Title: Quantizing causation

Speakers: Robert Spekkens

Collection: Quantizing Time

Date: June 14, 2021 - 10:40 AM

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Abstract: "Spatio-temporal relations are often taken to be more primitive than causal relations. Such a relationship is assumed whenever it is suggested that it is part of the definition of a causal relation that the cause must precede the effect in time. There are good reasons, however, to take causation to be the more primitive notion, with spatio-temporal relations merely describing aspects of causal relations. In such an approach, to understand what possibilities there are for an intrinsically quantum notion of time, it is helpful to understand what possibilities there are for an intrinsically quantum notion of causation. In short, how time is quantized is informed by how causation is quantized. The latter question will be the focus of this talk. I will describe a research program wherein the transition from classical to quantum is understood as an innovation to the notions of causation and inference. This is done by introducing the notion of a causal-inferential theory: a triple consisting of a theory of causal influences, a theory of inferences (of both the Boolean and Bayesian varieties), and a specification of how these interact. The possibility of defining causal-inferential theories by the axioms they satisfy provides a means of providing abstract and structural characterizations of the notions of causation and inference. In other words, within this approach, the new notions of causation and inference will stand to the traditional notions in much the same way that the notions of points and lines in nonEuclidean geometry stand to their traditional counterparts in Euclidean geometry.
Based on: D. Schmid, J. Selby, and R. Spekkens, Unscrambling the omelette of causation and inference: The framework of causal-inferential theories, arXiv:2009.03297 (quant-ph)."

Quantizing Causation

Robert Spekkens
Perimeter Institute for Theoretical Physics

Joint work with David Schmid and John Selby

Quantizing Time
June14, 2021

Hypothesis:

Causal relations are more primitive than spatio-temporal relations

Implication:

How the notion of time is modified in a quantum world depends on how the notion of causation is modified in a quantum world

“[...] our present QM formalism is not purely epistemological; it is a peculiar mixture describing in part realities of Nature, in part incomplete human information about Nature all scrambled up by Heisenberg and Bohr into an omelette that nobody has seen how to unscramble.

— E.T. Jaynes, 1989

"[...] our present QM formalism is not purely epistemological; it is a peculiar mixture describing in part realities of Nature, in part incomplete human information about Nature all scrambled up by Heisenberg and Bohr into an omelette that nobody has seen how to unscramble.

Yet we think that the unscrambling is a prerequisite for any further advance in basic physical theory. For, if we cannot separate the subjective and objective aspects of the formalism, we cannot know what we are talking about; it is just that simple.

— E.T. Jaynes, 1989

arXiv:2009.03297

Unscrambling the omelette of causation and inference: The framework of causal-inferential theories

David Schmid*
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Using a process-theoretic formalism, we introduce the notion of a *causal-inferential theory*: a triple consisting of a theory of causal influences, a theory of inferences, and a specification of how these interact. Recasting the notions of operational and realist theories in this mold clarifies what a realist account of an experiment offers beyond an operational account. It also yields a novel characterization of the assumptions and implications of standard no-go theorems for realist representations of operational quantum theory, namely, those based on Bell's notion of locality and those based on generalized noncontextuality. Moreover,

Causal theory

Inferential theory

"[...] our present QM formalism is not purely epistemological; it is a peculiar mixture describing in part realities of Nature, in part incomplete human information about Nature all scrambled up by Heisenberg and Bohr into an omelette that nobody has seen how to unscramble.

Yet we think that the unscrambling is a prerequisite for any further advance in basic physical theory. For, if we cannot separate the subjective and objective aspects of the formalism, we cannot know what we are talking about; it is just that simple.

So we want to speculate on the proper tools to do this."

— E.T. Jaynes, 1989

Causal-inferential theory

The objective:

Realism in Quantum Theory

The notion of realism we seek to salvage:

Statistical correlations have causal explanations

The problem: Bell's theorem & Kochen-Specker theorem

The idea:

By allowing **intrinsically quantum notions of causation and inference,** one can provide satisfactory explanations while salvaging the spirit of locality and noncontextuality

EPR’s reality criterion:

“the criterion is, in the parlance of philosophers, *analytic*. That is, this criterion follows just from the very meanings of the words used in it.”

-- Tim Maudlin

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Such conceptual dogmatism has no place in physics

A hypothetical no-go theorem:

- The relativity principle
- The light postulate
- The conventional notions of space and time

→ Contradiction

The meanings of
all concepts
in a physical theory

emerge from

The axioms defining
the physical theory

The meaning of
causal and inferential
concepts

emerge from

The axioms defining the
causal-inferential theory

Quantum
Causation and Inference

Classical
Causation and Inference

$\sim$

Relativistic
Notions of Space
and Time

PreRelativistic
Notions of Space
and Time

Prior work that we build on

Unscrambling the omelette of causation and inference

Quantum states are epistemic: C. A. Fuchs, arXiv:1003.5209 (2010); J. Emerson, (2002), arXiv:0211035; R. W. Spekkens, Physical Review A 75, 032110 (2007)

Classical unscrambling: J. Pearl, Causality (Cambridge university press, 2009)

Quantum causal models: M. S. Leifer and R. W. Spekkens, Phys. Rev. A 88, 052130 (2013); J.-M. A. Allen, J. Barrett, D. C. Horsman, C. M. Lee, and R. W. Spekkens, Phys. Rev. X 7, 031021 (2017)

Quotiented Operational Theories

L. Hardy, 0101012 (2001)

The category-theoretic approach: S. Abramsky and B. Coecke, Proc. of the 19th Annual IEEE Symposium, p. 415 (2004)

J. Barrett, Phys. Rev. A 75, 032304 (2007)

G. Chiribella, G. M. D'Ariano, and P. Perinotti, Phys. Rev. A 81, 062348 (2010)

Hardy's duotensor formalism: L. Hardy, arXiv:1104.2066 (2011)

O. Oreshkov, F. Costa, C. Brukner Nature Communications 3, 1092 (2012)

Unquotiented Operational Theories and Leibnizianity

Generalized noncontextuality: R. W. Spekkens, Phys. Rev. A 71, 052108 (2005).

