Title: Indefinite causal order and the arrow of time

Speakers: Giulio Chiribella

Series: Quantum Foundations, Quantum Information

Date: September 17, 2024 - 10:50 AM

URL: https://pirsa.org/24090087

Abstract: At the fundamental level, the dynamics of quantum particles and fields is time-symmetric: their dynamical equations are invariant under inversion of the time coordinate, possibly in conjunction with the change of other physical properties, such as charge and parity. At the operational level, the time-symmetry of the fundamental equations implies that certain quantum devices are bidirectional, meaning that the role of their inputs and outputs can be exchanged. Here we characterize the largest set of operations that can in principle be implemented on bidirectional devices, and show that this set includes operations in which the role of the input and output ports of the given devices becomes indefinite. An example of such an operation, called the â€œquantum time flip,â€• achieves input-output indefiniteness by adding quantum control to the direction in which a single device is used. We show that quantum operations with indefinite input-output directions can in principle achieve information-theoretic advantages over all possible operations with definite time direction, and can lead to an exetremely strong form of indefinite causal order.

INDEFINITE CAUSAL ORDER AND THE ARROW OF TIME

Giulio Chiribella
QICI, The University of Hong Kong

Quantum Information and Computation Initiative

Causalworlds 2024,
Perimeter Institute, Waterloo Canada, Sep 10-20 2024

SPACETIME AND THE QUANTUM

The unification of quantum theory with Einstein's theory of general relativity is a **major open problem in contemporary physics.**

In Einstein's theory, spacetime is a physical system, which interacts with the other physical systems.

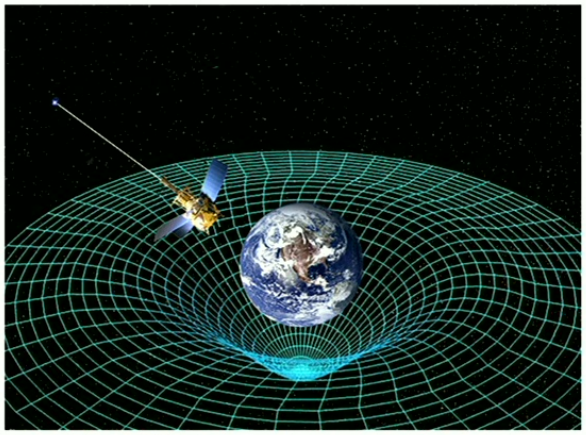


Image from NASA

But at the fundamental level, all physical systems we know are quantum systems.

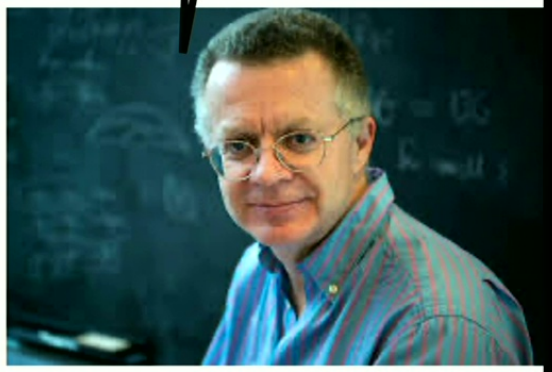
Shouldn't spacetime itself be a quantum system, too?

INTRODUCTION:

INDEFINITE CAUSAL STRUCTURE IN QUANTUM MECHANICS

FROM QUANTUM GRAVITY TO QUANTUM INFORMATION

General relativity is
a deterministic theory with non-fixed causal structure.
Quantum theory is
a probabilistic theory with fixed causal structure.
In this paper we build a framework
for probabilistic theories with non-fixed causal structure.
This combines the radical elements
of general relativity and quantum theory.



Lucien Hardy, Perimeter Institute

Journal of Physics A: Mathematical and Theoretical

Towards quantum gravity: a framework for probabilistic theories with non-fixed causal structure

Lucien Hardy

Published 7 March 2007 • 2007 IOP Publishing Ltd

Journal of Physics A: Mathematical and Theoretical, Volume 40, Number 12

Springer Link

Quantum Reality, Relativistic Causality, and Closing the Epistemic Circle pp 379-401 | Cite as

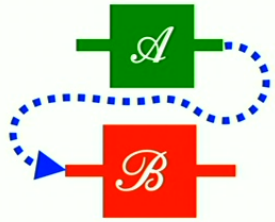
Quantum Gravity Computers: On the Theory of Computation with Indefinite Causal Structure

Authors Authors and affiliations

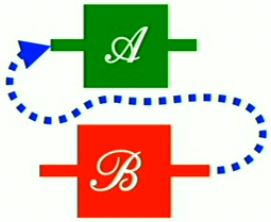
Lucien Hardy

A FIRST EXAMPLE: THE QUANTUM SWITCH

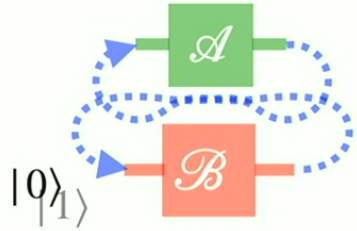
Chiribella, D'Ariano, Perinotti, Valiron, arXiv:0912.0195; Phys. Rev. A 88, 022318 (2013)



Causal structure $|0\rangle$
process A precedes process B



Causal structure $|1\rangle$
event B precedes event A



Coherent superposition of causal structures $|0\rangle + |1\rangle$
incompatible with any fixed order of $\mathscr{A}$ **and** $\mathscr{B}$

ADVANTAGES IN QUANTUM INFORMATION TASKS

Rapid Communication

Perfect discrimination of no-signalling channels via quantum superposition of causal structures

Giulio Chiribella
Phys. Rev. A **86**, 040301(R) – Published 10 October 2012

Editors' Suggestion

Computational Advantage from Quantum-Controlled Ordering of Gates

Mateus Araújo, Fabio Costa, and Časlav Brukner
Phys. Rev. Lett. **113**, 250402 – Published 18 December 2014

Enhanced Communication with the Assistance of Indefinite Causal Order

Daniel Ebler, Sina Salek, and Giulio Chiribella
Phys. Rev. Lett. **120**, 120502 – Published 22 March 2018

Quantum Metrology with Indefinite Causal Order

Xiaobin Zhao, Yuxiang Yang, and Giulio Chiribella
Phys. Rev. Lett. **124**, 190503 – Published 14 May 2020

Quantum Refrigeration with Indefinite Causal Order

David Felce and Vlatko Vedral
Phys. Rev. Lett. **125**, 070603 – Published 11 August 2020

Measuring Incompatibility and Clustering Quantum Observables with a Quantum Switch

Ning Gao, Dantong Li, Anchit Mishra, Junchen Yan, Kyrylo Simonov, and Giulio Chiribella
Phys. Rev. Lett. **130**, 170201 – Published 27 April 2023

+ many others…

TABLE-TOP SIMULATIONS WITH PHOTONS

Experimental superposition of orders of quantum gates

Lorenzo M. Procopio, Amir Moqanaki, Mateus Araújo, Fabio Costa, Irati Alonso Calafell, Emma G. Dowd, Deny R. Hamel, Lee A. Rozema, Časlav Brukner & Philip Walther

