Title: Cyclic quantum causal models and violations of causal inequalities

Speakers: Ognyan Oreshkov

Collection: Indefinite Causal Structure

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Abstract: I will present an extension of the recent theory of quantum causal models to cyclic causal structures. This offers a novel causal perspective on processes beyond those corresponding to standard circuits, such as processes with dynamical causal order and causally nonseparable processes, including processes violating causal inequalities. As an application, I will use the algebraic structure of process operators that is induced by the causal structure to prove that all unitarily extendible bipartite processes are causally separable, i.e., their unitary extensions are variations of the quantum SWITCH. Remarkably, the latter implies that all unitarily extendible tripartite quantum processes have realizations on time-delocalized systems within standard quantum mechanics. This includes, in particular, classical processes violating causal inequalities, which admit simple implementations! I will explain what the violation of causal inequalities implies for the variables of interest in these implementations. The answer is given again by the theory of cyclic causal models.
Based on joint works with Jonathan Barrett, Cyril Branciard, Robin Lorenz, and Julian Wechs.

Beyond Quantum Computers

G. Chiribella, G. M. D'Ariano, P. Perinotti, B. Valiron

*(Submitted on 1 Dec 2009 (v1), revised 20 Dec 2009 (this version, v2), **latest version 27 Oct 2013** (v4))*

The manuscript poses and addresses a new very fundamental issue in Quantum Computer Science, which is going to have a radical impact on the way we currently conceive quantum computation. We show that there exists a new kind of "higher-order" quantum computation, potentially much more powerful than the usual quantum processing, which is feasible, but cannot be realized by a usual quantum circuit. In order to implement this new kind of computations one needs to change the rules of quantum circuits, also considering circuits with the geometry of the connections that can be itself in a quantum superposition. The new kind of computation poses also fundamental problems for unexplored aspects of quantum mechanics in a non-fixed causal framework, which go far beyond computer-science problems, and may be of relevance in quantum gravity.

Quantum computations without definite causal structure

Giulio Chiribella, Giacomo Mauro D'Ariano, Paolo Perinotti, and Benoit Valiron
Phys. Rev. A **88**, 022318 – Published 14 August 2013

We show that quantum theory allows for transformations of black boxes that cannot be realized by inserting the input black boxes within a circuit in a predefined causal order. The simplest example of such a transformation is the *classical switch of black boxes*, where two input black boxes are arranged in two different orders conditionally on the value of a classical bit. The quantum version of this transformation—the *quantum switch*—produces an output circuit where the order of the connections is controlled by a quantum bit, which becomes entangled with the circuit structure. Simulating these transformations in a circuit with fixed causal structure requires either postselection or an extra query to the input black boxes.

Cyclic quantum causal models and violations of causal inequalities

Ognyan Oreshkov

Université libre de Bruxelles

Based on ongoing works with J. Barrett, C. Branciard, R. Lorenz, and J. Wechs

Indefinite Causal Structure, Perimeter Institute, December 2019

Main idea:

Extension of the theory of quantum causal models to processes beyond those corresponding to fixed circuits

Outline

- Review of the PM framework and main idea of quantum causal models

- Cyclic quantum causal models

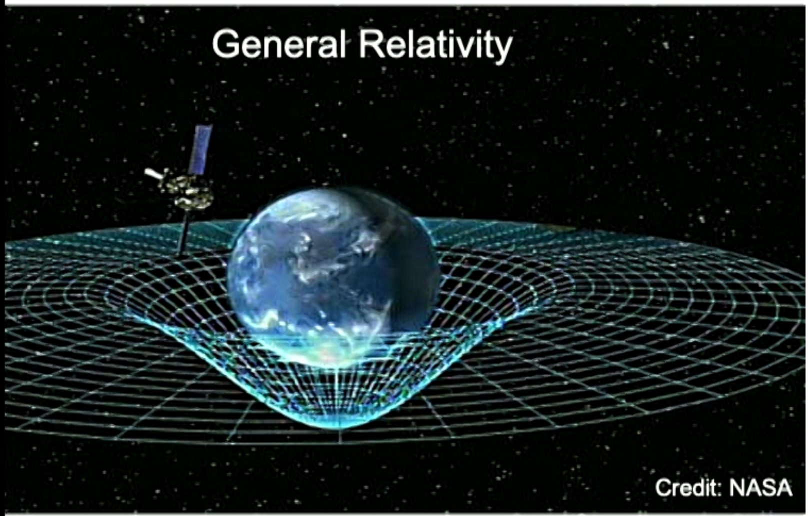
  - *Theorem*: compatibility → Markovianity
  - *Conjectur*e: Markovianity → compatibility ?

- Examples (quantum SWITCH, the Baumeler-Wolf noncausal process)

- An application: all unitarily extendible bipartite processes are causally separable

- Consequence: all unitarily extendible tripartite processes have realizations on time-delocalized systems → **causal inequalities can be violated, even with classical systems!**

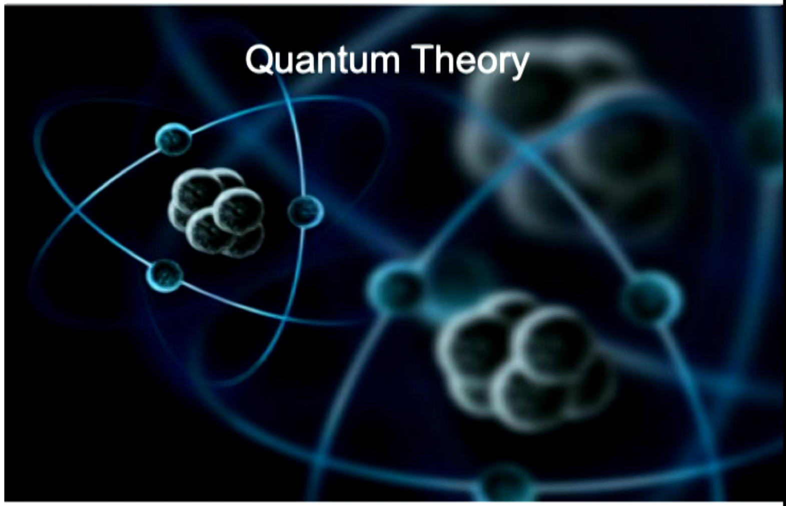
- What does the violation of a causal inequality imply for the variables involved?



deterministic theory
dynamical causal structure

conceptual gap

probabilistic theory
predefined causal structure



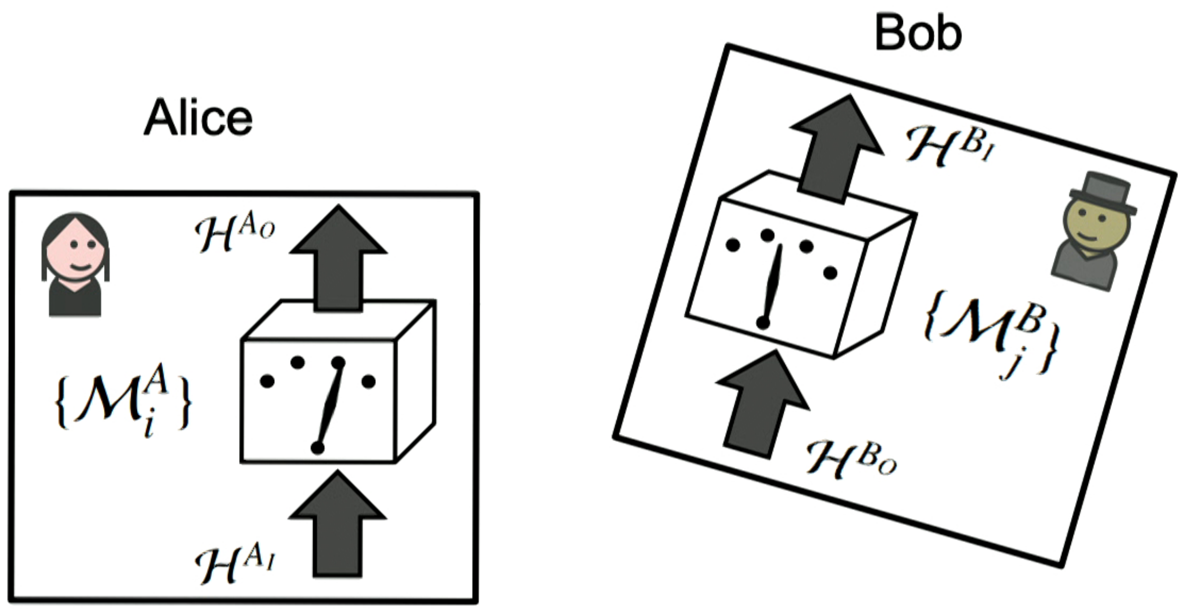
"It is reasonable to expect that quantum gravity will be a probabilistic theory with dynamic causal structure."

Lucien Hardy, *Probability Theories with Dynamic Causal Structure: A New Framework for Quantum Gravity* (2005).

"It is therefore likely that, in a theory of quantum gravity, we will have indefinite causal structure."

Lucien Hardy, *Quantum gravity computers: On the theory of computation with indefinite causal structure (2007).*

The quantum process matrix framework



No assumption of global causal order

O. O., F. Costa, and Č. Brukner, Nat. Commun. 3, 1092 (2012).

The quantum process matrix framework

Joint probabilities

$$p(\mathcal{M}_i^A, \mathcal{M}_j^B, \cdots) = \mathrm{Tr}\left[W^{A_{\mathrm{in}}A_{\mathrm{out}}B_{\mathrm{in}}B_{\mathrm{out}}\cdots}\left(M_i^{A_{\mathrm{in}}A_{\mathrm{out}}} \otimes M_j^{B_{\mathrm{in}}B_{\mathrm{out}}} \otimes \cdots\right)\right]$$

Process matrix

CJ operators

The quantum process matrix framework

Joint probabilities

$$p(\mathcal{M}_i^A, \mathcal{M}_j^B, \cdots) = \mathrm{Tr}\left[W^{A_{\mathrm{in}}A_{\mathrm{out}}B_{\mathrm{in}}B_{\mathrm{out}}\cdots}\left(M_i^{A_{\mathrm{in}}A_{\mathrm{out}}} \otimes M_j^{B_{\mathrm{in}}B_{\mathrm{out}}} \otimes \cdots\right)\right]$$

Process matrix

CJ operators

1. Non-negative probabilities: $W^{A_{\mathrm{in}}A_{\mathrm{out}}B_{\mathrm{in}}B_{\mathrm{out}}\cdots} \geq 0$

2. Probabilities sum up to 1:

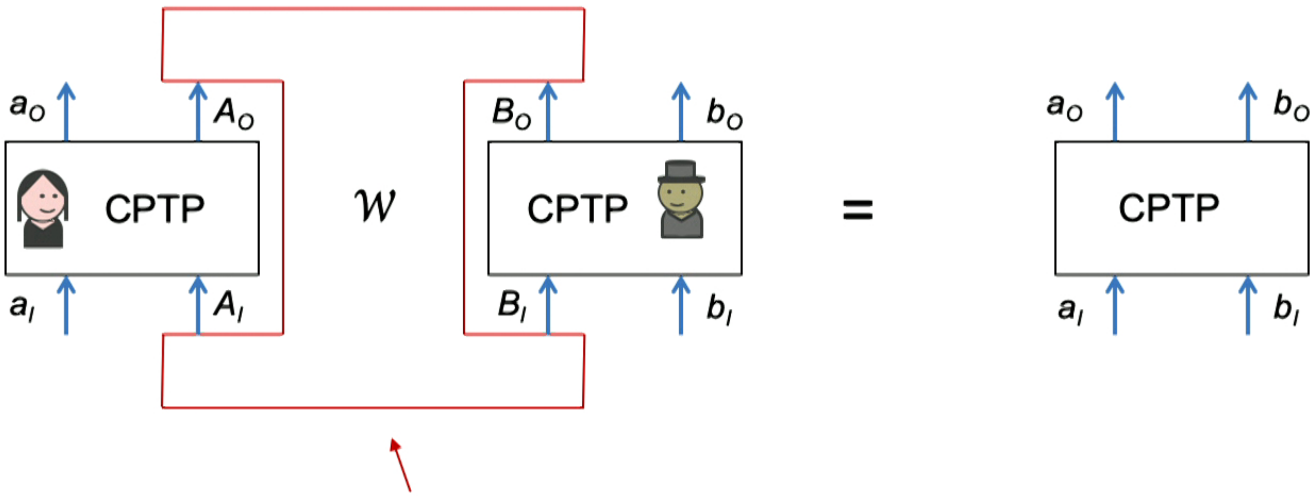
$$\mathrm{Tr}\left[W^{A_{\mathrm{in}}A_{\mathrm{out}}B_{\mathrm{in}}B_{\mathrm{out}}\cdots}\left(M^{A_{\mathrm{in}}A_{\mathrm{out}}} \otimes N^{B_{\mathrm{in}}B_{\mathrm{out}}} \otimes \cdots\right)\right] = 1$$

on all CPTP $M^{A_{\mathrm{in}}A_{\mathrm{out}}}$, $N^{B_{\mathrm{in}}B_{\mathrm{out}}}$, ...