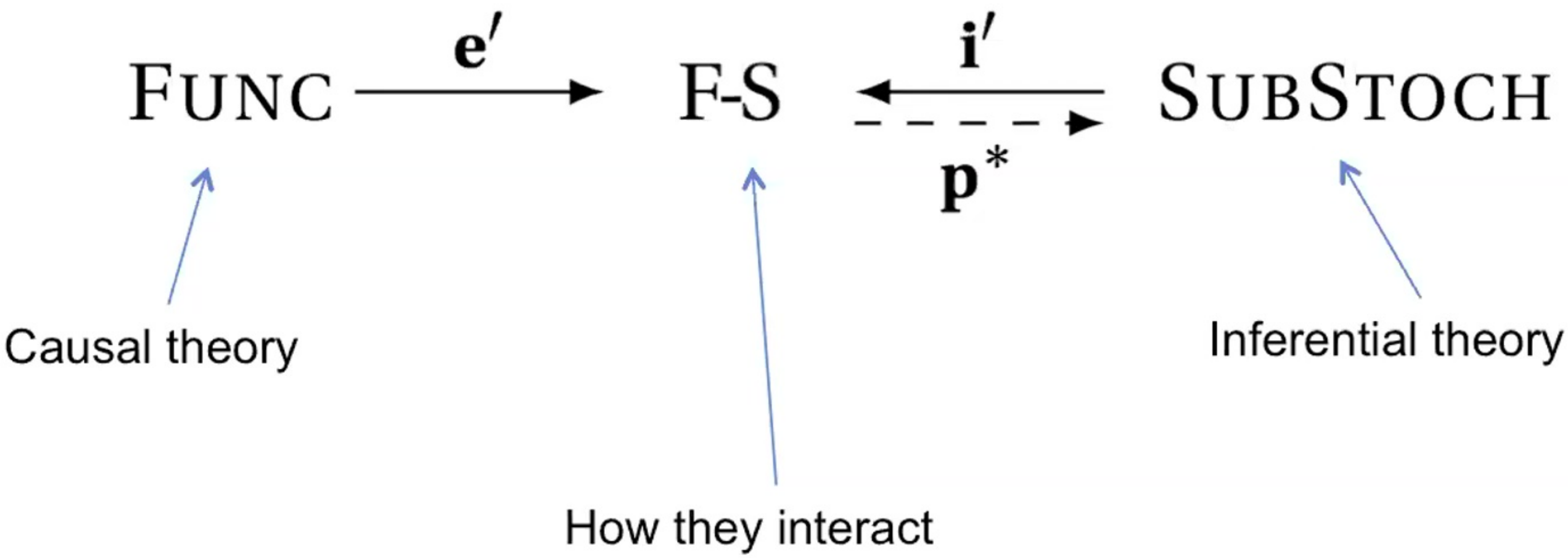
Leibnizianity: R. W. Spekkens, arXiv:1909.04628 (2019)

Fully compositional: D. Schmid, J. H. Selby, M. F. Pusey, and R. W. Spekkens, arXiv:2005.07161 (2020)

Quotiented ontological Theories

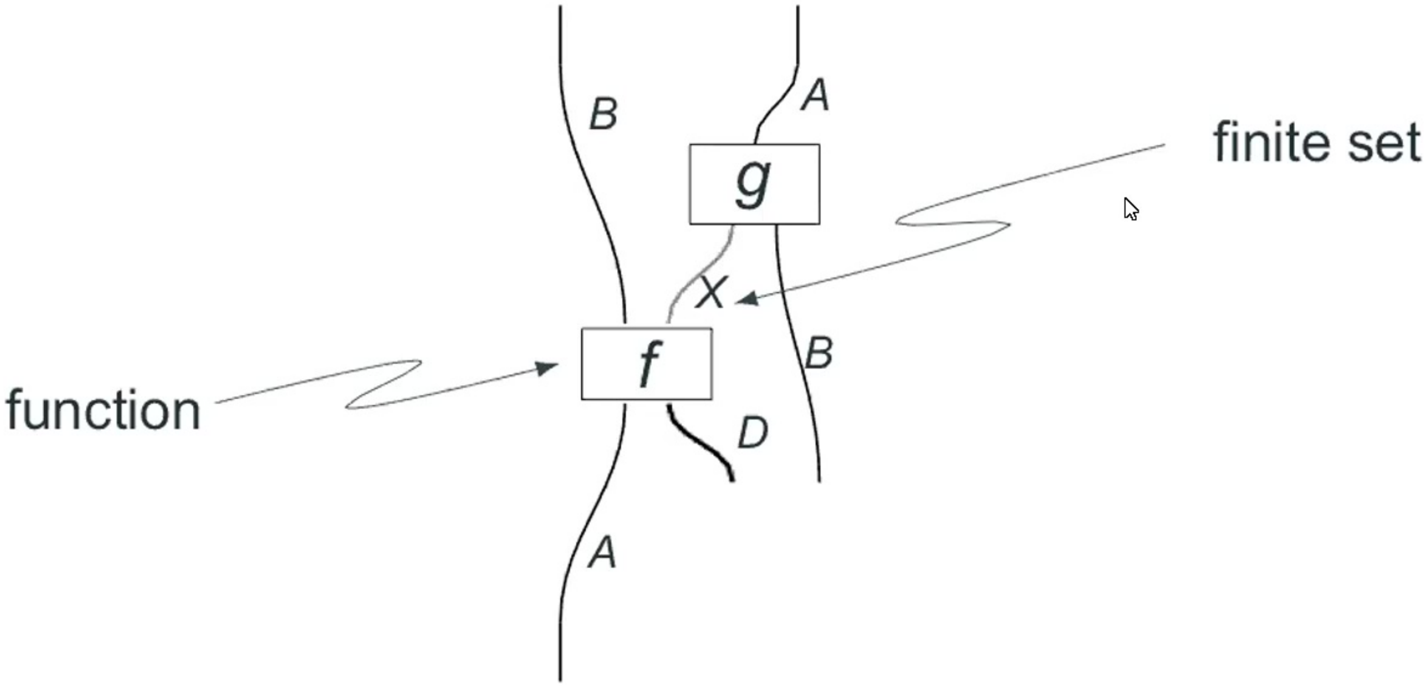
N. Harrigan and R. W. Spekkens, Foundations of Physics 40, 125 (2010)