Nature Communications **6**, Article number: 7913 (2015) | Cite this article

Editors' Suggestion

Experimental verification of an indefinite causal order

Giulia Rubino[1,*], Lee A. Rozema[1], Adrien Feix[1,2], Mateus Araújo[1,2], Jonas M. Zeuner[1], Lorenzo ...
+ See all authors and affiliations

Science Advances 24 Mar 2017:
Vol. 3, no. 3, e1602589
DOI: 10.1126/sciadv.1602589

Indefinite Causal Order in a Quantum Switch

K. Goswami, C. Giarmatzi, M. Kewming, F. Costa, C. Branciard, J. Romero, and A. G. White
Phys. Rev. Lett. **121**, 090503 – Published 31 August 2018

Experimental Quantum Switching for Exponentially Superior Quantum Communication Complexity

Kejin Wei, Nora Tischler, Si-Ran Zhao, Yu-Huai Li, Juan Miguel Arrazola, Yang Liu, Weijun Zhang, Hao Li, Lixing You, Zhen Wang, Yu-Ao Chen, Barry C. Sanders, Qiang Zhang, Geoff J. Pryde, Feihu Xu, and Jian-Wei Pan
Phys. Rev. Lett. **122**, 120504 – Published 28 March 2019

Experimental Transmission of Quantum Information Using a Superposition of Causal Orders

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
Phys. Rev. Lett. **124**, 030502 – Published 24 January 2020

+ recent reviews

Experiments on quantum causality

AVS Quantum Sci. 2, 037101 (2020); https://doi.org/10.1116/5.0010747

K. Goswami[a] *and* J. Romero[b]

Experimental aspects of indefinite causal order in quantum mechanics

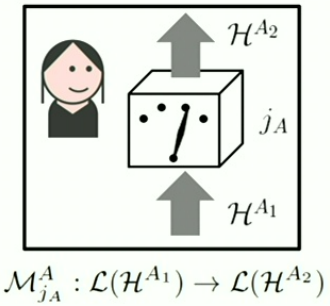
Lee A. Rozema, Teodor Strömberg, Huan Cao, Yu Guo, Bi-Heng Liu & Philip Walther

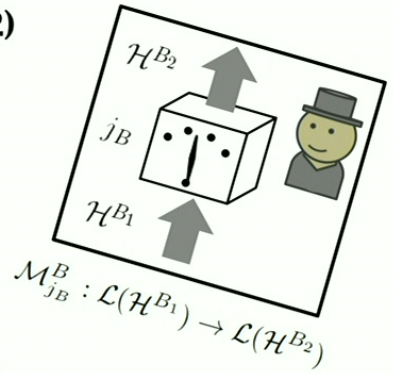
Nature Reviews Physics **6**, 483–499 (2024) | Cite this article

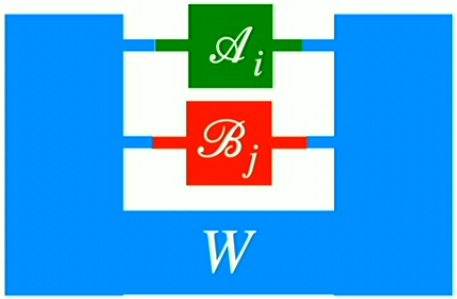
MORE GENERAL TYPES OF INDEFINITE ORDER: PROCESS MATRICES

Oreshkov, Costa, Brukner, Nature Communications 3, 1092 (2012)

General rule for assigning probabilities
to the outcomes of experiments
in local laboratories,
without assuming a definite order
between them.







$$p(i,j) = \mathrm{Tr}[(A_i \otimes B_j)\, W]$$

$$W \geq 0$$

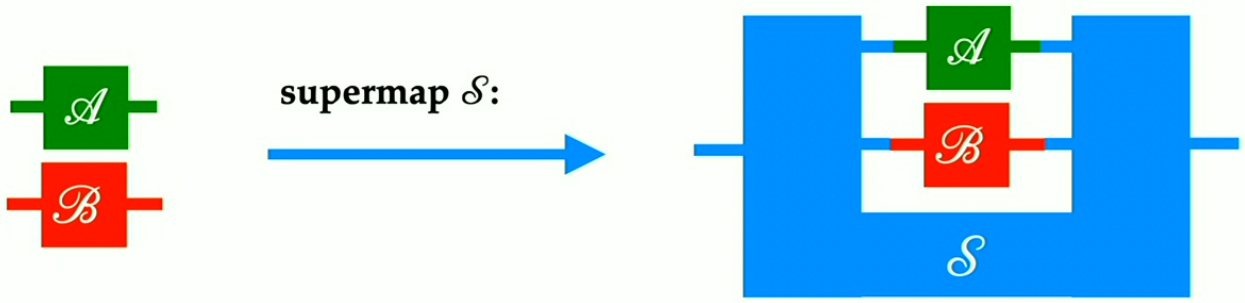
$$\mathrm{Tr}[(A \otimes B)\, W] = 1$$

$$\forall A \text{ such that } \mathrm{Tr}_{A_{\mathrm{out}}}[A] = I_{A_{\mathrm{in}}}$$

$$\forall B \text{ such that } \mathrm{Tr}_{B_{\mathrm{out}}}[B] = I_{B_{\mathrm{in}}}$$

SUPERMAP FORMULATION

The quantum switch and the process matrices are examples of ***supermaps:*** linear maps that transform quantum processes into quantum processes.
Chiribella, D'Ariano, Perinotti, Valiron, Phys. Rev. A 88, 022318 (2013)



input:
pair of processes

output:
a new process

(for process matrices, the input/output of the new process are trivial)