The quantum process matrix framework

An equivalent formulation as a second-order transformation:

[Quantum supermaps, Chiribella, D'Ariano, and Perinotti, EPL 83, 30004 (2008)]



a channel from $A_O B_O$ to $A_I B_I$

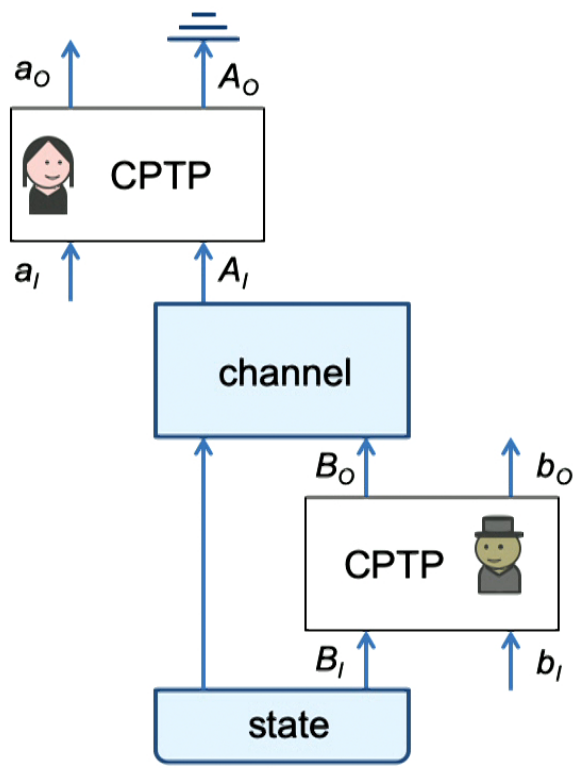
Processes compatible with fixed causal order (quantum combs)

Bipartite example:

$$W^{A \npreceq B}$$

The most general bipartite process with no signalling from A to B

$$W^{A_{\text{in}}A_{\text{out}}B_{\text{in}}B_{\text{out}}} = W^{A_{\text{in}}B_{\text{in}}B_{\text{out}}} \otimes \mathbb{1}^{A_{\text{out}}}$$



Bipartite processes with causal realization

$W^{A\npreceq B}$ – no signalling from A to B

$W^{B\npreceq A}$ – no signalling from B to A

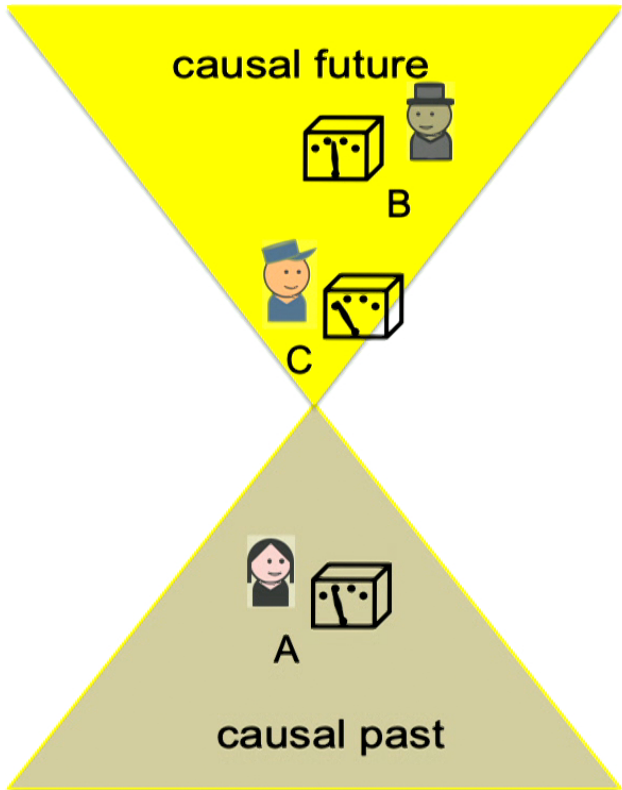
More generally, we may conceive probabilistic mixtures of fixed-order processes:

$$W_{cs}^{A_1A_2B_1B_2} = qW^{A\npreceq B} + (1-q)W^{B\npreceq A}$$

↑

causally separable process

(!) Multipartite causal separability is more complicated due to the possibility of *dynamical causal order*

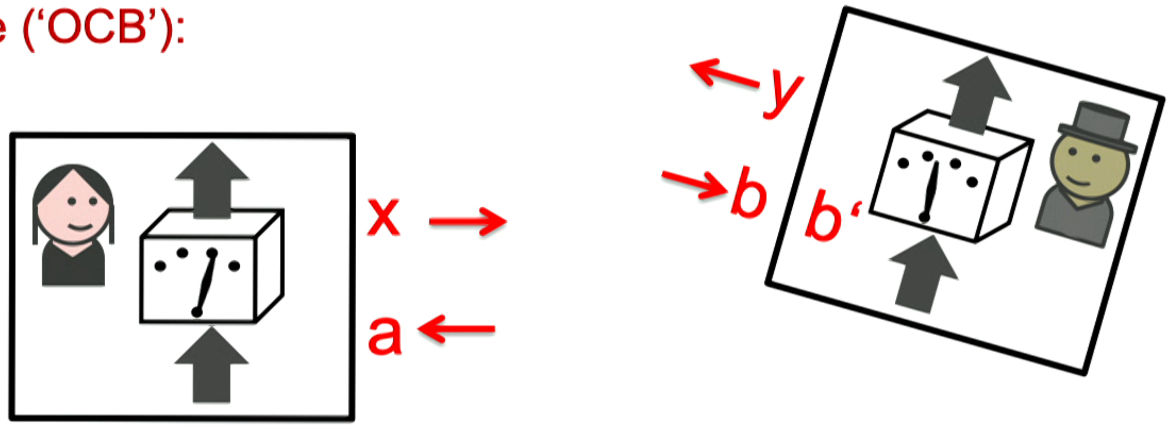


Oreshkov and Giarmatzi, NJP (2016); See also Wechs, Abbott, and Branciard, NJP (2019)

There are process matrices that are not causally separable.

Violation of causal inequalities

Example ('OCB'):



Definite causal order →

$$p_{succ} = \frac{1}{2}[P(x = b|b' = 0) + P(y = a|b' = 1)] \leq \frac{3}{4}$$

O. O., F. Costa, and Č. Brukner, Nat. Commun. 3, 1092 (2012).

The (original) assumptions behind causal inequalities

Everything is imagined to be about events.

1) Causal Order: There is a global causal order on all events (systems entering and leaving the labs, parties obtaining the input variables and producing the output variables). The event of a system entering a given lab is the causal past of the event of a system leaving that lab.

2) Free Choice: Each input variable (here a, b, b') can only be correlated with events in its causal future.

3) Closed Laboratories: The output variable produced by Alice can be correlated with the input variable given to Bob only if Alice receives a system in her lab after Bob has sent out his system.

O. O., F. Costa, and Č. Brukner, Nat. Commun. 3, 1092 (2012).

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Note: the formulation of 2) and 3) requires 1).

O. O., F. Costa, and Č. Brukner, Nat. Commun. 3, 1092 (2012).

A causally nonseparable process

Can violate the inequality with $p_{succ} = \frac{2+\sqrt{2}}{4} > \frac{3}{4}$.

$$W^{A_{\rm in}A_{\rm out}B_{\rm in}B_{\rm out}} = \frac{1}{4}\left[1 + \frac{1}{\sqrt{2}}\left(\sigma_z^{A^{\rm out}}\sigma_z^{B^{\rm in}} + \sigma_z^{A^{\rm in}}\sigma_x^{B^{\rm in}}\sigma_z^{B^{\rm out}}\right)\right]$$

two-level systems

If we believe that 2) and 3) would hold if 1) holds, we must conclude that 1) does not hold.

O. O., F. Costa, and Č. Brukner, Nat. Commun. 3, 1092 (2012).

Other causal inequalities and violations

Bipartite inequalities:

Simplest inequalities:
Branciard, Araujo, Feix, Costa, Brukner, NJP 18, 013008 (2016)

Biased version of the original inequality:
Bhattacharya and Banik, arXiv:1509.02721 (2015)

Multiparite inequalities:

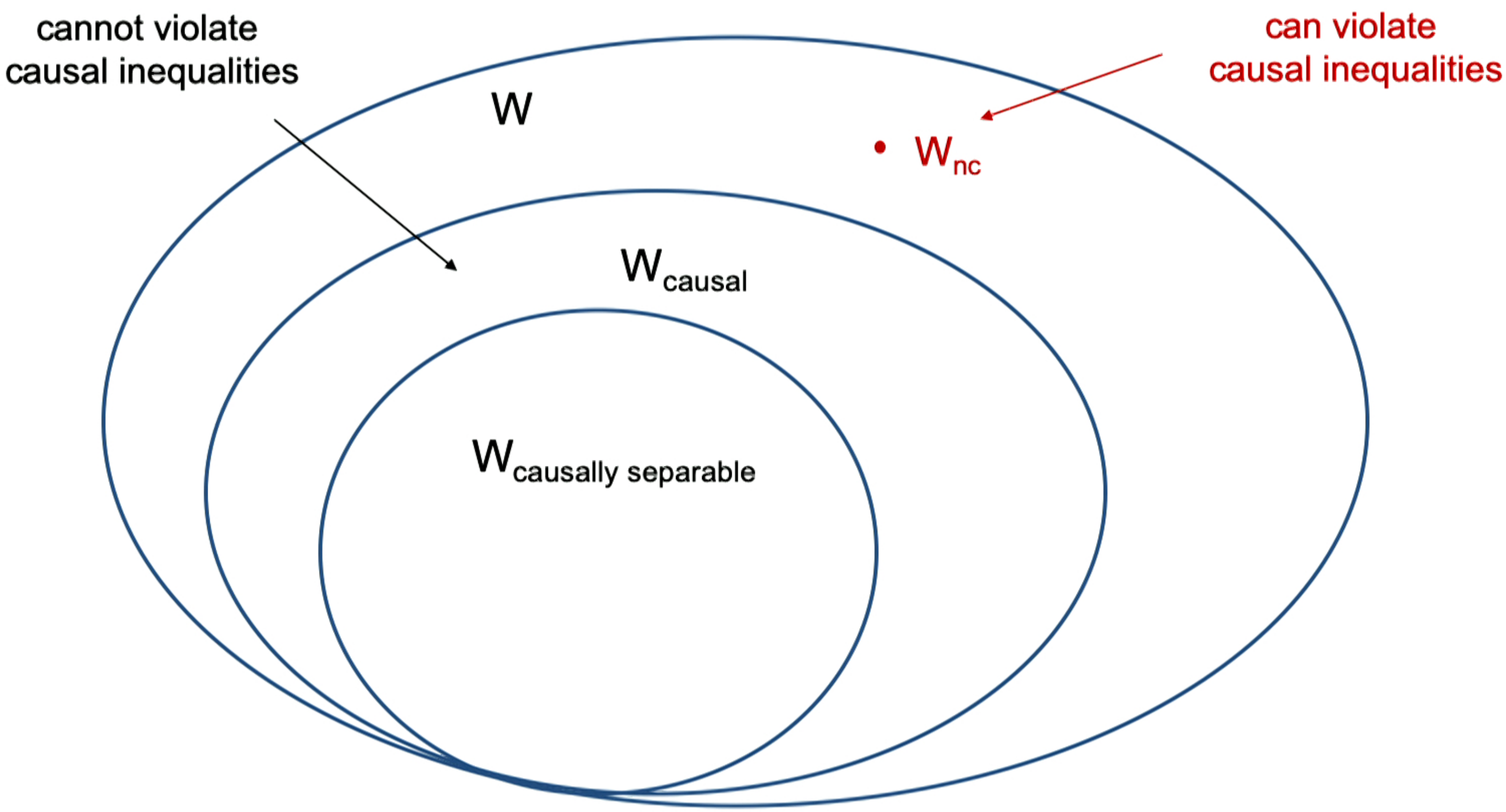
Violation with perfect signaling:
Baumeler and Wolf, Proc. ISIT 2014, 526-530 (2014)

Violation by classical processes and operations:
Baumeler, Feix, and Wolf, PRA 90, 042106 (2014)
Baumeler and Wolf, NJP 18, 013036 (2016)