A Classical Realist Causal-Inferential Theory

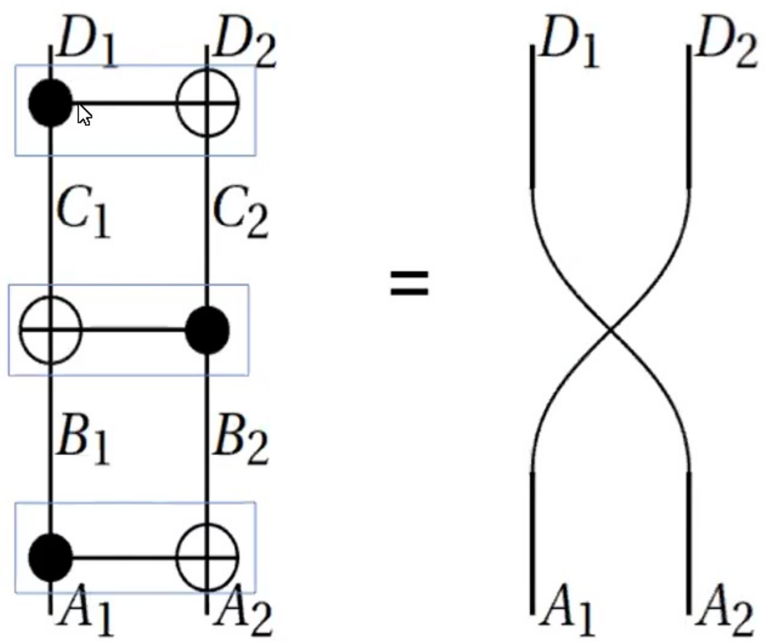


Causal theory

FUNC



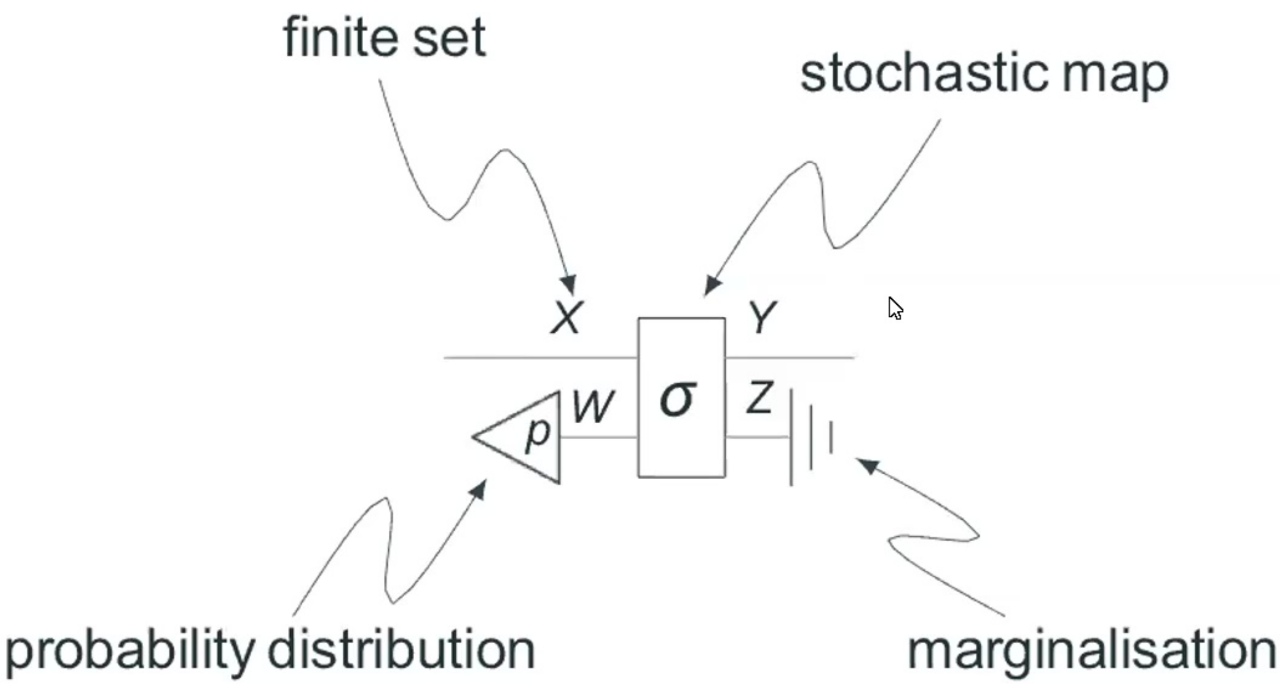
FUNC has nontrivial equalities



Inferential Theory = Bayesian Probability Theory + Boolean Propositional Logic

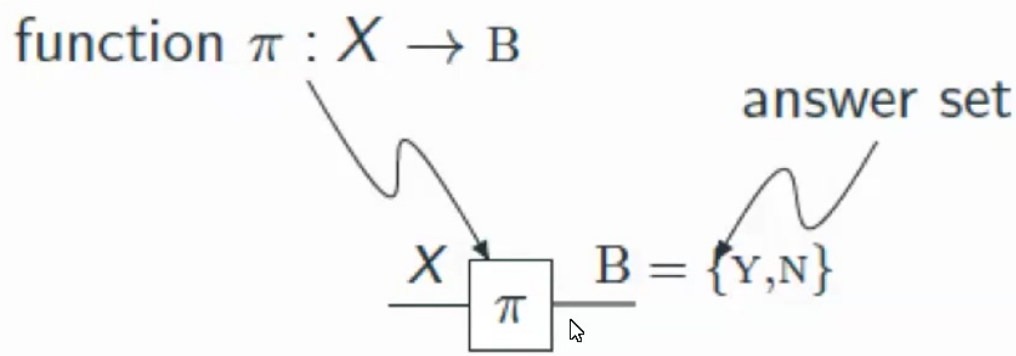
Bayesian probability theory

BAYES

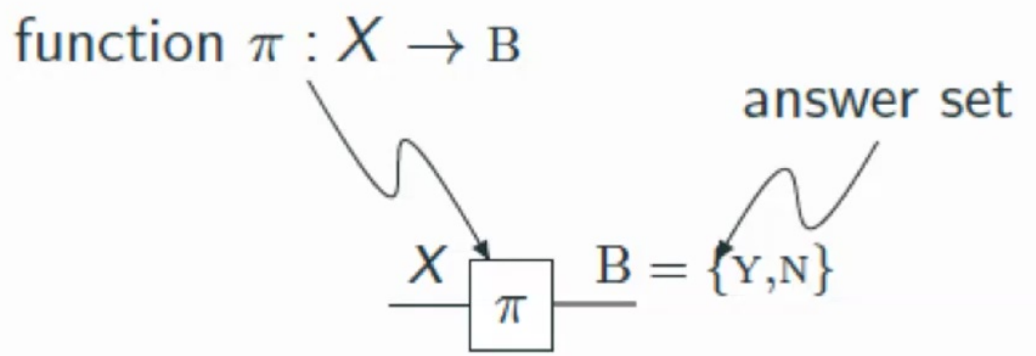


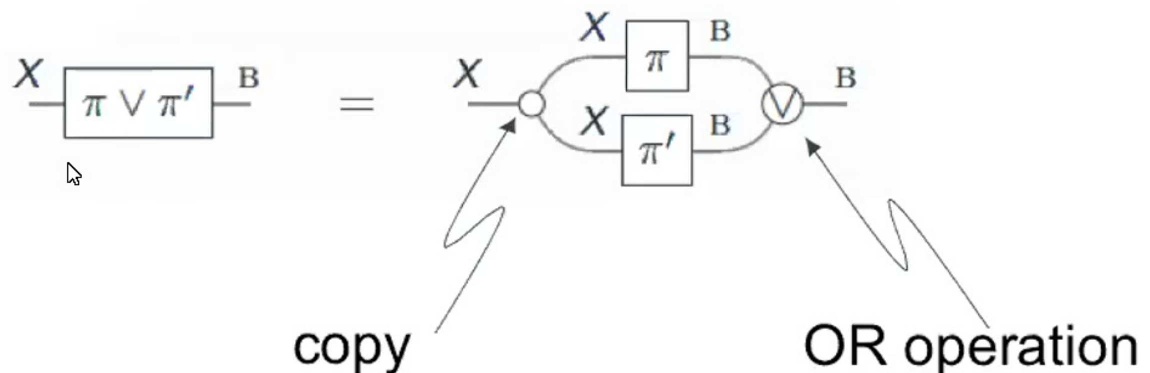
Boolean propositional logic

BOOLE



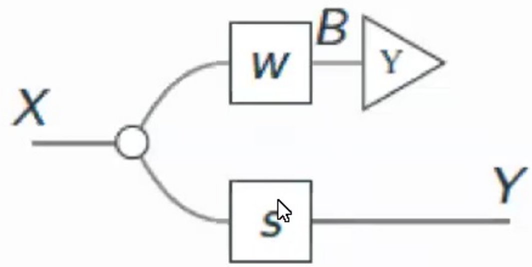
Boolean propositional logic
BOOLE





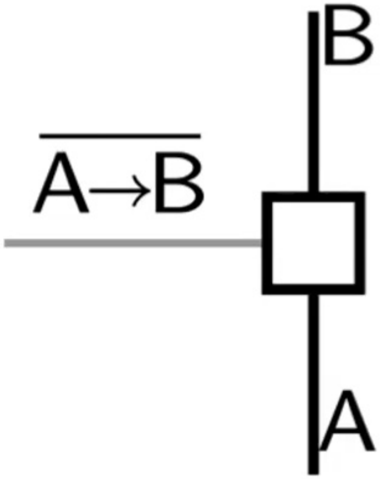
We find that $\textsc{Bayes}, \textsc{Boole} \subseteq \textsc{SubStoch}$