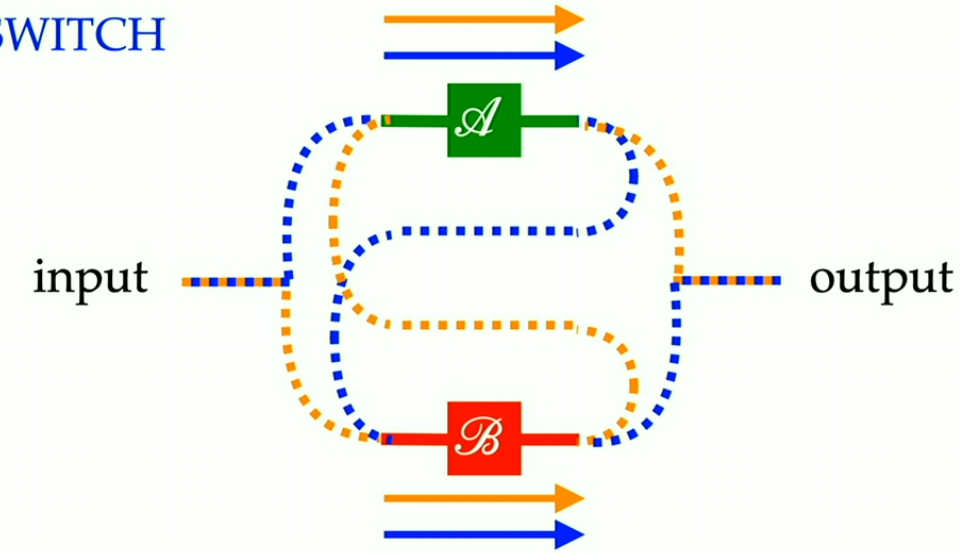
FROM INDEFINITE CAUSAL ORDER TO INDEFINITE INPUT-OUTPUT DIRECTION

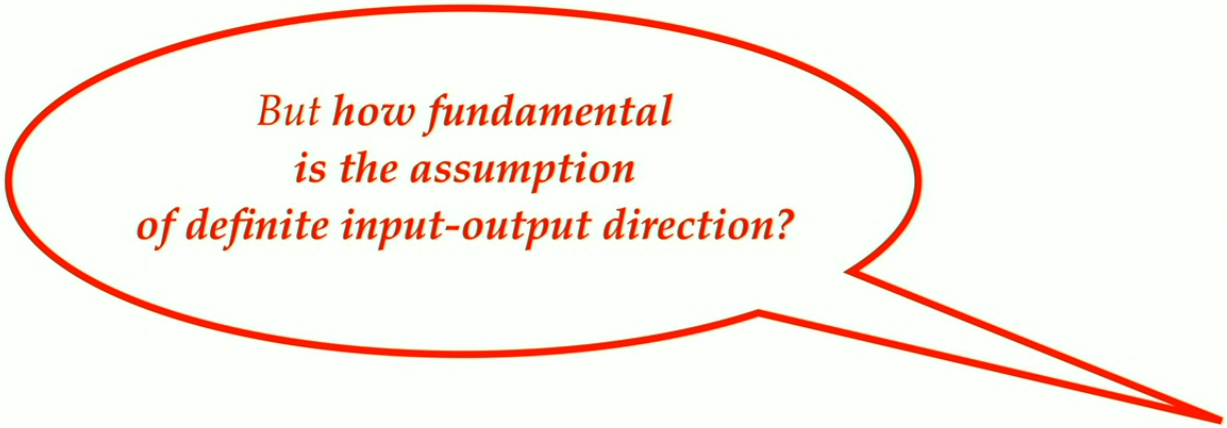
PROCESSES STUDIED SO FAR

All the processes considered so far
use quantum devices in a *definite input-output direction.*

Even the processes with indefinite causal order
have definite input-output direction!

e.g. quantum SWITCH

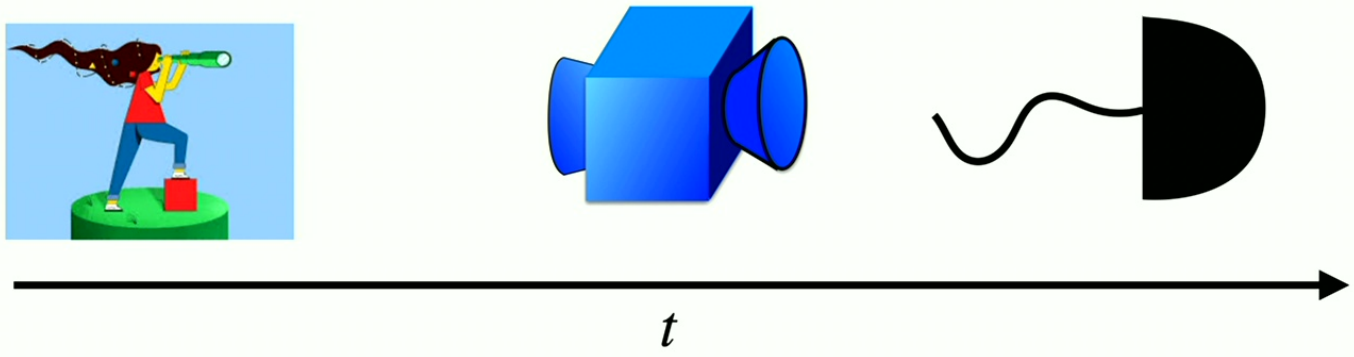



But how fundamental
is the assumption
of definite input-output direction?

TIME SYMMETRY
AT THE FUNDAMENTAL LEVEL

At the fundamental level,
the dynamics of particles and fields is time-symmetric:
inverting the direction of time
does not alter the form of the dynamical equations (cf. CPT theorem)

In contrast, ***our experimental capabilities are not time symmetric:***
we probe physical processes in the forward time direction,
not in the backward one.



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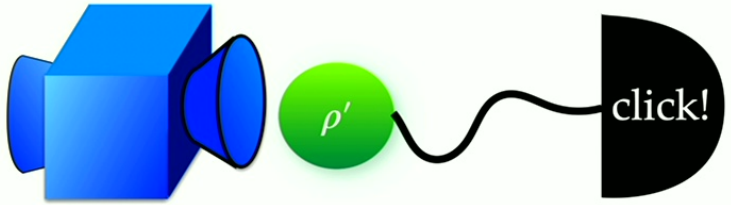
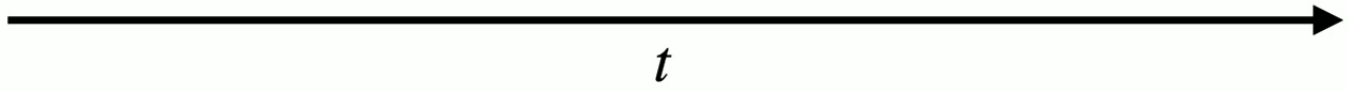




TIME ASYMMETRY AS AN AGENT-BASED NOTION

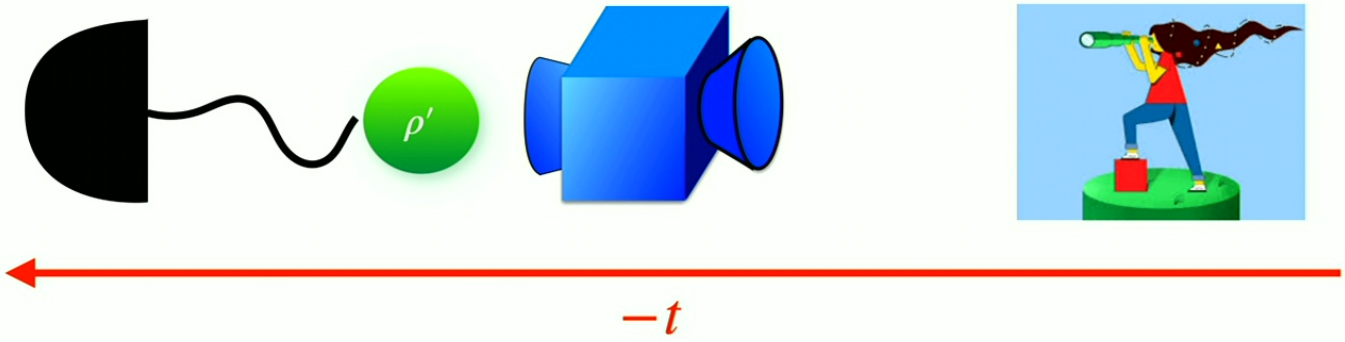
Time symmetry in quantum theory has been widely discussed.
In general,
there is a consensus that physics is fundamentally time-symmetric,
and ***time-asymmetry is an artifact of our own perspective as agents.***

Halliwell, Perez-Mercader, and Zurek, Physical origins of time asymmetry (CUP, 1996).
Lebowitz, Physics today 46, 32 (1993).
Wald, Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics 37, 394 (2006).
Maccone, Physical Review Letters 103, 080401 (2009).
Oreshkov and Cerf, Nature Phys. 11, 853-858 (2015)
Rovelli, The Philosophy of Cosmology , 285 (2017).