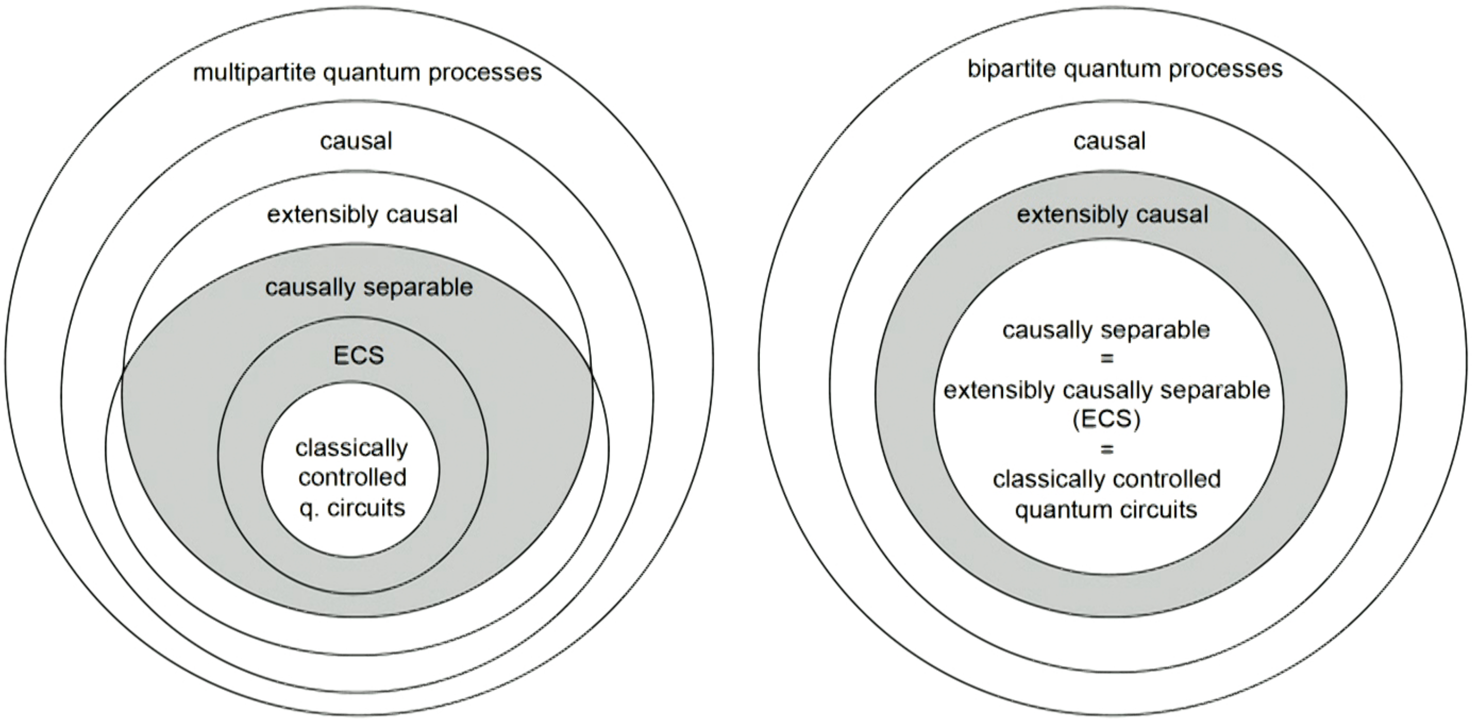
Simplest tripartite polytope:
Abbott, Giarmatzi, Costa, Branciard, PRA 94, 032131 (2016)

N-causal inequalities:
Abbott, Wechs, Costa, Branciard, Quantum 1, 39 (2017)

Causality versus causal separability



Causality versus causal separability

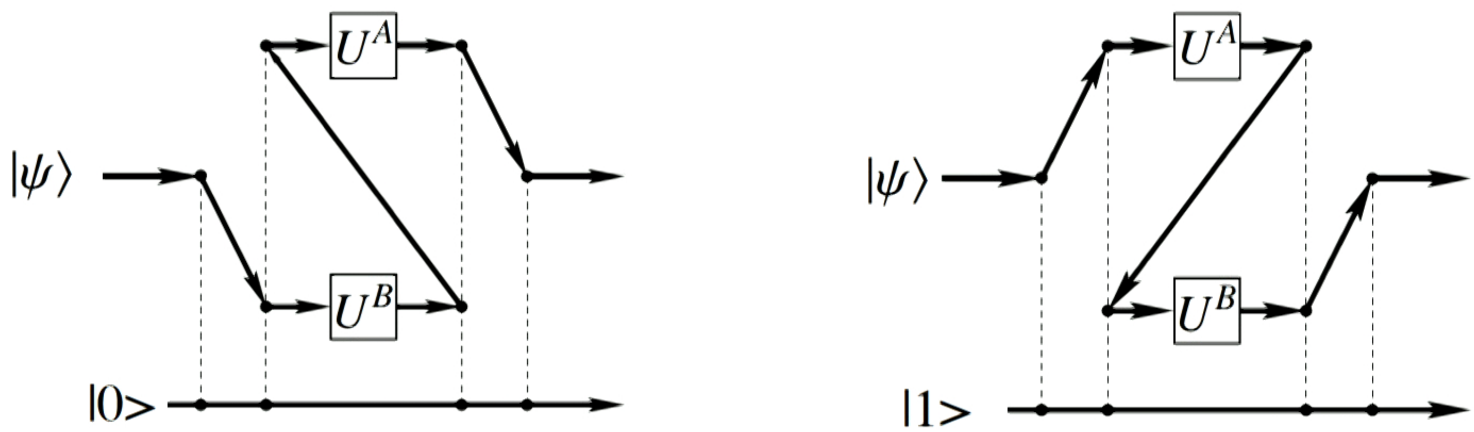


a) Multipartite case. b) Bipartite case.

Oreshkov and Giarmatzi, NJP (2016)
Feix, Araújo, and Brukner, NJP (2016)
Wechs, Abbott, and Branciard, NJP (2019)

Example: the quantum SWITCH

The order of operations depends on a variable in a quantum superposition:

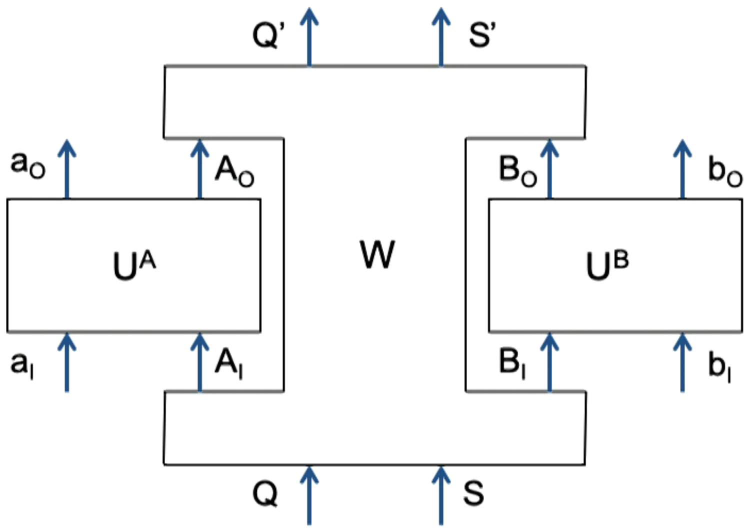


$$(\alpha|0\rangle + \beta|1\rangle)|\psi\rangle \rightarrow \alpha|0\rangle U^A U^B|\psi\rangle + \beta|1\rangle U^B U^A|\psi\rangle$$

Chiribella, D'Ariano, Perinotti, and Valiron, PRA 88, 022318 (2013), arXiv:0912.0195 (2009)

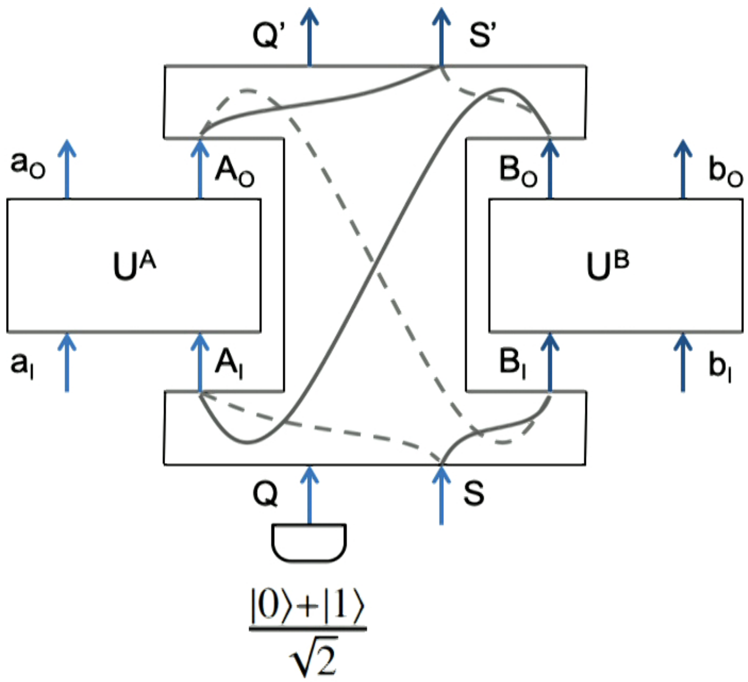
Example: the quantum SWITCH

A supermap:



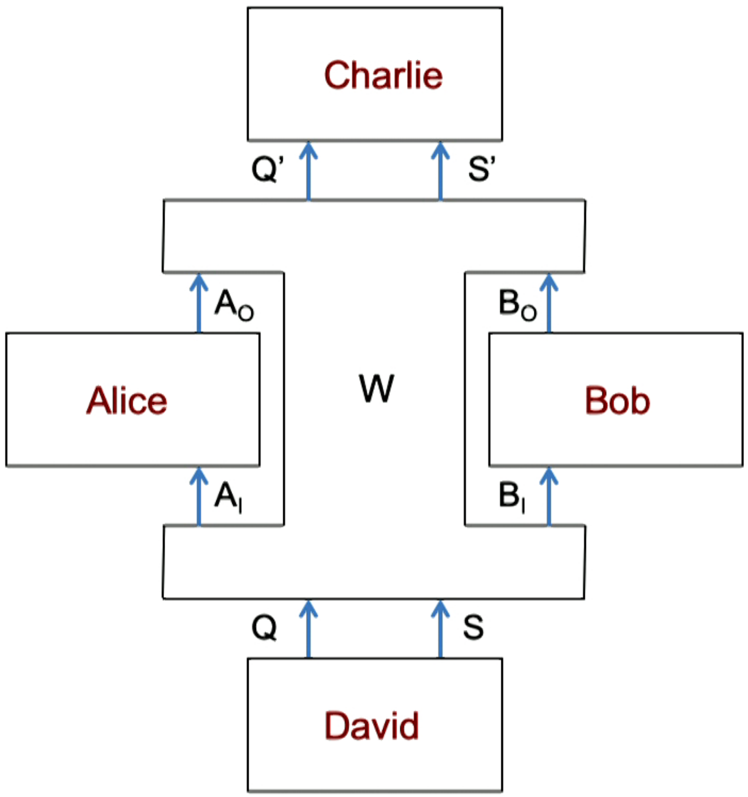
Example: the quantum SWITCH

A supermap:



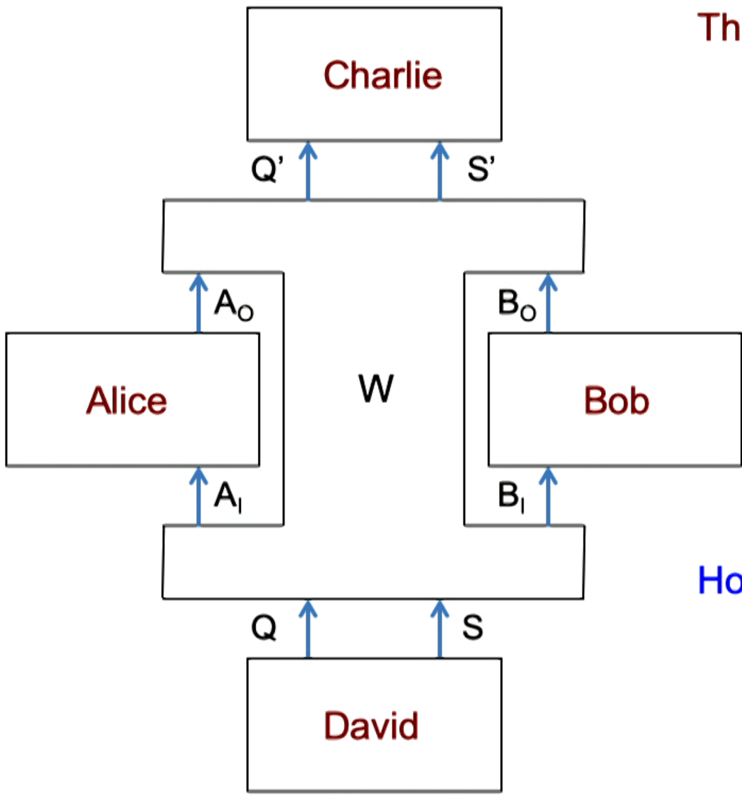
Example: the quantum SWITCH

A process matrix:



Example: the quantum SWITCH

A process matrix:



The process matrix is **not causally separable**:

W= |W><W|

(not a probabilistic mixture of different process matrices)

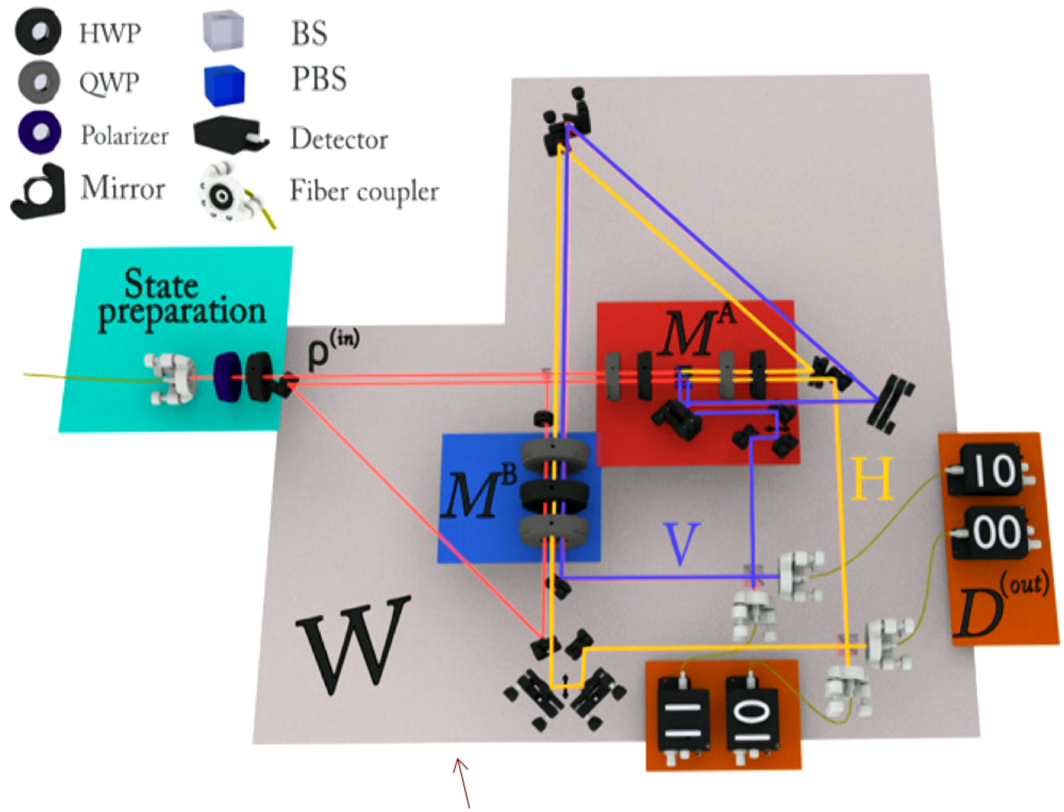
But it allows signaling from Alice to Bob and from Bob to Alice.