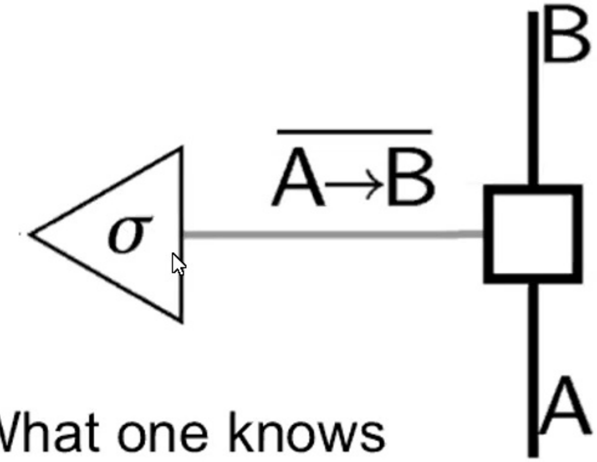
But Any substochastic map can be realised by:



where $s, w \in \textsc{Bayes}$ and $\curlyvee \in \textsc{Boole}$

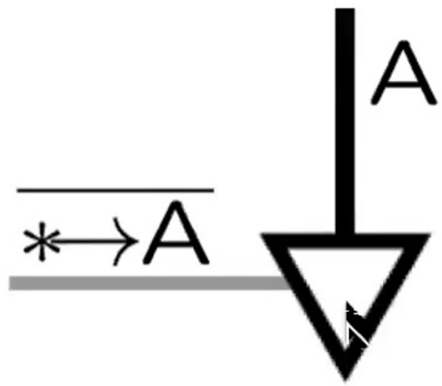
Generator 1:

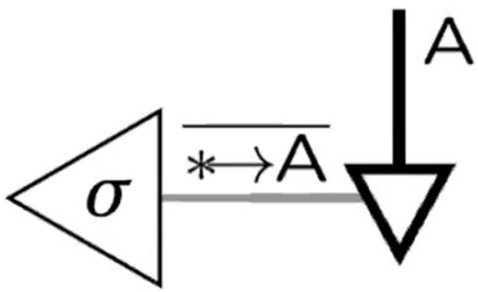




What one knows about the function from A to B.

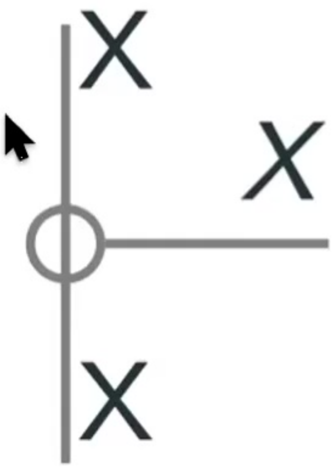
Special case of Generator 1:



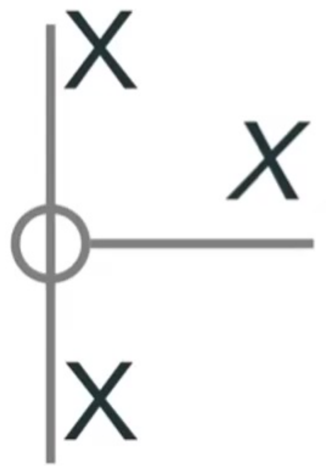


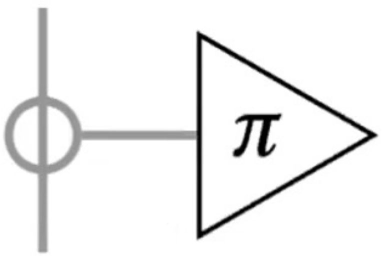
What one knows
about A

Generator 2:



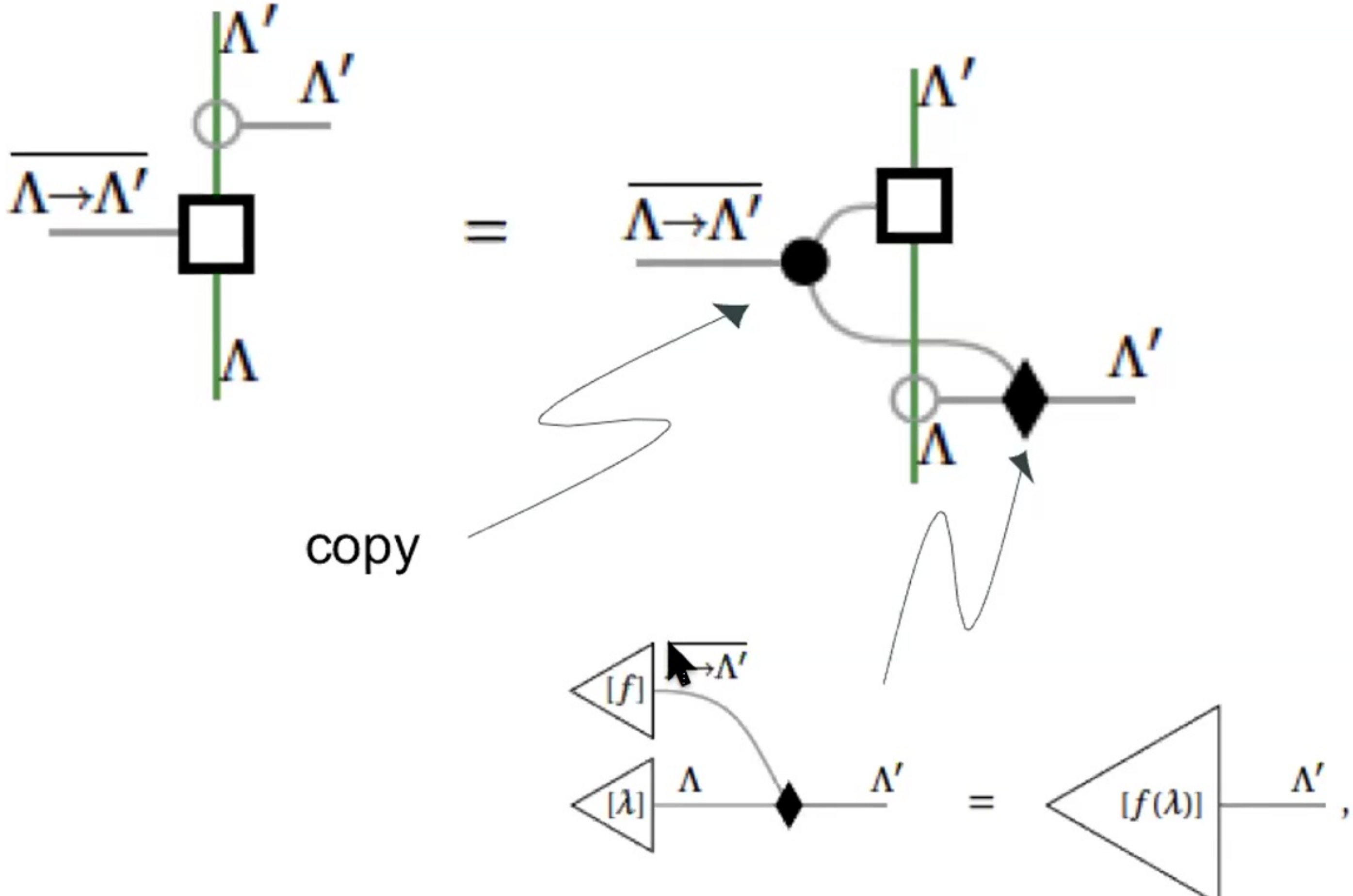
Generator 2:





The proposition concerning X about which one wishes to make predictions

Generator interaction

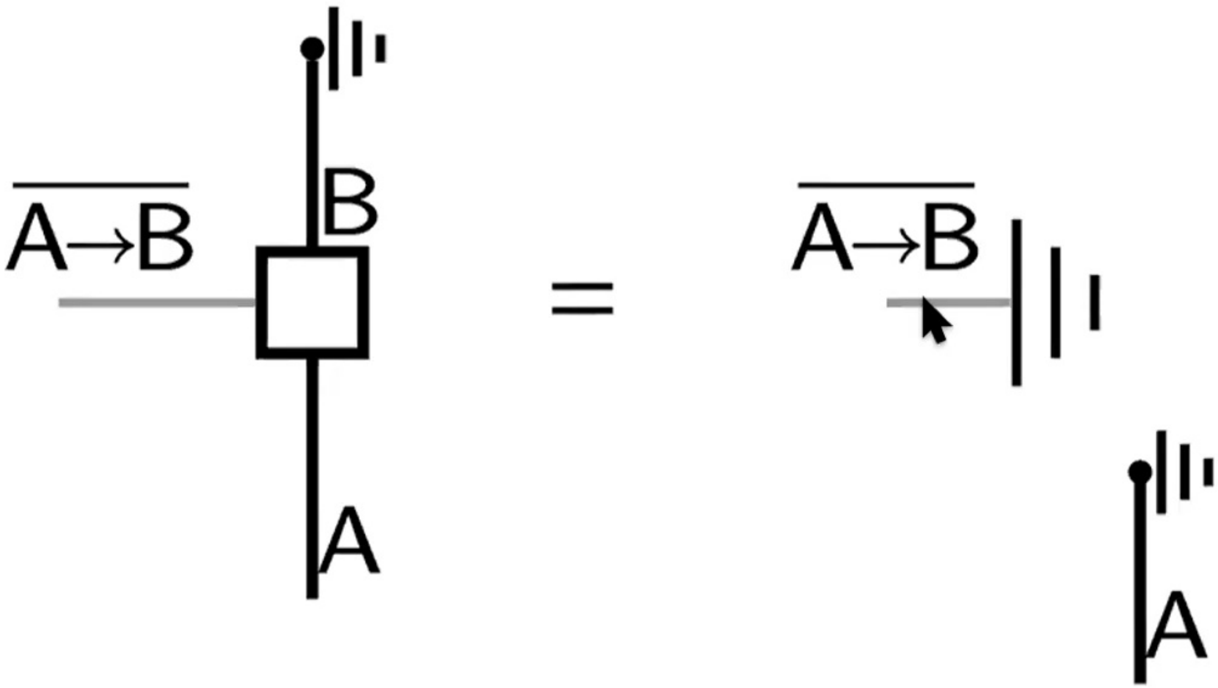


Generator 3:

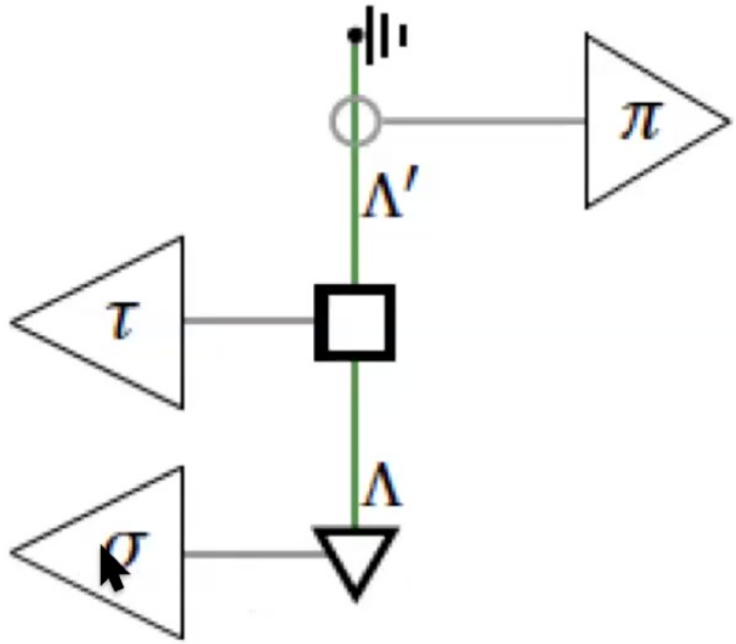
Marginalization over A

No further propositions about A or its causal descendents will be considered

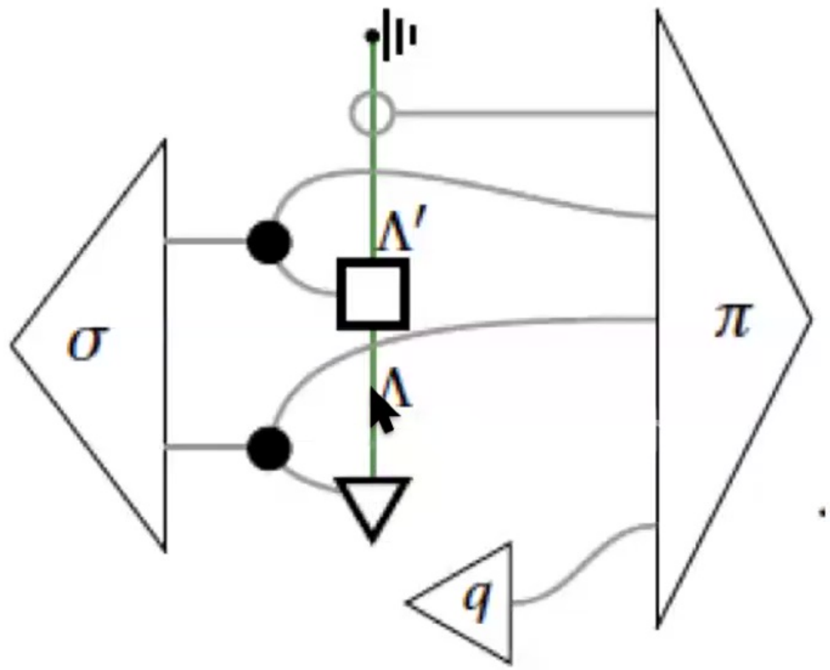
Generator interaction



In the case of no post-selection, there is no correlation between input and function



π
Λ′
τ
Λ
σ

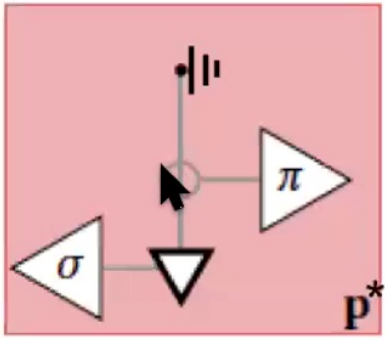


Λ′
σ
π
Λ
q

$$\textsc{Func} \xrightarrow{\mathbf{e}'} \textsc{F-S} \underset{\mathbf{p}^*}{\overset{\mathbf{i}'}{\leftrightarrows}} \textsc{SubStoch}$$

Prediction map

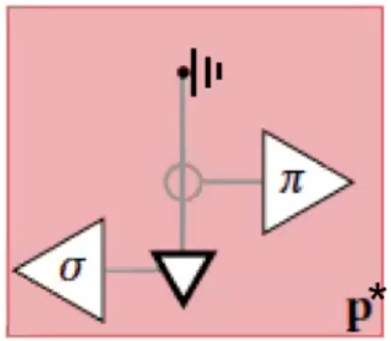
A partial map --- only defined for *causally closed diagrams*