Di Biagio, P. Dona, and C. Rovelli, Quantum 5, 520 (2021).
Hardy, arXiv:2104.00071 (2021).
Chiribella, Aurell, Życzkowski, Phys. Rev. Research, 3, 033028 (2021).

BACKWARD-FACING AGENTS?

In principle, one can imagine backward-facing agents,
who probe physical processes in the opposite time direction.



These agents may or may not exist in reality, but are a
useful conceptual device to reason about the time structure of quantum theory.

BIDIRECTIONAL DEVICES AND INPUT-OUTPUT INVERSION

Chiribella and Liu, Communication Physics 5, 190 (2022)

BIDIRECTIONAL DEVICES

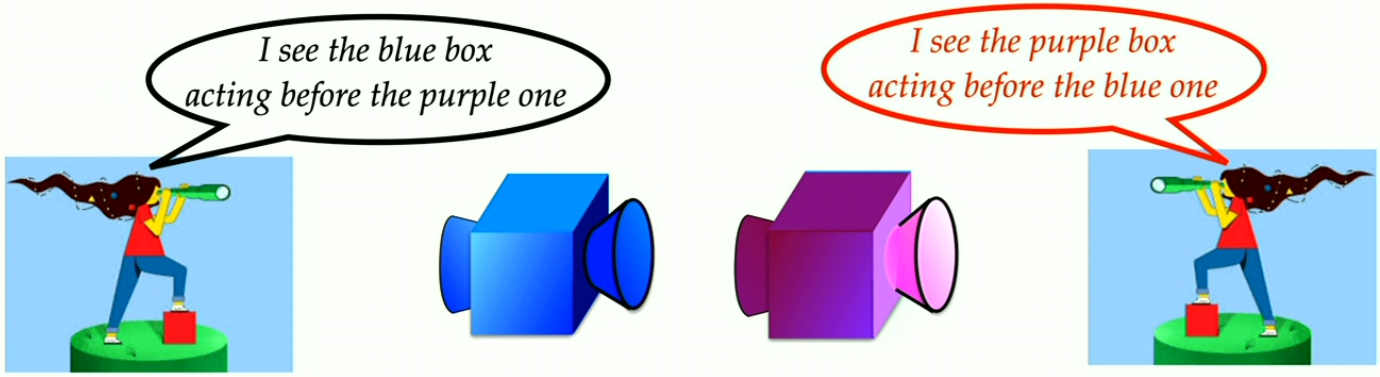
Bidirectional device:= device that can be used both in the forward and in the backward direction.

description of the forward agent: $\mathscr{C}$ description of the backward agent: $\Theta(\mathscr{C})$

We call the map $\Theta : \mathscr{C} \mapsto \Theta(\mathscr{C})$ the ***input-output inversion.***

FOUR AXIOMS FOR THE INPUT-OUTPUT INVERSION

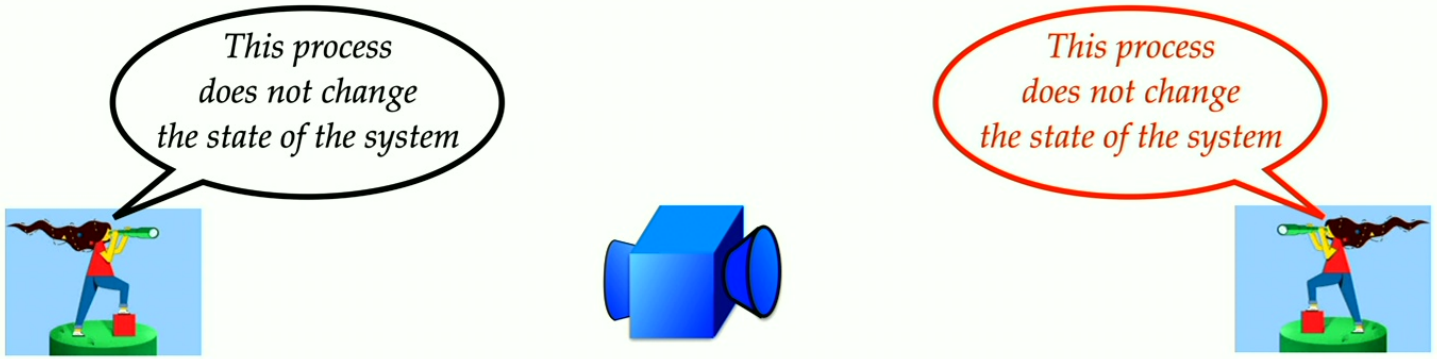
(1) ORDER INVERSION



Axiom (1): The input-output inversion inverts the order

$$\Theta(\mathscr{C}_1 \circ \mathscr{C}_2) = \Theta(\mathscr{C}_2) \circ \Theta(\mathscr{C}_1)$$