However, it cannot violate causal inequalities!

Oreshkov and Giarmatzi, NJP 18, 093020 (2016)

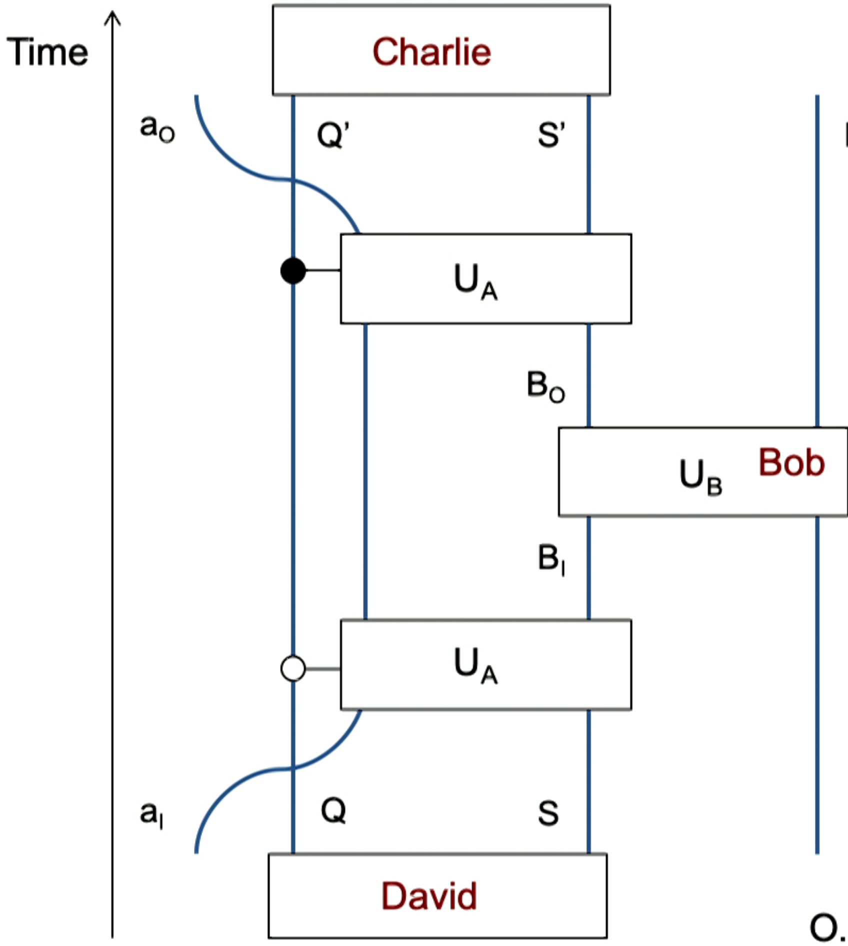
Araujo et al., NJP 17, 102001 (2015)

Experimental implementations of the quantum SWITCH



Procopio et al., Nat. Commun. (2015)   Rubio et al., Sci. Adv. (2017)   Goswami et al., PRL (2018)   ...

Time-delocalized quantum systems and operations



O. O., *Quantum 3, 206* (2019); arXiv:1801.07594

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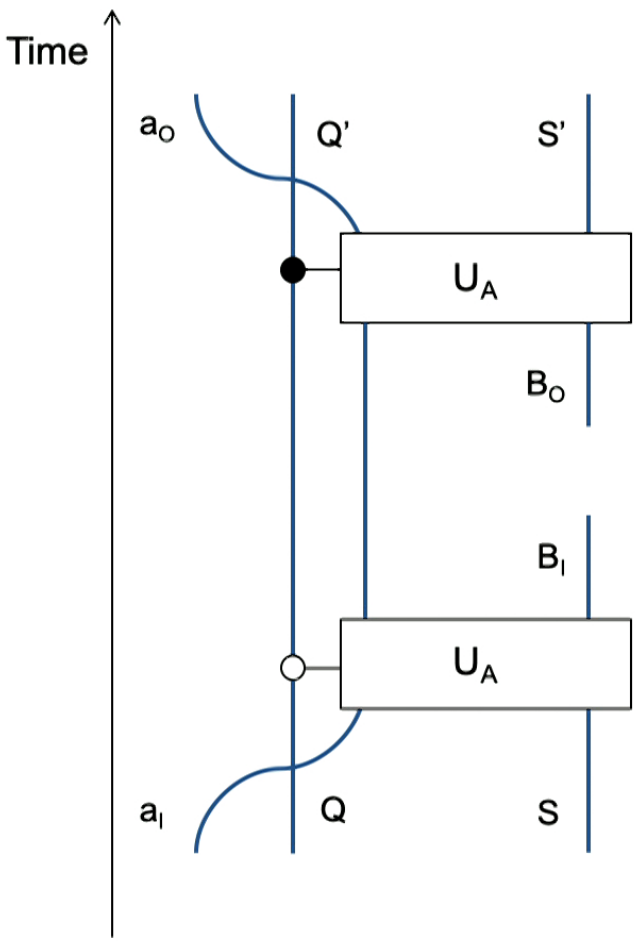

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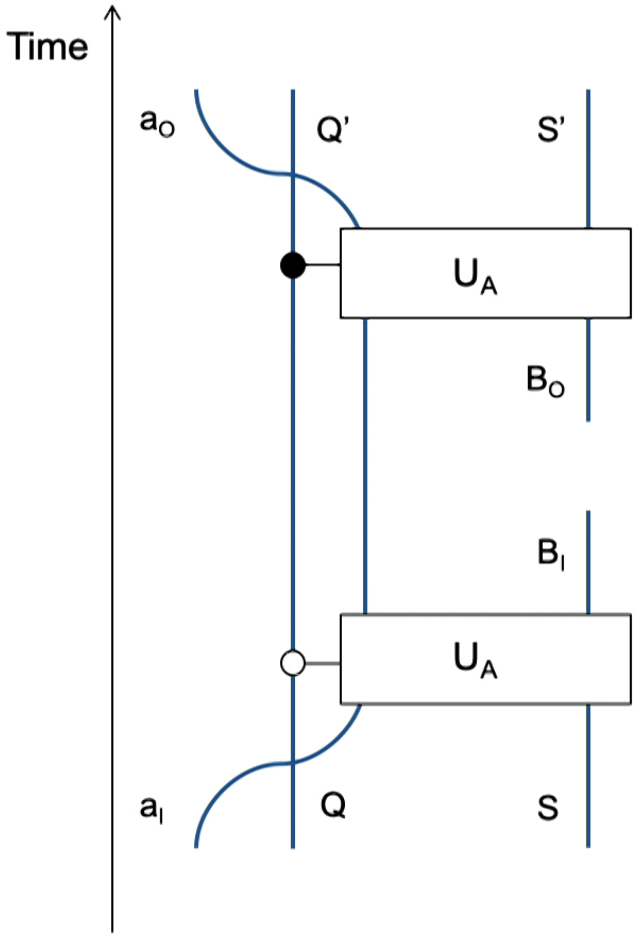


Identifying Alice's operation:

$$U^{a_I Q S B_O \to a_O Q' S' B_I} = U_A^{a_I A_I \to a_O A_O} \otimes \mathbb{1}^{\overline{A_I} \to \overline{A_O}}$$

where A_I is a nontrivial *subsystem* of QSB_O, defined by the algebra of operators

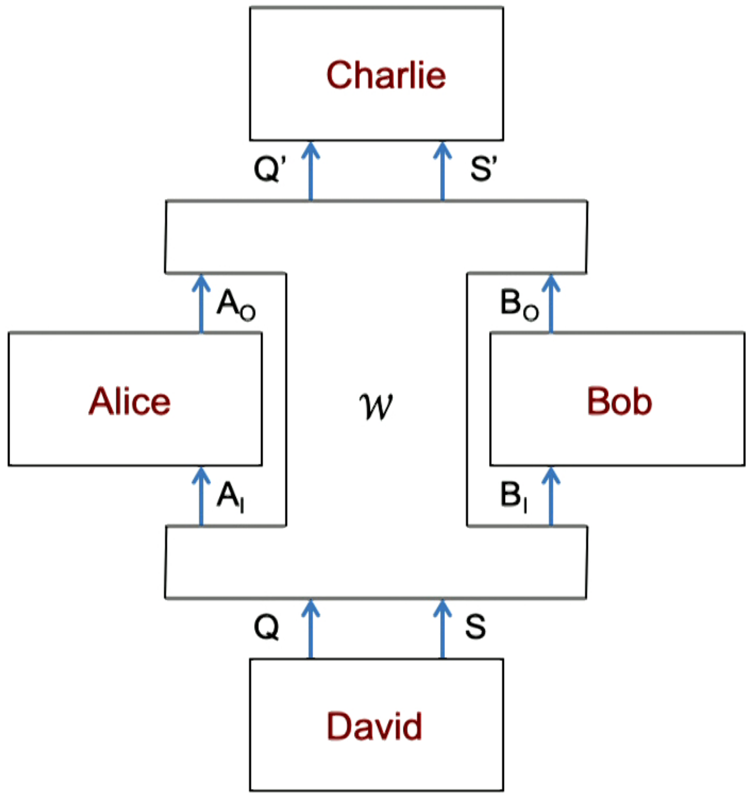
$$O^{A_I} \equiv |0\rangle\langle 0|^Q \otimes O^S \otimes \mathbb{1}^{B_O} + |1\rangle\langle 1|^Q \otimes \mathbb{1}^S \otimes O^{B_O},$$

and A_O is a nontrivial *subsystem* of $Q'S'B_I$, defined by the algebra of operators

$$O^{A_O} \equiv |0\rangle\langle 0|^{Q'} \otimes \mathbb{1}^{S'} \otimes O^{B_I} + |1\rangle\langle 1|^{Q'} \otimes O^{S'} \otimes \mathbb{1}^{B_I}.$$

O. O., *Quantum 3, 206* (2019); arXiv:1801.07594

With respect to A_I and A_O, the experiment has the structure of a circuit with a cycle.



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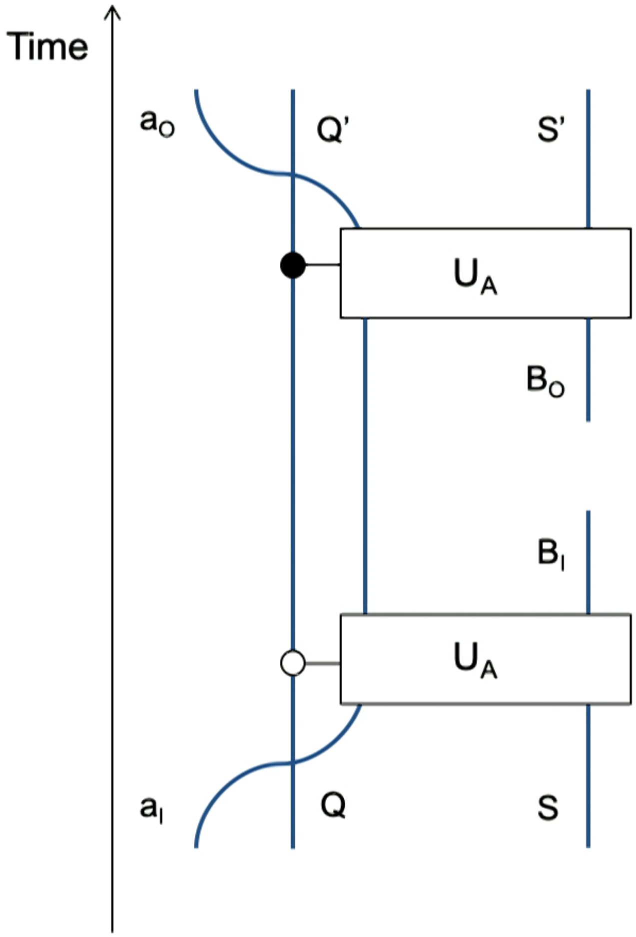