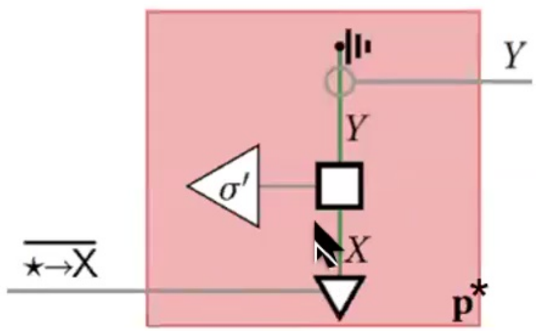
$= \mathrm{Prob}(\pi : \sigma),$

Prediction map

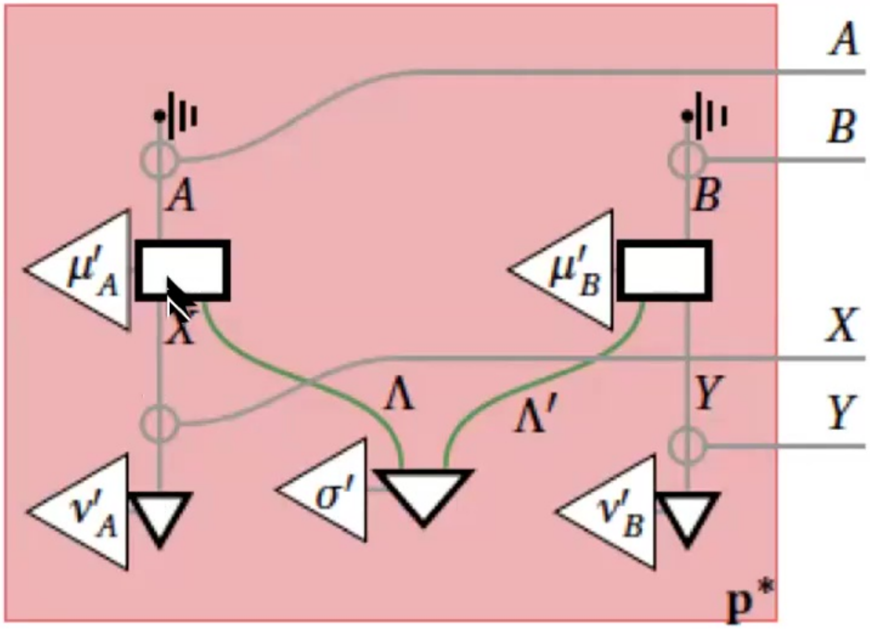
A partial map --- only defined for *causally closed diagrams*



$$= \text{Prob}(\pi : \sigma),$$



$$= P(Y|X)$$



$= P(A,B,X,Y)$

Operational Causal-Inferential Theories

$$\textsc{Proc} \xrightarrow{\ \mathbf{e}\ } \text{P-S} \underset{\mathbf{p}}{\overset{\mathbf{i}}{\leftrightarrows}} \textsc{SubStoch}$$

This framework has natural applications
to the field of classical causal inference

The key dichotomy thus far:

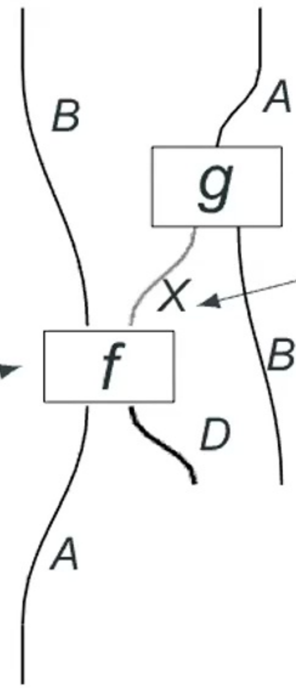
Causal
vs.
Inferential

Operational Causal-Inferential Theories

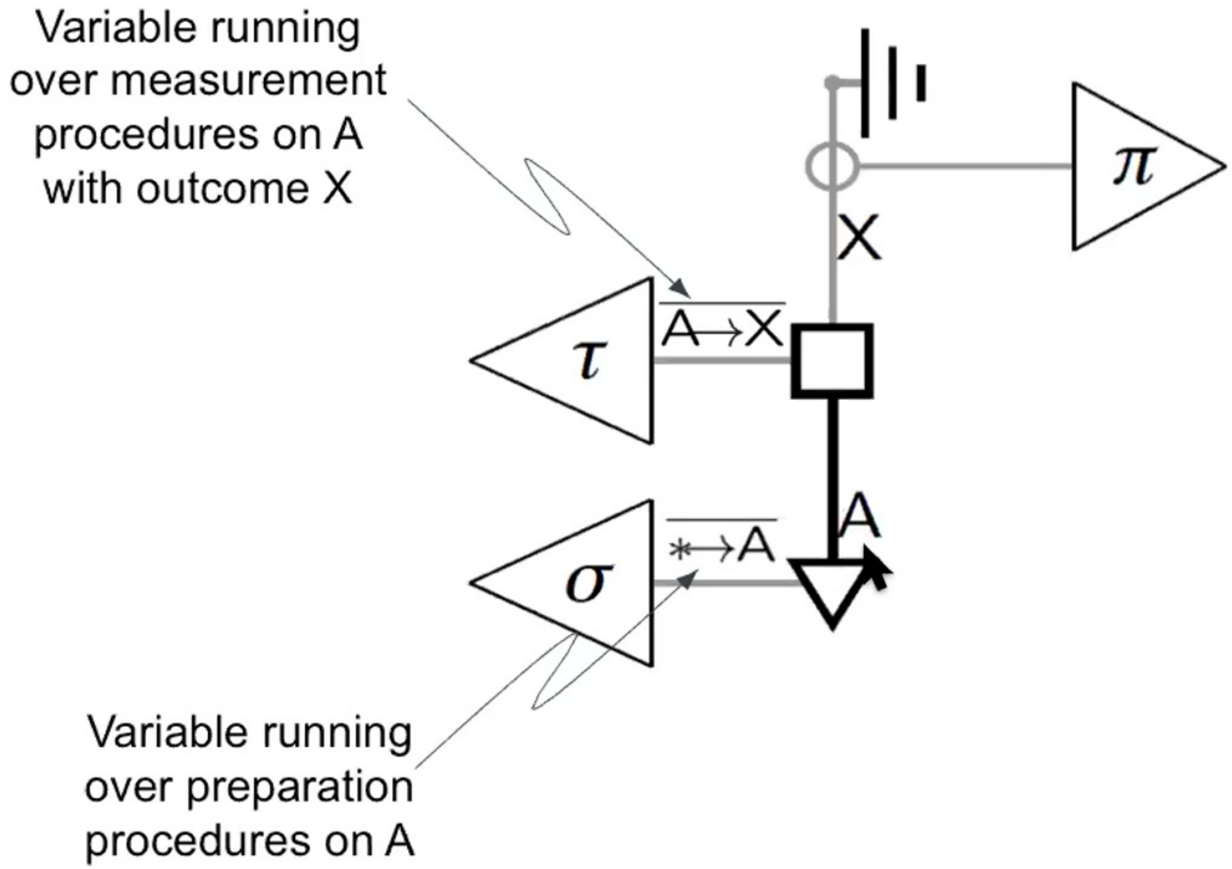
$$\textsc{Proc} \xrightarrow{\mathbf{e}} \text{P-S} \underset{\mathbf{p}}{\overset{\mathbf{i}}{\leftrightarrows}} \textsc{SubStoch}$$