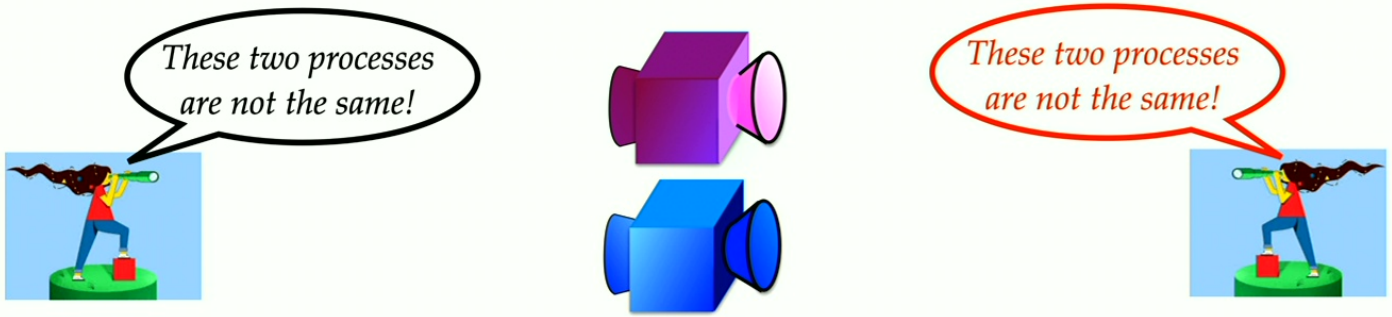
(2) PRESERVATION OF THE IDENTITY



Axiom (2): The identity channel is invariant under input-output inversion

$$\Theta(\mathscr{I}) = \mathscr{I}$$

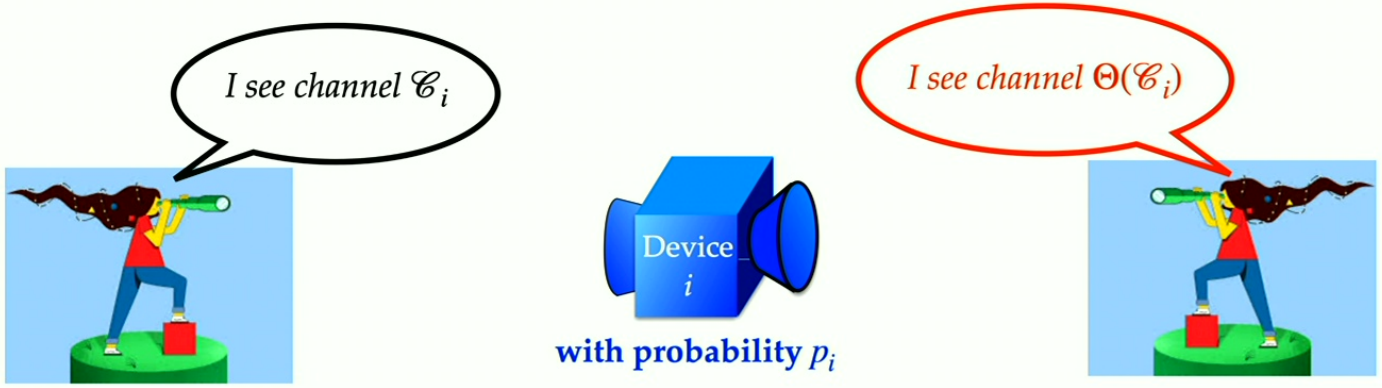
(3) PRESERVATION OF DISTINCTNESS



Axiom (3): The input-output inversion preserves the distinctness of quantum channels

$$\mathscr{C}_1 \neq \mathscr{C}_2 \Longrightarrow \Theta(\mathscr{C}_1) \neq \Theta(\mathscr{C}_2)$$

(4) CONSISTENCY WITH RANDOMIZATIONS



Axiom (4): The input-output inversion of a mixture of channels is the mixture of their input-output inverses.

$$\Theta\left(p\,\mathscr{C}_1 + (1-p)\,\mathscr{C}_2\right) = p\,\Theta(\mathscr{C}_1) + (1-p)\,\Theta(\mathscr{C}_2)$$

CHARACTERIZATION OF INPUT-OUTPUT INVERSION

Theorem 2. For general processes,
there are only two types of input-output inversion
satisfying Axioms 1-4 and defined on all unitary channels:

- unitarily equivalent to the adjoint $\mathscr{C} \mapsto \mathscr{C}^\dagger$
- unitarity equivalent to the transpose $\mathscr{C} \mapsto \mathscr{C}^T$

Theorem 2 applies not only to time-reversal!

It applies every time we can exchange the roles of two ports of a device.

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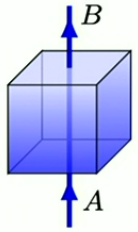
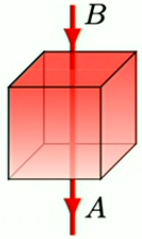
Theorem 2 applies not only to time-reversal!

It applies every time we can exchange the roles of two ports of a device.

e.g. optical crystal

same mathematics
as for time-reversal!





CHARACTERIZATION OF THE BIDIRECTIONAL DEVICES

Theorem 3. If all unitary channels are bidirectional, then set of bidirectional devices corresponds to the set of *bistochastic channels*, that is, maps of the form

$$\mathscr{C} : \rho \mapsto \sum_i C_i \rho C_i^\dagger$$

$$\text{with } \sum_i C_i^\dagger C_i = \sum_i C_i C_i^\dagger = I$$

Which operations
can a general agent perform
on a bidirectional device?

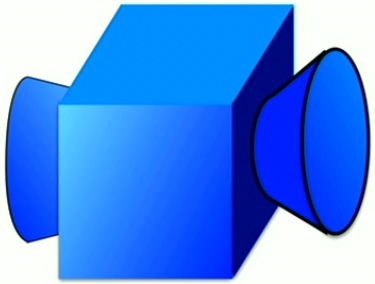
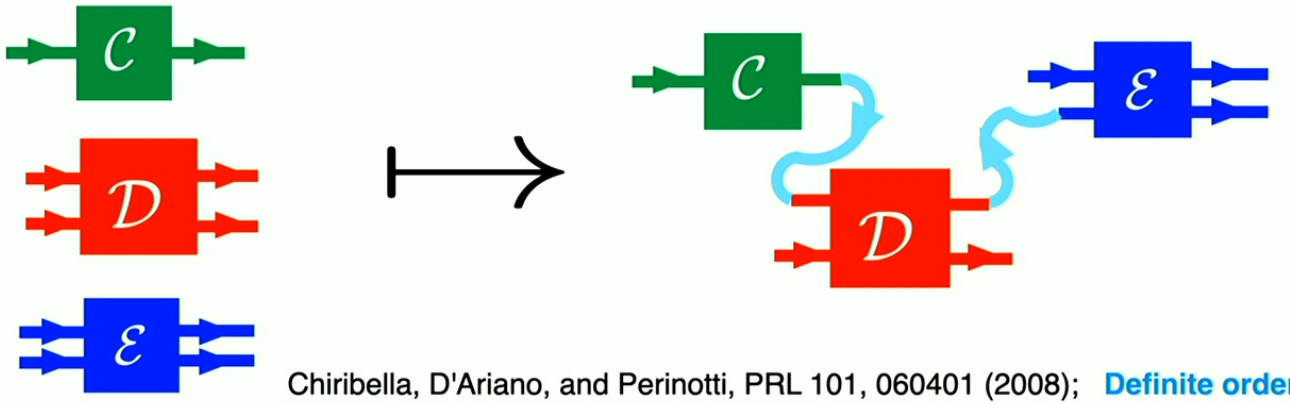


image from https://mario.fandom.com/wiki/Builder_Mario

THE FRAMEWORK OF QUANTUM SUPERMAPS

Framework for operations on quantum processes: ***quantum supermaps.***

They describe the ***possible ways to interact with a given set of quantum devices.***