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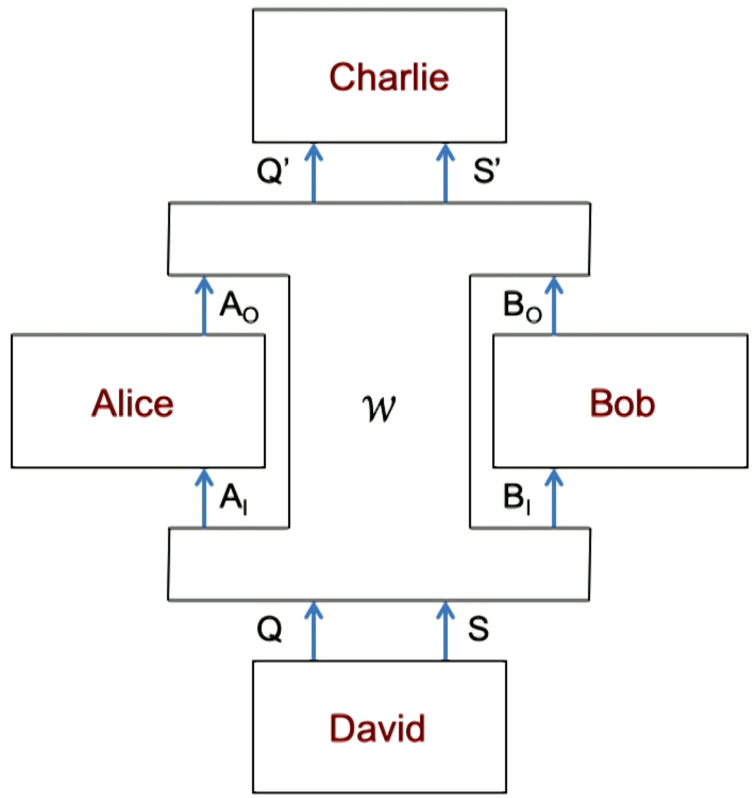
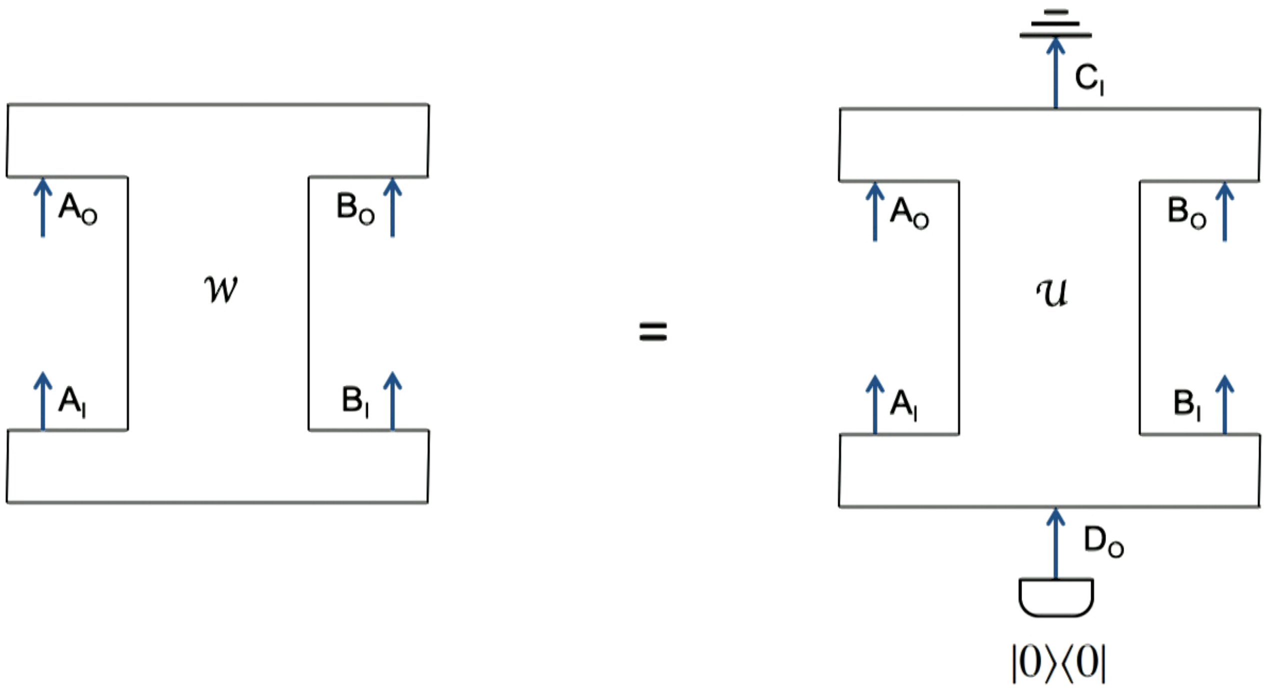


Unitarily extendible processes (bipartite example)



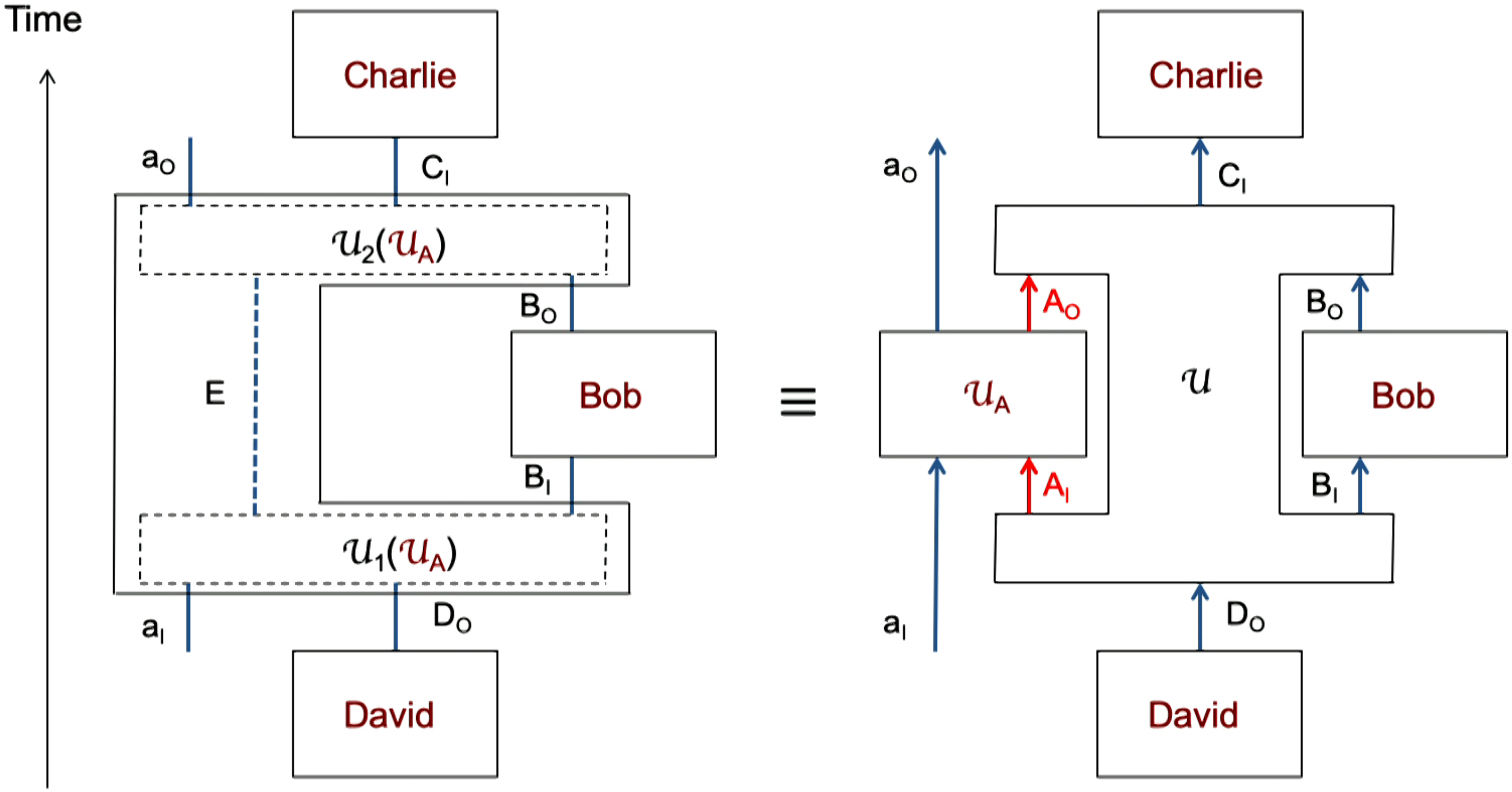
Not all processes are unitarily extendible!

(Example: the 'OCB' process is not)

Araujo, Feix, Navascues, Brukner, Quantum 1, 10 (2017)

Claim:

All unitary extensions of bipartite processes have realizations on time-delocalized systems



O. O., *Quantum 3, 206* (2019); arXiv:1801.07594

Quantum causal models

Allen, Barrett, Horsman, Lee, Spekkens, PRX 7, 031021 (2017)
Barrett, Lorenz, Oreshkov, arXiv:1906.10726

Quantum causal models

Note on conventions:

CJ representation of a CP map: $\mathcal{E} : \mathcal{L}(\mathcal{H}_A) \to \mathcal{L}(\mathcal{H}_B)$

$$\rho^{\mathcal{E}}_{B|A} := \sum_{i,j} \mathcal{E}(|i\rangle_A \langle j|) \otimes |i\rangle_{A^*} \langle j|$$

Node *A*: $\mathcal{H}_{A^{\mathrm{in}}}$ - the incoming Hilbert space
$\mathcal{H}_{A^{\mathrm{out}}}$ - (copy of) the *dual* of the outgoing Hilbert space

Interventions inside nodes represented by transposed CJ operators:

$$\tau_A^{k_A} := \left(\rho^{\mathcal{E}^{k_A}}_{A^{\mathrm{out}*}|A^{\mathrm{in}}}\right)^T$$

Process operator (process matrix) on nodes $A_1 \ldots A_n$:

$$\sigma_{A_1 \ldots A_n} \in \mathcal{L}(\bigotimes_i \mathcal{H}_{A_i^{in}} \otimes \mathcal{H}_{A_i^{out}})$$

Quantum causal models

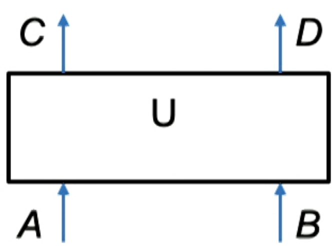
Main idea:

causal relations = influence through unitary channels

Quantum causal models

Main idea:

causal relations = influence through unitary channels

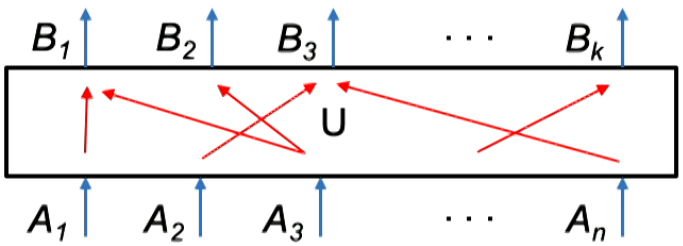


No influence from *A* to *D* through *U*: $\mathrm{Tr}_C[\rho^U_{CD|AB}] = \rho^{\mathcal{M}}_{D|B} \otimes \mathbb{1}_{A^*}$ (1)

(No possibility of signaling from *A* to *D* through *U*)

A is a **direct cause** of *D* in *U*, if and only if (1) does not hold.

Factorization of unitaries from no-influence conditions



(red arrow means influence)

Theorem 4.5. (Factorization of a unitary channel from no-influence conditions): *Let $\rho^U_{B_1\ldots B_k|A_1\ldots.A_n}$ be the CJ representation of a unitary channel with n input and k output systems. Let $S_i \subseteq \{A_1,...,A_n\}$, $i = 1,...,k$, be k subsets of input systems such that there is no influence from the complementary sets to B_i, i.e., $A_j \nrightarrow B_i$ for all $A_j \notin S_i$. Then the operator factorizes in the following way*

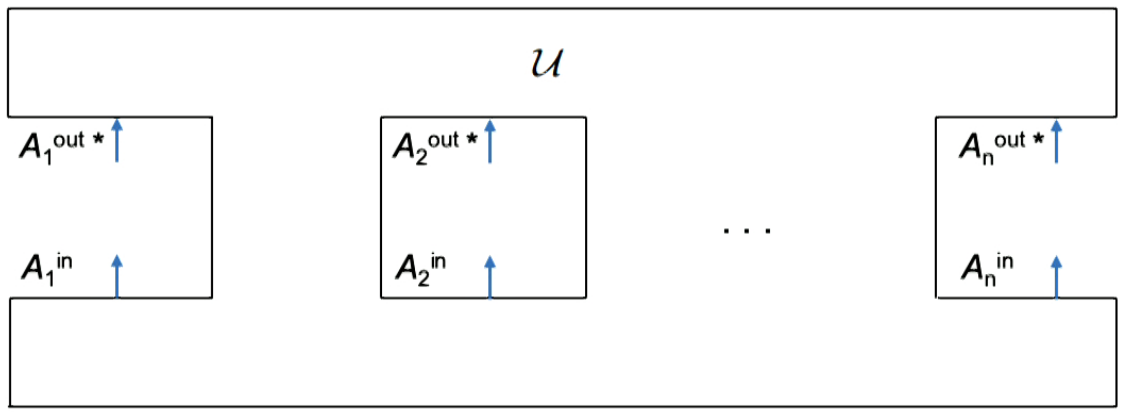
$$\rho^U_{B_1\ldots B_k|A_1\ldots.A_n} = \prod_{i=1}^{k} \rho_{B_i|S_i} \ ,$$

where the marginal channels commute pairwise, $[\rho_{B_i|S_i}\ ,\ \rho_{B_j|S_j}] = 0$ for all i,j.