Operational causal theory
PROC

description of laboratory procedure



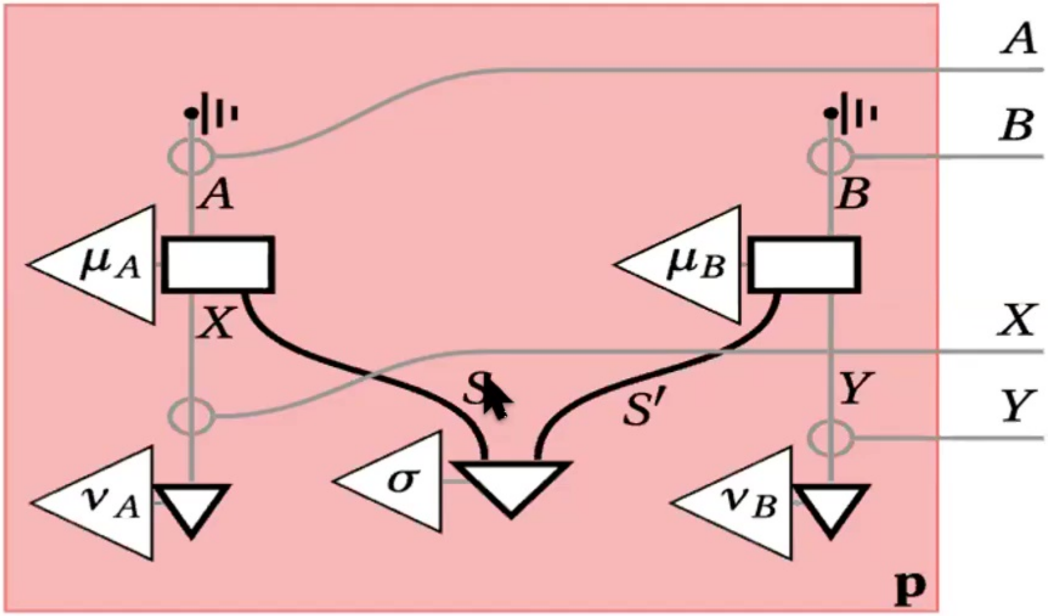
Abstract labels for systems (some of which are classical)


Variable running over measurement procedures on A with outcome X
π
X
τ
A→X
A
σ
*→A
Variable running over preparation procedures on A

Operational Causal-Inferential Theories

$$\textsc{Proc} \xrightarrow{\ \mathbf{e}\ } \text{P-S} \underset{\mathbf{p}}{\overset{\mathbf{i}}{\leftrightarrows}} \textsc{SubStoch}$$

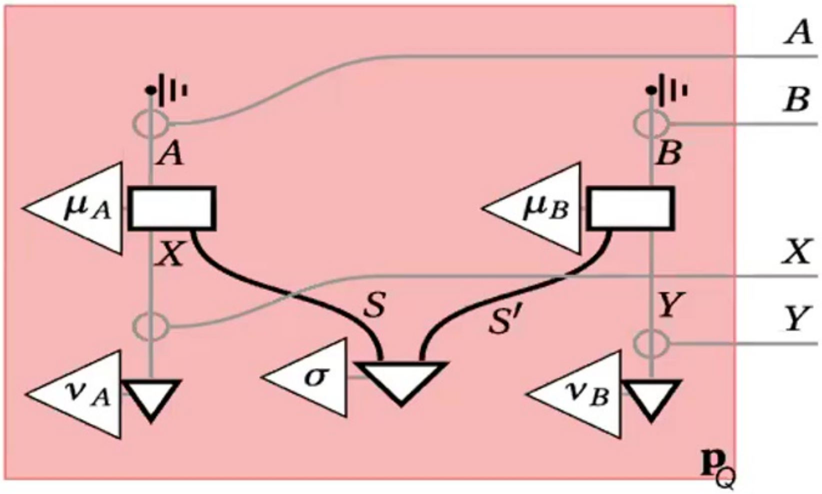
The prediction map



$= P(A,B,X,Y)$

Quantum Operational CI theory

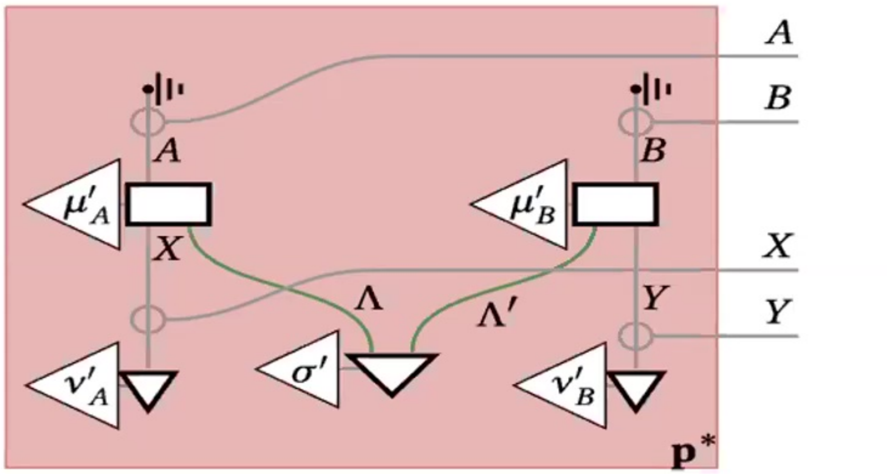
$\text{PROC}_Q \xrightarrow{\mathbf{e}} \text{P}_Q\text{-S} \underset{\mathbf{p}_Q}{\overset{\mathbf{i}}{\rightleftarrows}} \text{SUBSTOCH}$



P(ABXY) is P_Q-S-realizable

Classical realist CI theory

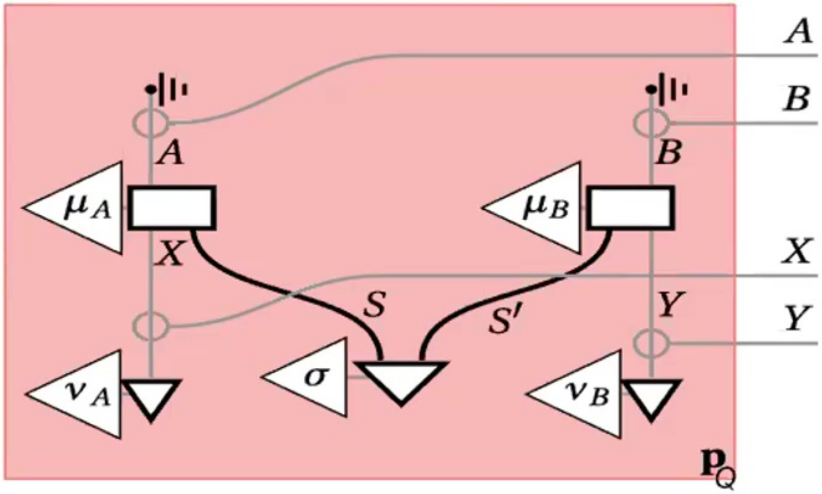
$\text{FUNC} \xrightarrow{\mathbf{e}'} \text{F-S} \underset{\mathbf{p}^*}{\overset{\mathbf{i}'}{\rightleftarrows}} \text{SUBSTOCH}$