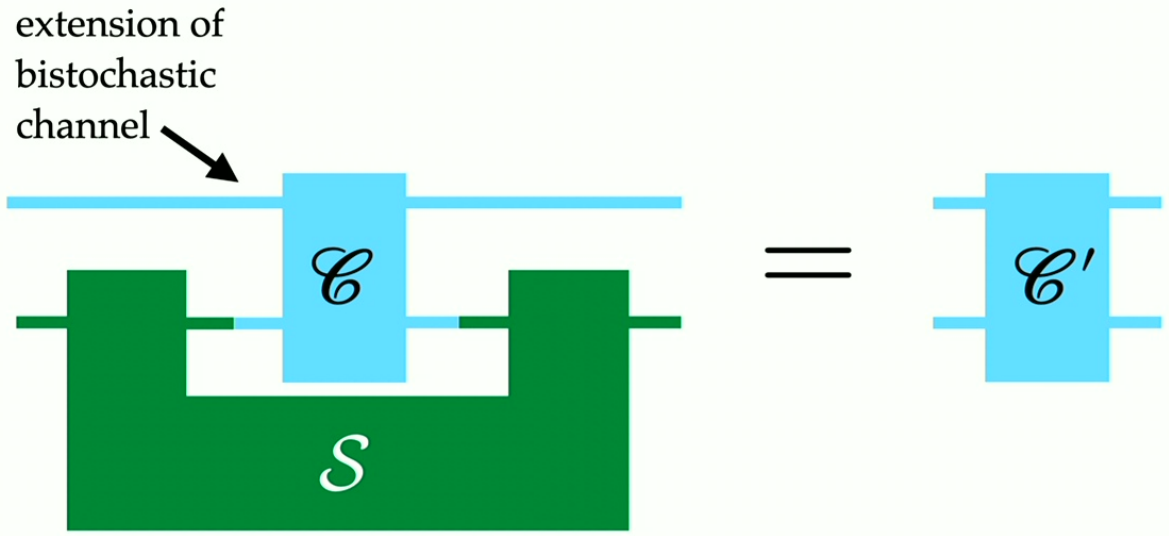


Chiribella, D'Ariano, and Perinotti, PRL 101, 060401 (2008); **Definite order**
EPL 83, 30004 (2008); PRA 80, 022339 (2009);

PRA 88, 022318 (2013) **Indefinite order**
Bisio and Perinotti,
Proc. R. Soc. A 475 20180706 (2019)

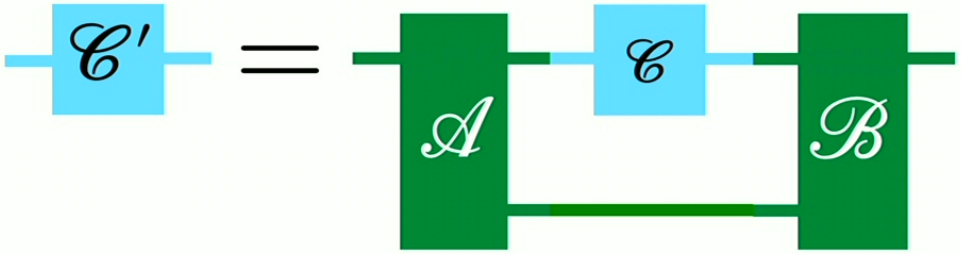
SUPERMAPS ON BISTOCHASTIC CHANNELS

Must be **linear** and **send bistochastic channels into (bistochastic) channels,**
even when acting locally on one part of a bipartite channel

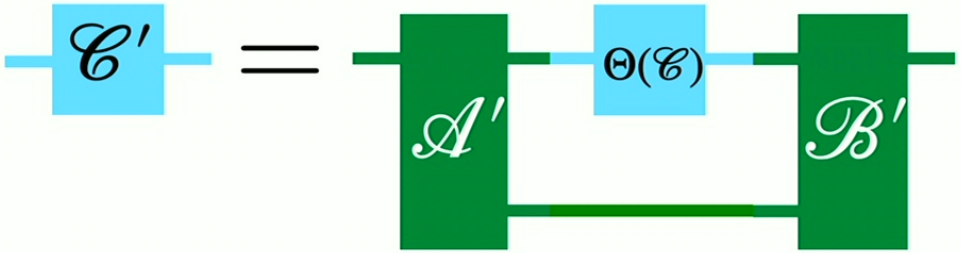


DEFINITE INPUT-OUTPUT DIRECTION

Forward supermaps:
use the device in
one direction



Backward supermaps:
use the device in the
opposite direction



INDEFINITE INPUT-OUTPUT DIRECTION

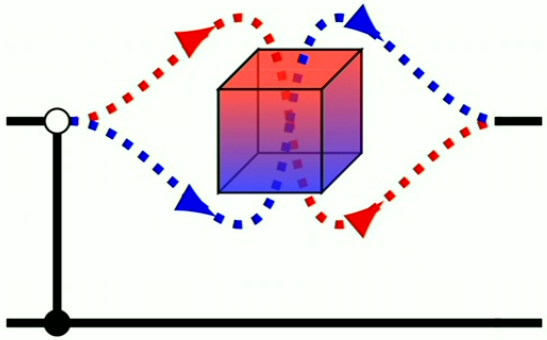
Definition. A supermap $\mathcal{S}$ on bistochastic channels has ***indefinite input-output direction*** if it is impossible to decompose it as $\mathcal{S} = p\,\mathcal{S}_{\text{fwd}} + (1-p)\,\mathcal{S}_{\text{bwd}}$ for some probability p and some forward (backward) supermap $\mathcal{S}_{\text{fwd}}$ ($\mathcal{S}_{\text{bwd}}$)

This definition is the analogue of the definition of operations with indefinite causal order.

Oreshkov, Costa, Brukner, Nat. Commun. 3, 1 (2012)
Araújo et al, NJP 17 10 (2015)
Oreshkov and Giarmatzi, New J. Phys. 18, 093020 (2016)

THE QUANTUM TIME FLIP (QTF)

The QTF maps
bistochastic channels $\mathscr{C}$
with Kraus operators $\{C_i\}$
into
bipartite bistochastic channels $\mathscr{F}(\mathscr{C})$
with Kraus operators



$$F_i := C_i \otimes |0\rangle\langle 0| + C_i^T \otimes |1\rangle\langle 1|$$

Name "quantum *time* flip" originally due to the time-reversal setting, but can also refer to general input-output inversions.

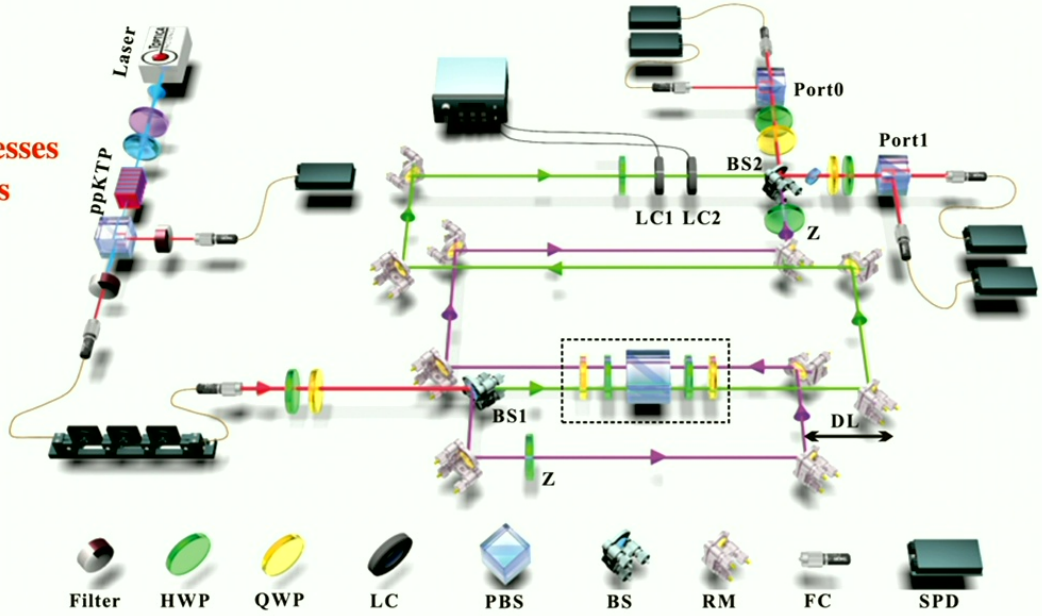
Experimental Demonstration of Input-Output Indefiniteness in a Single Quantum Device

Yu Guo, Zixuan Liu, Hao Tang, Xiao-Min Hu, Bi-Heng Liu, Yun-Feng Huang, Chuan-Feng Li, Guang-Can Guo, and Giulio Chiribella

Phys. Rev. Lett. **132**, 160201 – Published 16 April 2024

- introduced framework of **witnesses of input-output indefiniteness**

- **experimentally witnessed input-output indefiniteness with more than 69 standard deviations**



AN INFORMATION-THEORETIC ADVANTAGE

GAME

A Referee gives Alice two black boxes,
implementing two unitary gates U and V.