Barrett, Lorenz, Oreshkov, arXiv:1906.10726

Unitary quantum processes

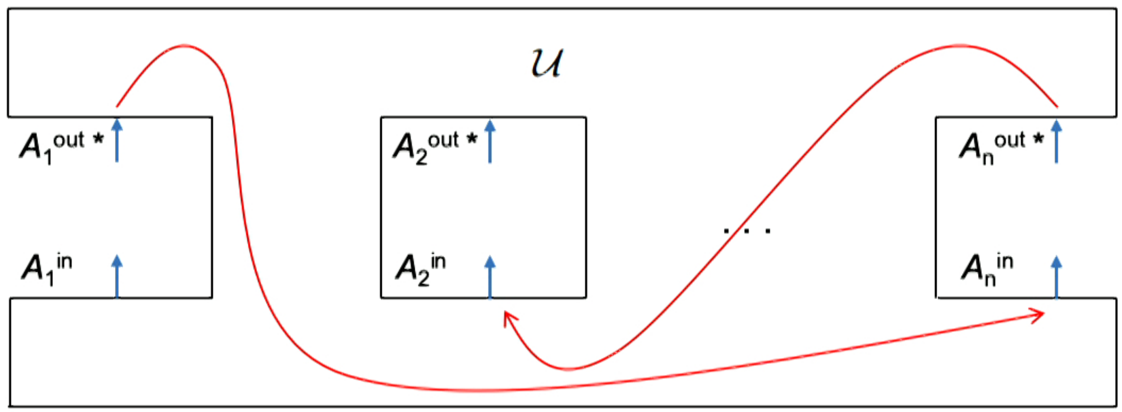
$$\sigma_{A_1 \dots A_n} = \rho^{\mathcal{U}}_{A_1^{\mathrm{in}} A_2^{\mathrm{in}} \dots A_n^{\mathrm{in}} | A^{\mathrm{out}}{}_1^* A^{\mathrm{out}}{}_2^* \dots A^{\mathrm{out}}{}_n^*} := \rho^{\mathcal{U}}_{A_1 A_2 \cdots A_n | A_1 A_2 \cdots A_n}$$



Note: some of the input and output systems could be trivial (1-dimensional)

Direct cause-effect relations in a unitary process

Node A_i is a ***direct cause*** of node A_j, iff there is influence from $A_i^{out\,*}$ to A_j^{in} through $\mathcal{U}$.



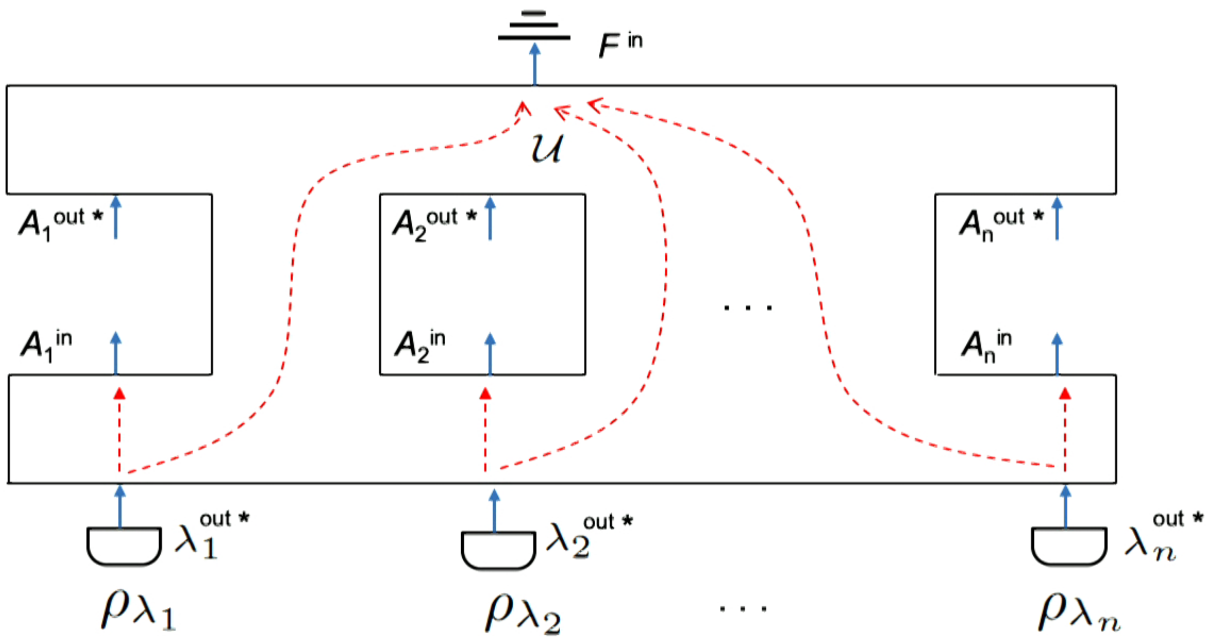
The directed graph of cause-effect relations between the nodes:
causal structure of the unitary process

In arXiv:1906.10726, we considered only cases where the cause-effect relations form a DAG!

Compatibility with a DAG

A process operator is called compatible with a DAG, iff it can be extended to a unitary process as sketched below, where the unitary obeys the following no-influence conditions:

1) no influence between nodes if no edge in the DAG
2) λ_i can influence at most A_i and F (as sketched)



Markov condition

Given a DAG on a set of nodes $A_1, \ldots, A_n$, a process operator $\sigma_{A_1 \ldots A_n}$ is called Markov for it, iff

$$\sigma_{A_1 \ldots A_n} = \prod_i \rho_{A_i | Pa(A_i)}$$

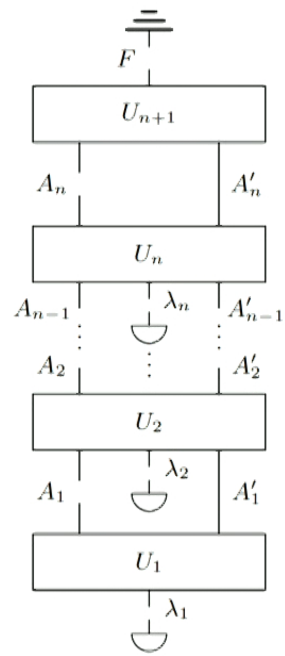
(The operators $\rho_{A_i | Pa(A_i)}$ describe channels and commute pairwise.)

Central theorem from arXiv:1906.10726

Equivalence of Markovianity and compatibility:

A process is Markov for a DAG iff it is compatible with the DAG.

Furthermore, a unitary extension of the following form can be found:



Quantum causal model (Definition)

A quantum causal model is given by:

1) a DAG
2) a set of quantum nodes $A_1, \ldots, A_n$ corresponding to the vertices of the DAG, and a set of CJ operators of channels $\rho_{A_i|Pa(A_i)}$ that commute pairwise.

The product $\sigma_{A_1 \ldots A_n} = \prod_i \rho_{A_i|Pa(A_i)}$ defines a process operator.

For notions of conditional independence and their link to causal structure, see arXiv:1906.10726.

Observation:

The notion of causal relation defined as influence through unitary channels is applicable to any unitarily extendible process.

However, for processes that are no compatible with fixed order of the nodes, **the causal structure would include cycles.**

Proposal:

Drop the restriction of *acyclicity* of the causal structure.

With R. Lorenz and J. Barrett,

Generalized quantum causal model (Definition)

A quantum causal model is given by:

1) a DG
2) a set of quantum nodes $A_1, \ldots, A_n$ corresponding to the vertices of the DG, and a set of CJ operators of channels $\rho_{A_i|Pa(A_i)}$ that commute pairwise,

such that $\sigma_{A_1 \ldots A_n} = \prod_i \rho_{A_i|Pa(A_i)}$ defines a process operator.

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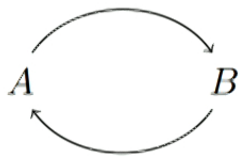
Generalized Markov condition

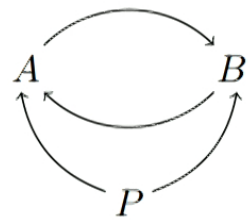
Remark: Similarly to arXiv:1906.10726, we can define cyclic classical split-node models (which reduce to cyclic classical models).

Not all DGs admit faithful causal models.

Example:



However, the following larger graph admits:



Theorem:

Compatibility → Markovianity

Proof: Same as for DAGs (arXiv:1906.10726)

Note: Every unitary process is compatible with its causal structure. Similarly, for every deterministic classical process map.

Conjecture:

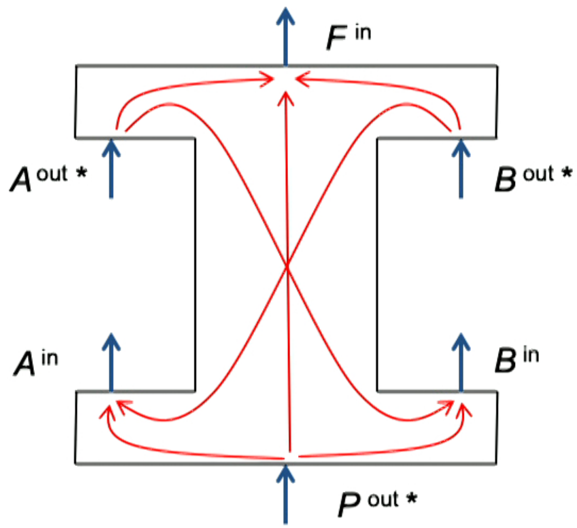
Markovianity → Compatibility?

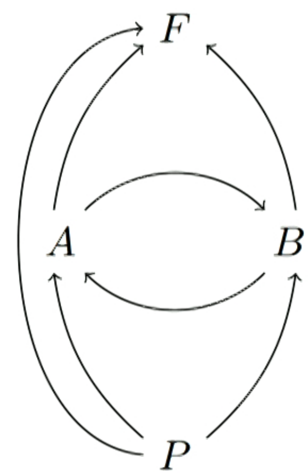
Remark: There is always a unitary dilation of the process to a unitary channel with the required no-influence properties. The question is if this dilation is a valid process.

(An analogous conjecture stands for cyclic classical split-node models.)

Examples of cyclic quantum causal models

The quantum SWITCH:



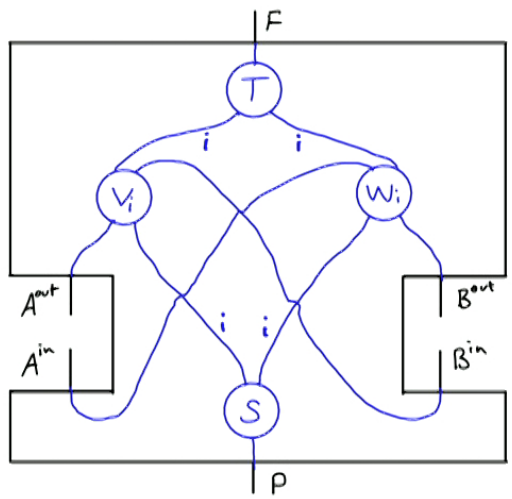


Causal structure of the quantum SWITCH

Examples of cyclic quantum causal models

The quantum SWITCH:

Subsystem structure – a finer-grained description of 'information flow'



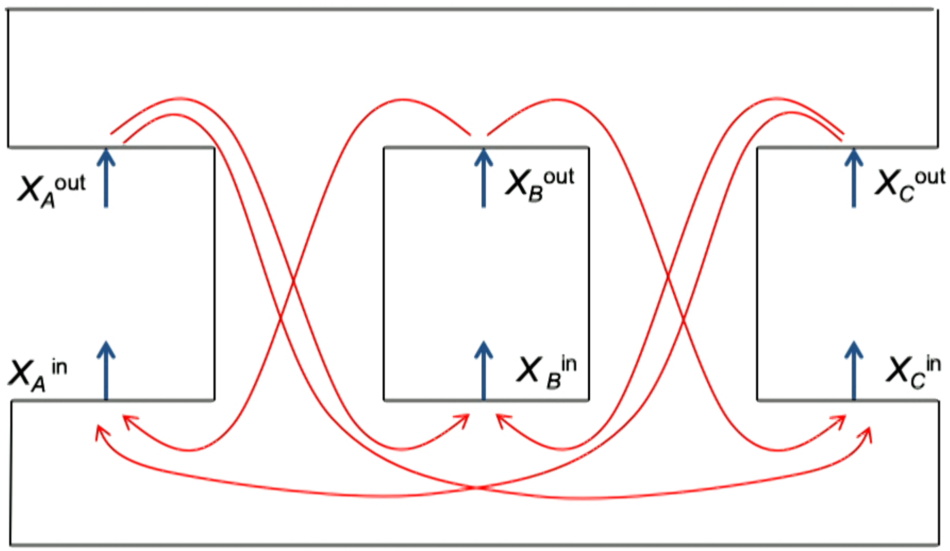
(Dot formalism by Barret and Lorenz)

Examples of cyclic quantum causal models

Deterministic noncausal classical process by Baumeler and Wolf):

$$\begin{cases} X_A^{in} = \neg X_B^{out} \wedge X_C^{out} \\ X_B^{in} = \neg X_C^{out} \wedge X_A^{out} \\ X_C^{in} = \neg X_A^{out} \wedge X_B^{out} \end{cases}$$

Violates causal inequalities.



