and heat generation in the computing process. *IBM Journal of Research and Development*, 5(3):183–191, 1961. https://ieeexplore.ieee.org/document/5392446.

[27] C. H. Bennett. The thermodynamics of computation—a review. *International Journal of Theoretical Physics*, 21:905–940, 1982. https://link.springer.com/article/10.1007/BF02084158#citeas.

[28] C. G. Knott. *Life and Scientific Work of Peter Guthrie Tait.* Cambridge University Press, London, 1911. Reproduced in *The Scientific Letters and Papers of James Clerk Maxwell II: 1862–1873*, edited by P. M. Harman, Cambridge University Press, Cambridge, 1995. https://archive.org/details/lifescientificwo00knotuoft/page/212/mode/2up?view=theater.

[29] Stephen D. Bartlett, Terry Rudolph, and Robert W. Spekkens. Reference frames, superselection rules, and quantum information. *Reviews of Modern Physics*, 79(2):555–609, 2007. http://dx.doi.org/10.1103/RevModPhys.79.555.

[30] Leon Loveridge, Takayuki Miyadera, and Paul Busch. Symmetry, reference frames, and relational quantities in quantum mechanics. *Foundations of Physics*, 48:135–198, 2018. https://doi.org/10.1007/s10701-018-0138-3.

[31] Flaminia Giacomini, Esteban Castro-Ruiz, and Časlav Brukner. Quantum mechanics and the covariance of physical laws in quantum reference frames. *Nature Communications*, 10:494, 2019. https://doi.org/10.1038/s41467-018-08155-0.

[32] Augustin Vanrietvelde, Philipp A. Hoehn, Flaminia Giacomini, and Esteban Castro-Ruiz. A change of perspective: switching quantum reference frames via a perspective-neutral framework. *Quantum*, 4:225, 2020. http://dx.doi.org/10.22331/q-2020-01-27-225.

[33] Anne-Catherine de la Hamette, Thomas D. Galley, Philipp A. Hoehn, Leon Loveridge, and Markus P. Mueller. Perspective-neutral approach to quantum frame covariance for general symmetry groups. 10 2021.

[34] Esteban Castro-Ruiz and Ognyan Oreshkov. Relative subsystems and quantum reference frame transformations, 2023. https://arxiv.org/abs/2110.13199.

[35] Titouan Carette, Jan Glowacki, and Leon Loveridge. Operational quantum reference frame transformations. *Quantum*, 9:1680, 2025. http://dx.doi.org/10.22331/q-2025-03-27-1680.

[36] Viktoria Kabel, Anne-Catherine de la Hamette, Luca Apadula, Carlo Cepollaro, Henrique Gomes, Jeremy Butterfield, and Časlav Brukner. Identification is pointless: Quantum coordinates, localisation of events, and the quantum hole argument, 2025. https://arxiv.org/abs/2402.10267.