The gates U and V are completely unknown to Alice,
except for one thing:
the Referee promises that either $UV^T = U^TV$ or $UV^T = -U^TV$.

The Referee asks Alice to determine which of these two alternatives holds.

NO QUANTUM CIRCUIT WITH FIXED TIME DIRECTION CAN ACHIEVE THE TASK

If Alice can probe the two boxes in a superposition of time directions, she can win the game deterministically.

If Alice can only probe the two black boxes U and V in a fixed time direction (same for both boxes) then she will lose with probability at least 11%.
This bounds holds **even if the black boxes U and V are combined in an indefinite causal order!**

Experimental Demonstration of Input-Output Indefiniteness in a Single Quantum Device

Yu Guo, Zixuan Liu, Hao Tang, Xiao-Min Hu, Bi-Heng Liu, Yun-Feng Huang, Chuan-Feng Li, Guang-Can Guo, and Giulio Chiribella

Phys. Rev. Lett. **132**, 160201 – Published 16 April 2024

Experimental superposition of a quantum evolution with its time reverse

Teodor Strömberg, Peter Schiansky, Marco Túlio Quintino, Michael Antesberger, Lee A. Rozema, Iris Agresti, Časlav Brukner, and Philip Walther

Phys. Rev. Research **6**, 023071 – Published 19 April 2024

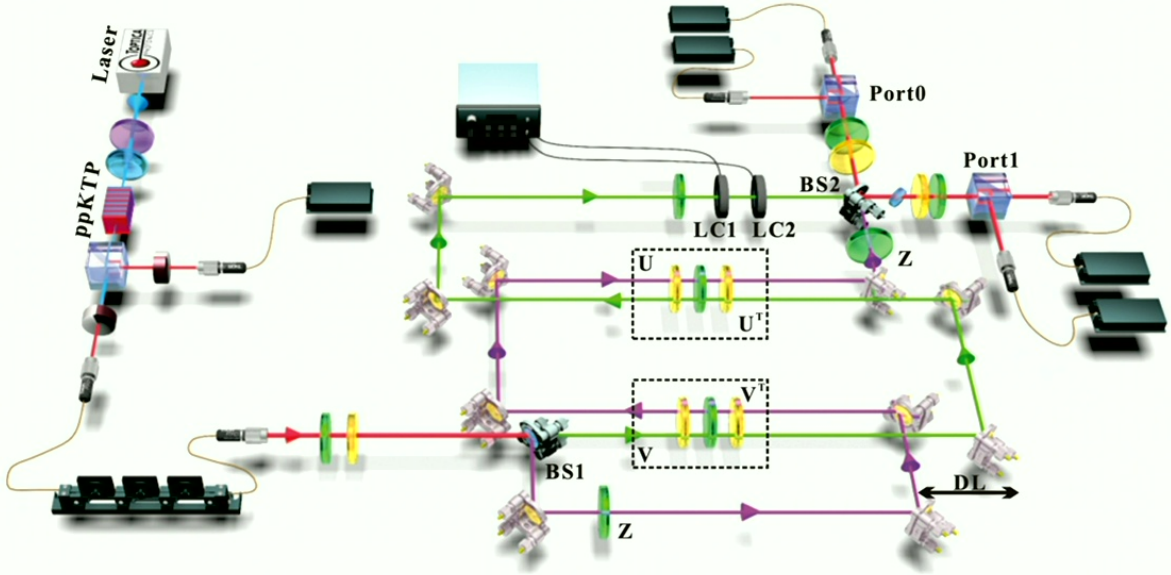
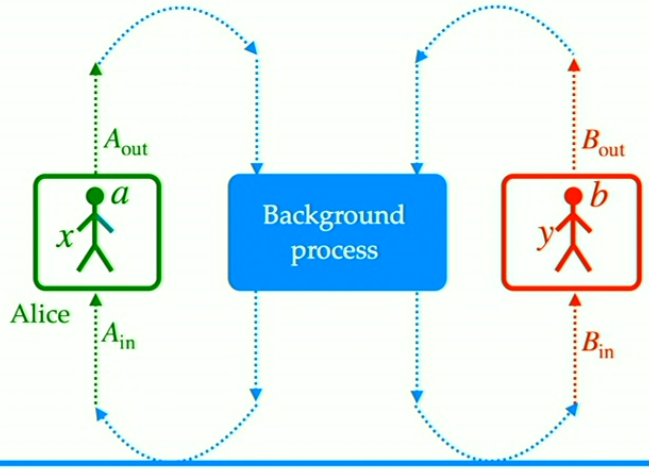


image from PRL 132 160201 (2024)

MAXIMAL VIOLATION OF CAUSAL INEQUALITIES

THE CAUSAL INEQUALITY FRAMEWORK

Alice and Bob can perform different measurements,
labelled by settings x and y, respectively.
The measurement give outcomes
a and b, respectively,
distributed with probability
$p(a,b|x,y)$



Long story short:

- Compatibility with a definite order between Alice and Bob imply a set of inequalities on the observed correlations, known as *causal inequalities.*
  Quantum theory allows (in principle) violations of causal inequalities.
  Oreshkov, Costa, Brukner, Nature Communications 3, 1092 (2012) + …

- The quantum violation of causal inequality satisfies non-trivial bounds, analogous to the Tsirelson bound to quantum nonlocality.
  Liu and Chiribella, arXiv:2403.02749

CAUSAL INEQUALITIES IN BISTOCHASTIC QUANTUM THEORY

Consider a **time-symmetric variant of quantum theory,**
where **the only allowed measurements are bistochastic,**
meaning that, for every setting x,
the map $\sum_a \mathscr{M}_{a|x}$ is **both trace-preserving and identity-preserving.**

Chiribella, Aurell, Życzkowski, Phys. Rev. Research 3, 033028 (2021)
Di Biagio, P. Dona, and C. Rovelli, Quantum 5, 520 (2021).
Hardy, arXiv:2104.00071

We call this variant **bistochastic quantum theory.**

Also in this case, one can define the set of admissible supermaps
and evaluate the maximum correlations achievable with arbitrary supermaps.