Bameler and Wolf, NJP 18, 013036 (2016)

In the acyclic case, every causal model has a physical realization: it can be thought of as arising from a unitary quantum comb with the corresponding causal structure.

Could cyclic QCMs admit a physical realization too?

In particular, do all unitary processes have a physical realization?

Remember that all unitary extensions of bipartite have realizations on time-delocalized subsystems (arXiv:1801.07594).

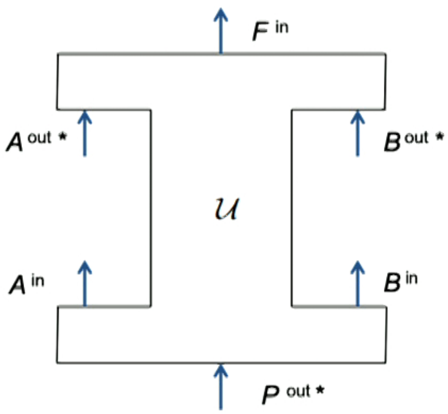
Using tools from the causal model perspective, we can show

Theorem: all bipartite processes that obey the unitary extension postulate are causally separable.

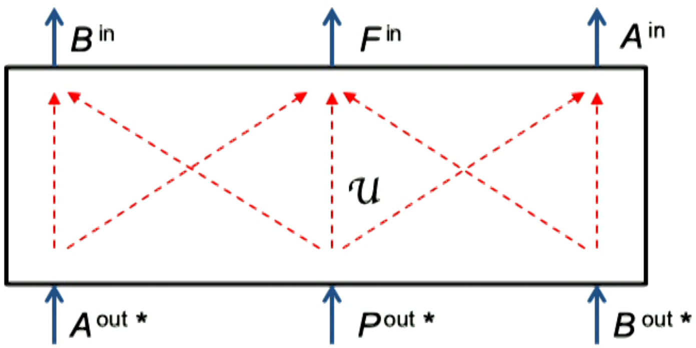
Hence, their unitary extensions are just variations of the quantum SWITCH.

Proof

Consider the unitary extension:

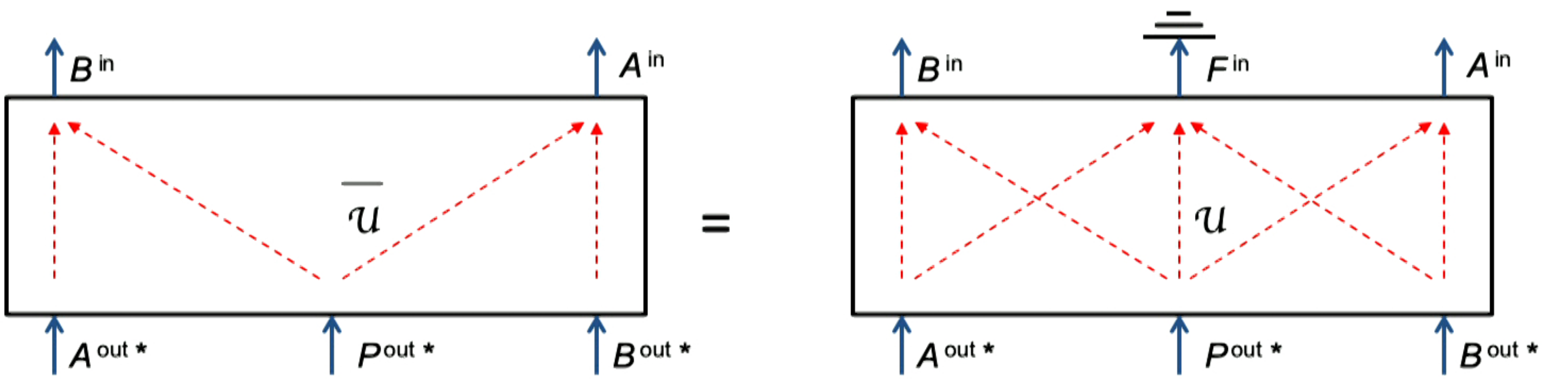


We have the following no-influence constraints for this channel:



This follows from the types of terms permitted in a process matrix.

Consider the reduced process obtained by tracing our F:



Let σ_{ABP} denote the reduced process operator (the CJ operator of the channel $\overline{\mathcal{U}}$).

Then, there exists a decomposition $\mathcal{H}_{P^{out*}} = \bigoplus_i \mathcal{H}_{L_i} \otimes \mathcal{H}_{R_i}$

such that $\sigma_{ABP} = \bigoplus_i \rho_{B^{in}|A^{out*}L_i} \otimes \rho_{A^{in}|B^{out*}R_i}$

[J.-M. Allen et al., PRX 7, 031021 (2017); J. Barrett, R. Lorenz, O. O., arXiv:1906.10726]

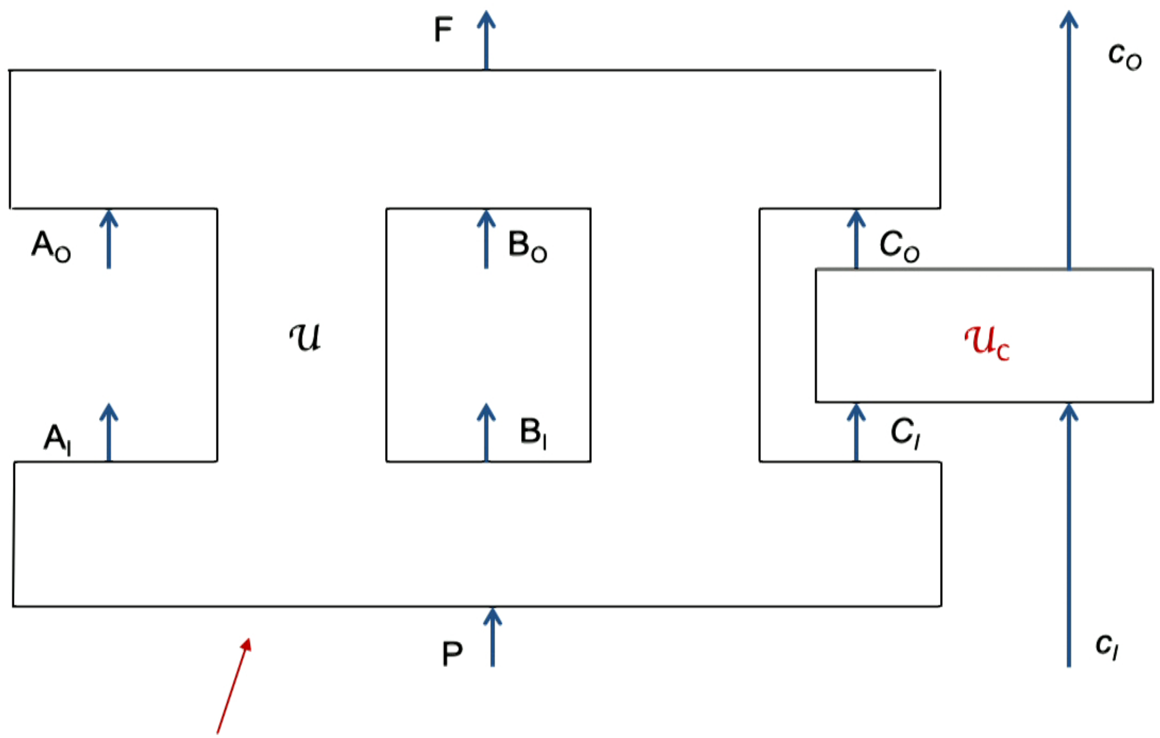
The previous theorem has striking implication for the realizability of unitarily extendible tripartite processes!

Theorem. All tripartite unitarily extendible tripartite processes, including their unitary extensions, have realizations on time-delocalized systems.

This includes processes violating causal inequalities!

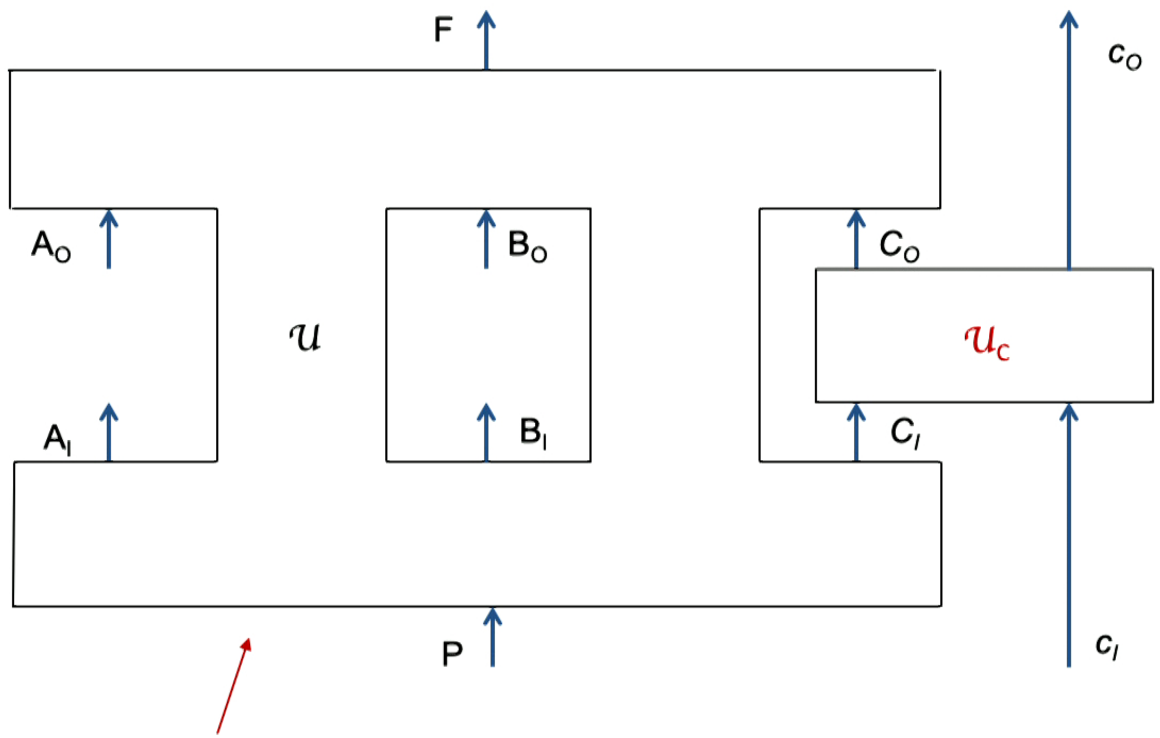
With J. Wechs, C. Branciard, in preparation.

Idea of proof



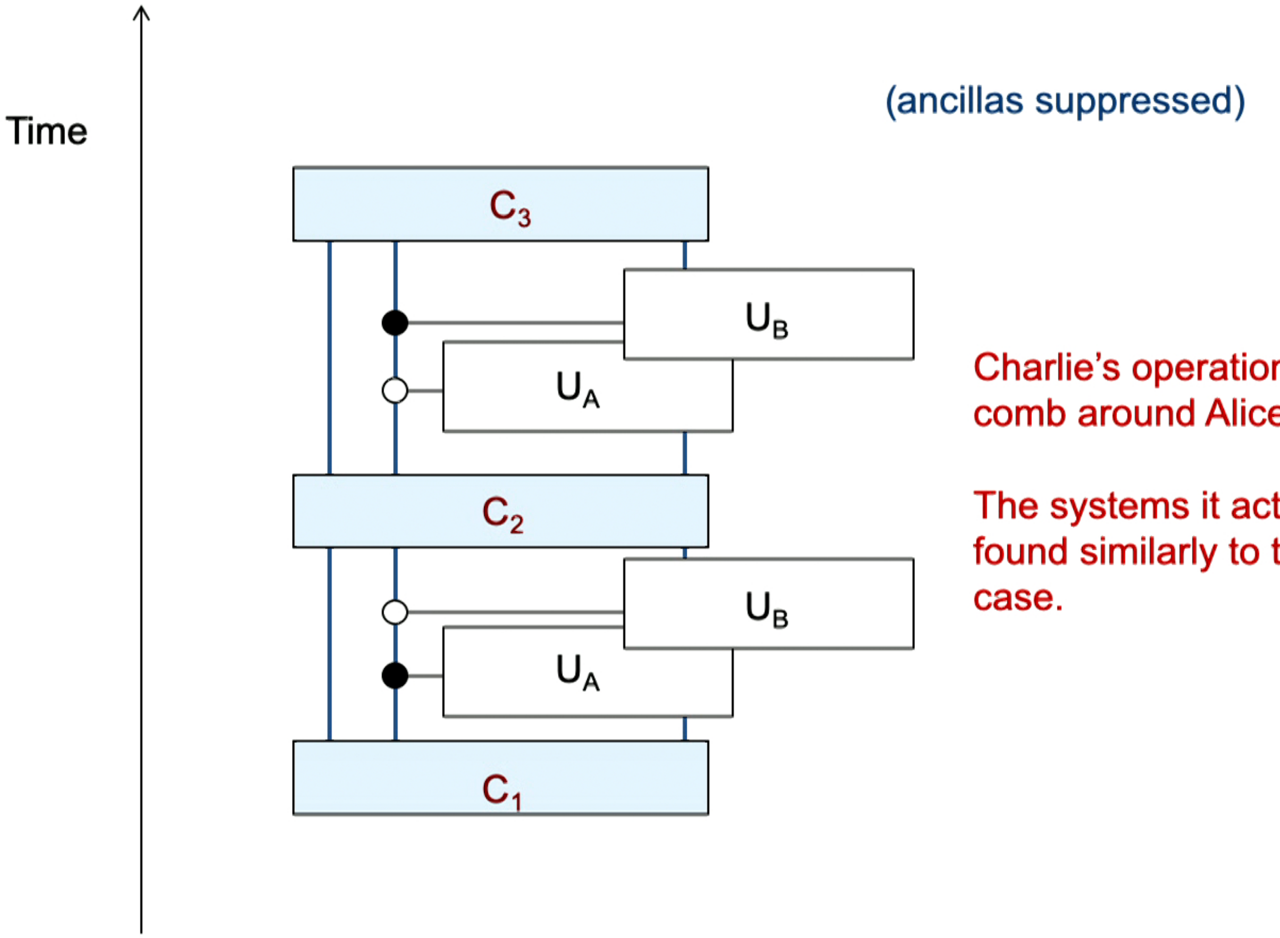
variation of the quantum SWITCH on Alice and Bob

Idea of proof



variation of the quantum SWITCH on Alice and Bob

There is a ***universal*** way of implementing all such processes, such that Alice and Bob act on **fixed** time-delocalized systems:



Charlie's operation is within the comb around Alice and Bob.