VIOLATION OF ALL CAUSAL INEQUALITIES TO THE ALGEBRAIC MAXIMUM

Theorem **(Liu and Chiribella, arXiv:2403.02749)**

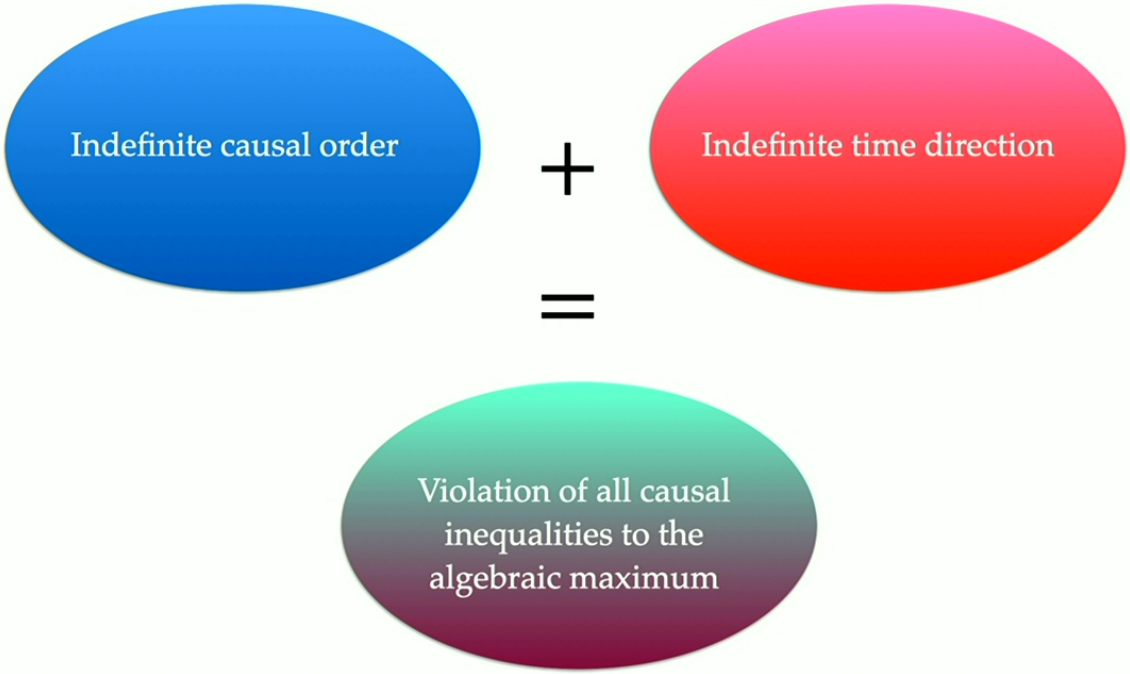
For every correlation and every number of parties,
the maximum correlation achievable value is equal to the
algebraic maximum.

In fact, the same result holds for the correlations arising in
bistochastic *classical* theory!

In particular, Alice can perfectly signal to Bob, and, at the same time,
Bob can perfectly signal to Alice.
In this way, they **can deterministically win the Guess Your Neighbor's Input Game**
Almeida *et al*, Physical Review Letters 104, 230404 (2010).

PHYSICAL INTERPRETATION

Bistochastic instruments represent the **most general quantum experiments** Alice and Bob can perform
without assuming a privileged direction of time outside Alice's and Bob's laboratories.



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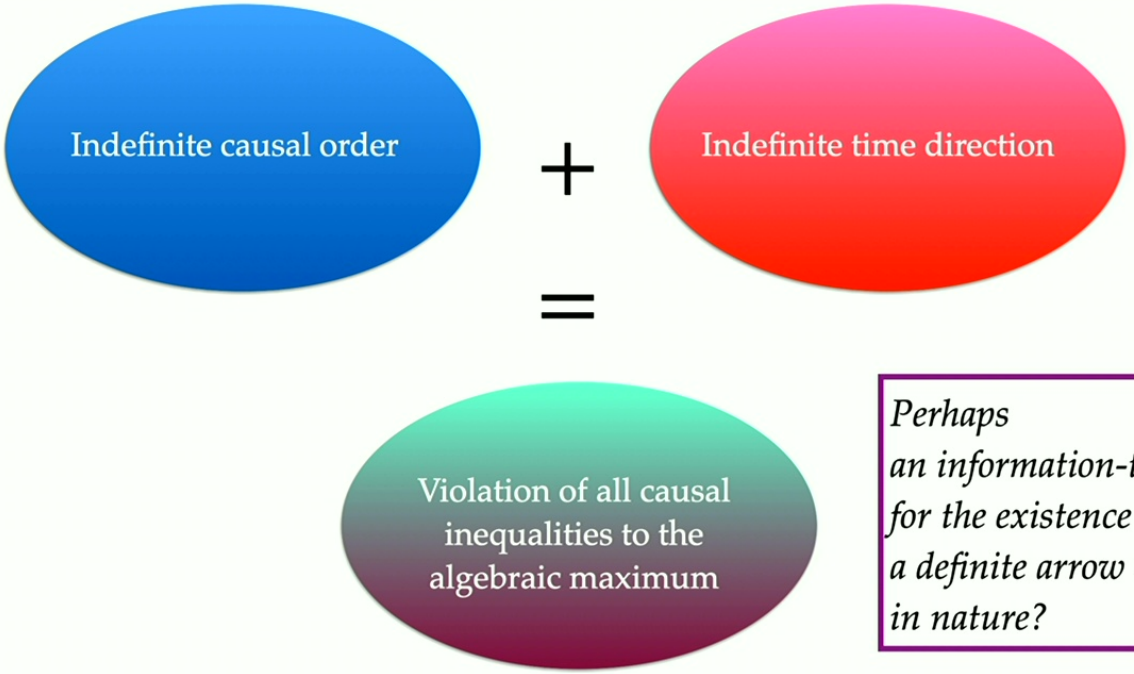

Perhaps an information-theoretic reason for the existence of a definite arrow of time in nature?

TAKE-HOME MESSAGES

- **A new form of indefinite causal structure: indefinite input-output direction**
- Bidirectional quantum devices = bistochastic channels
- Operations on bidirectional devices^{d}

  = supermaps on bistochastic channels
- Operations with indefinite input-output direction

  = operations that are ***not***

  mixtures of forward and backward operations
- Quantum information advantages, witnesses,

  and violation of causal inequalities to the algebraic maximum.

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NEWS IN BRIEF

New 'Time' To Keep Everything From Happening At Once

Published April 19, 2000

CAMBRIDGE, MA–On what is now known as "Monday," a team of MIT scientists unveiled "time," a revolutionary new event-sequencing protocol which organizes phenomena along a four-dimensional axis, preventing everything from taking place at once. "No longer will the extinction of the dinosaurs, the assassination of John F. Kennedy, and the Earth-Xabraxiq Pod Wars all collapse into a single point," theoretical physicist Dr. Lawrence Chang said. "With time, we can now contextualize each of the universe's infinite number of occurrences in its own spatial-temporal plane, creating order where there once was chaos." Added Dr. Erno Toffel: "Using time, one event can be positioned chronologically so as to be the cause of another. For example, a man's death may result in a gun being fired at him. Or the other way around. We're still working out some of the kinks."

h/t to
Charles Bennett