The systems it acts on can be found similarly to the bipartite case.

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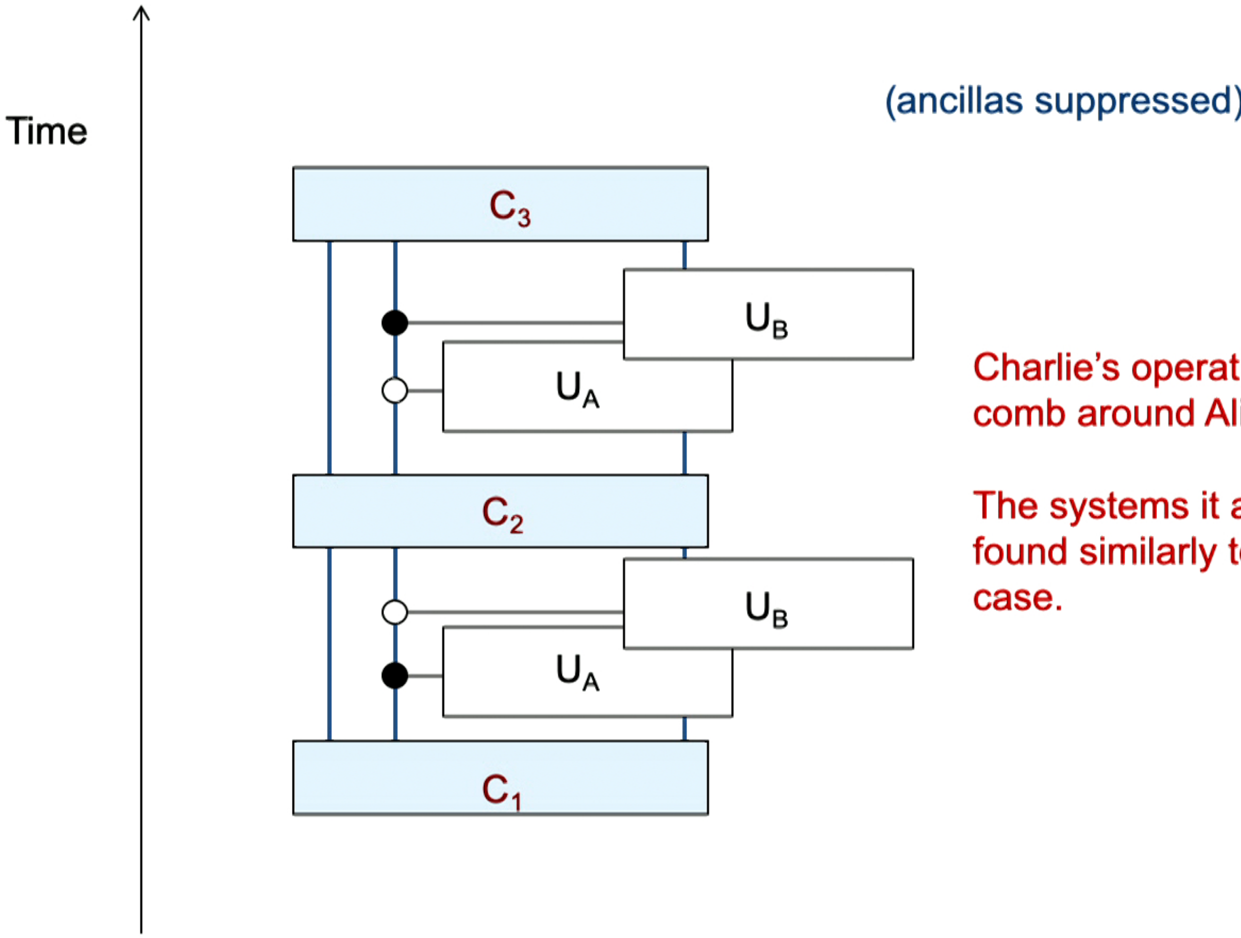


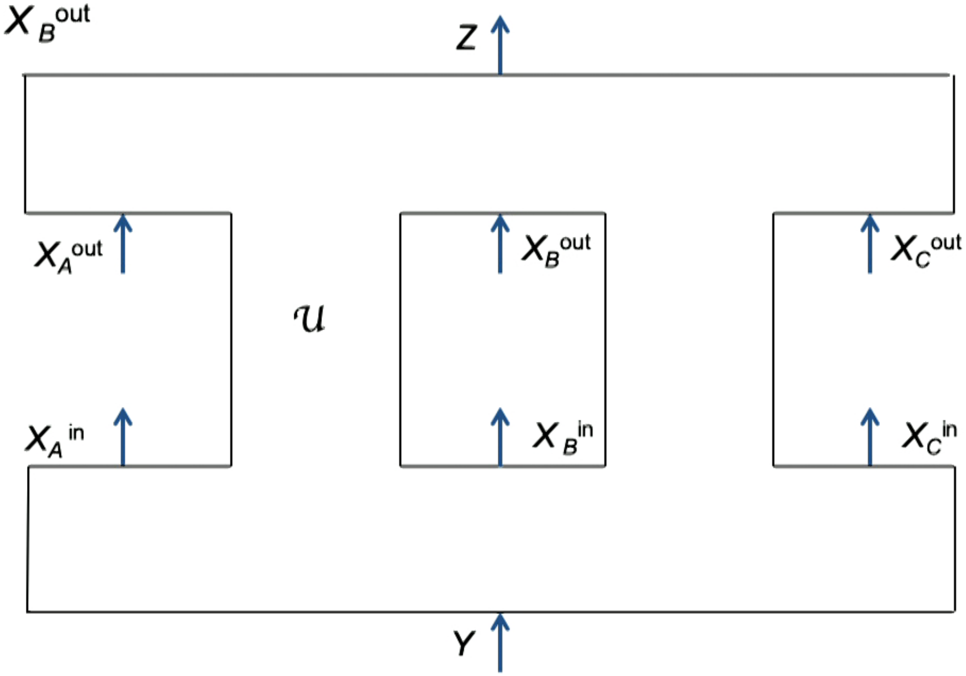
Charlie's operation is within the comb around Alice and Bob.

The systems it acts on can be found similarly to the bipartite case.

Example: The Baumeler-Wolf process

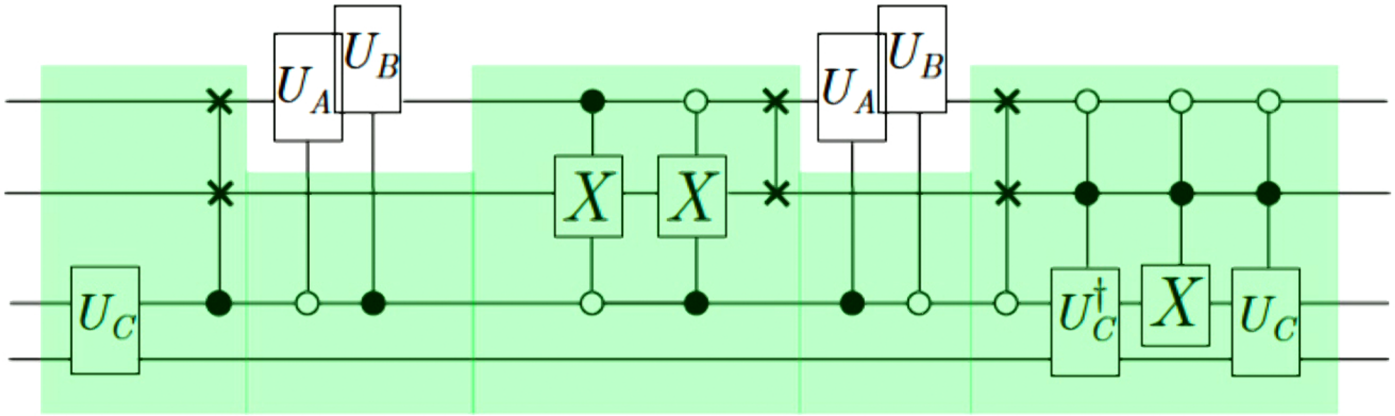
$$\begin{cases} X_A^{in} = \neg X_B^{out} \wedge X_C^{out} \\ X_B^{in} = \neg X_C^{out} \wedge X_A^{out} \\ X_C^{in} = \neg X_A^{out} \wedge X_B^{out} \end{cases}$$

Violates causal inequalities.



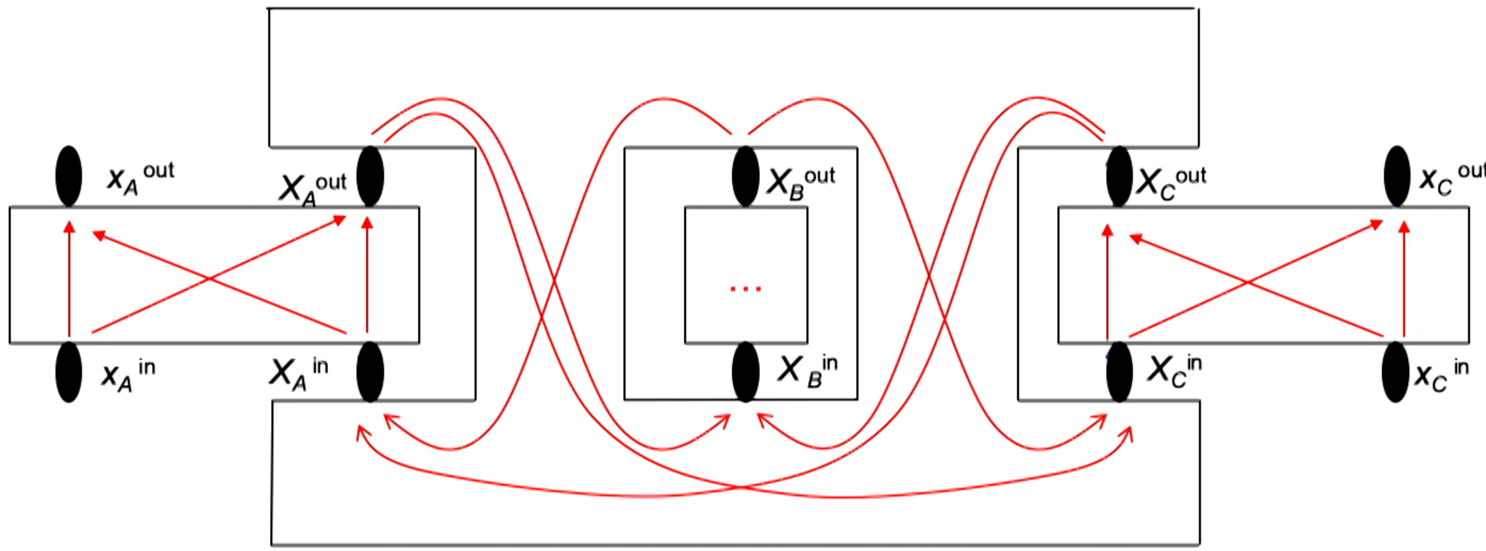
Admits unitary extension [Araujo et al., Quantum (2017)]

From Julian Wechs:



Closely linked to circuits previously found by Araujo, Guerin, and Brukner, PRA (2017), and Guérin and Brukner, NJP (2018).

What does a violation of a causal inequalities imply?



There are time-nonlocal classical variables with the following properties:

1) They form a cyclic causal model as illustrated above (which can be tested).

2) Under the assumption of free choice and closed laboratories (no causal arrows apart from those shown), the correlations cannot be explained by dynamical causal order.

Summary and questions

- Cyclic quantum causal models offer a causal perspective on a large class of processes beyond those compatible with a fixed causal structure.
- There are 'exotic' cyclic causal models that have realizations on time-delocalized nodes!
- Does Markovianity imply compatibility in the cyclic case too? What about unitarily nonextendible processes?
- Applications of causally nonseparable processes on time-delocalized nodes?
- Can the cyclic QCM perspective be useful in the context of quantum gravity?