P(ABXY) is F-S-realizable

Quantum Operational CI theory

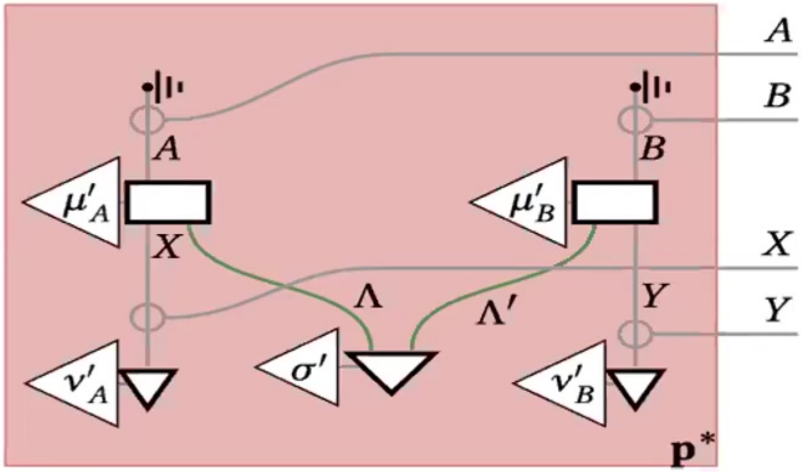
$$\mathrm{PROC}_Q \xrightarrow{\mathbf{e}} \mathrm{P_Q\text{-}S} \underset{\mathbf{p}_Q}{\overset{\mathbf{i}}{\leftrightarrows}} \mathrm{SUBSTOCH}$$



P(ABXY) is P_Q-S-realizable

Classical realist CI theory

$$\mathrm{FUNC} \xrightarrow{\mathbf{e}'} \mathrm{F\text{-}S} \underset{\mathbf{p}^*}{\overset{\mathbf{i}'}{\leftrightarrows}} \mathrm{SUBSTOCH}$$



P(ABXY) is F-S-realizable

Bell's theorem: There are distributions P(ABXY) that are P_Q-S-realizable but not F-S-realizable.

Quantum **operational** causal-inferential theory

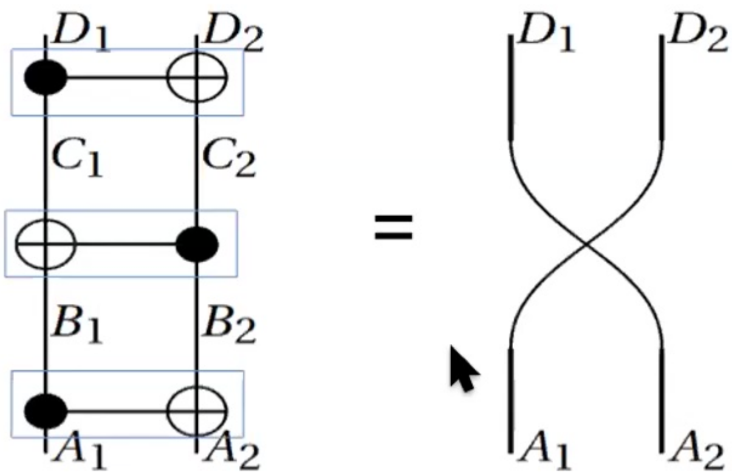
versus

Quantum **realist** causal-inferential theory

How operational CI theories differ from realist CI theories

The causal subtheory PROC has no nontrivial equalities

I.e., nothing like:



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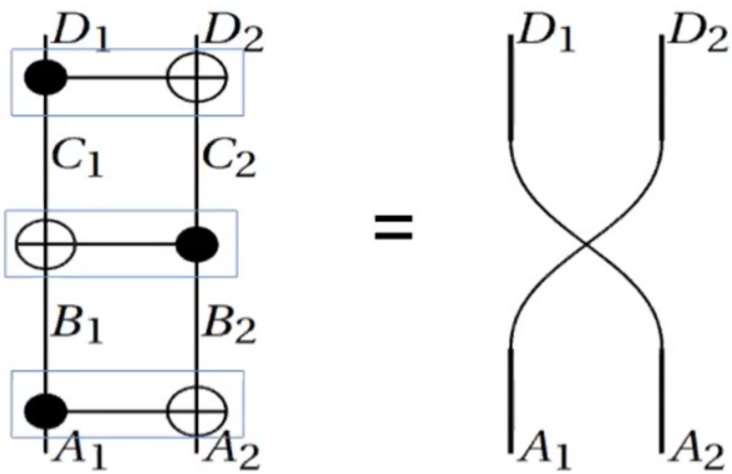

While FUNC specifies **actual** causal relations
PROC specifies **potential** causal relations

How operational CI theories differ from realist CI theories

The causal subtheory PROC has no nontrivial equalities

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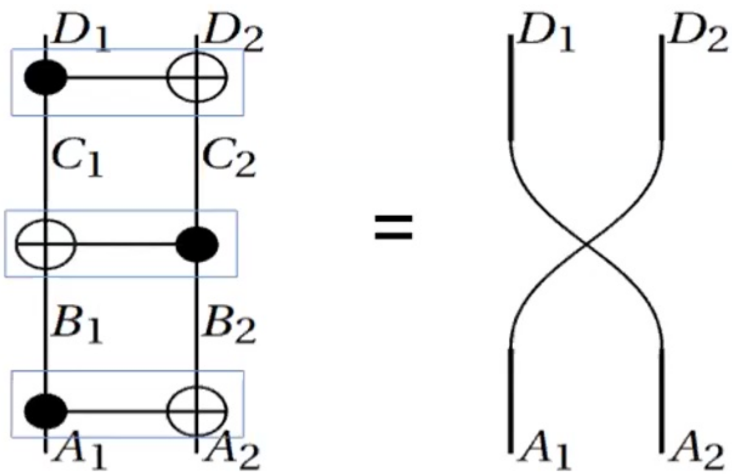
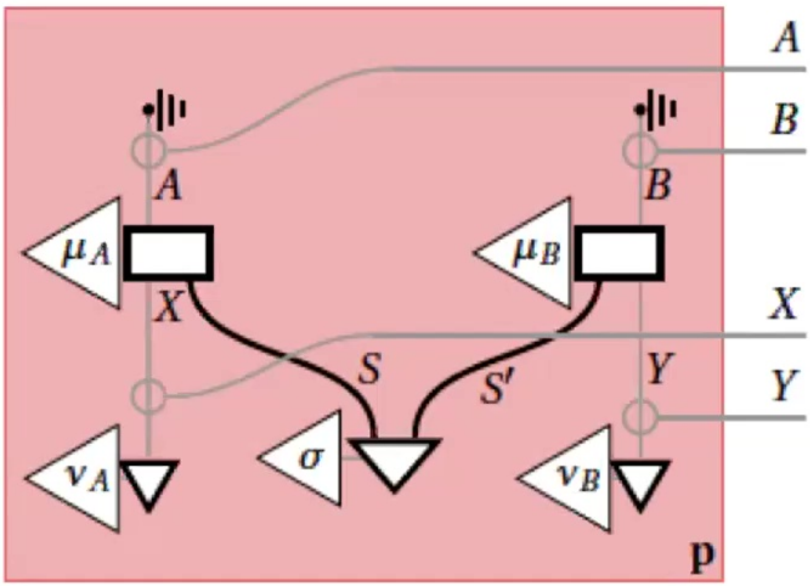


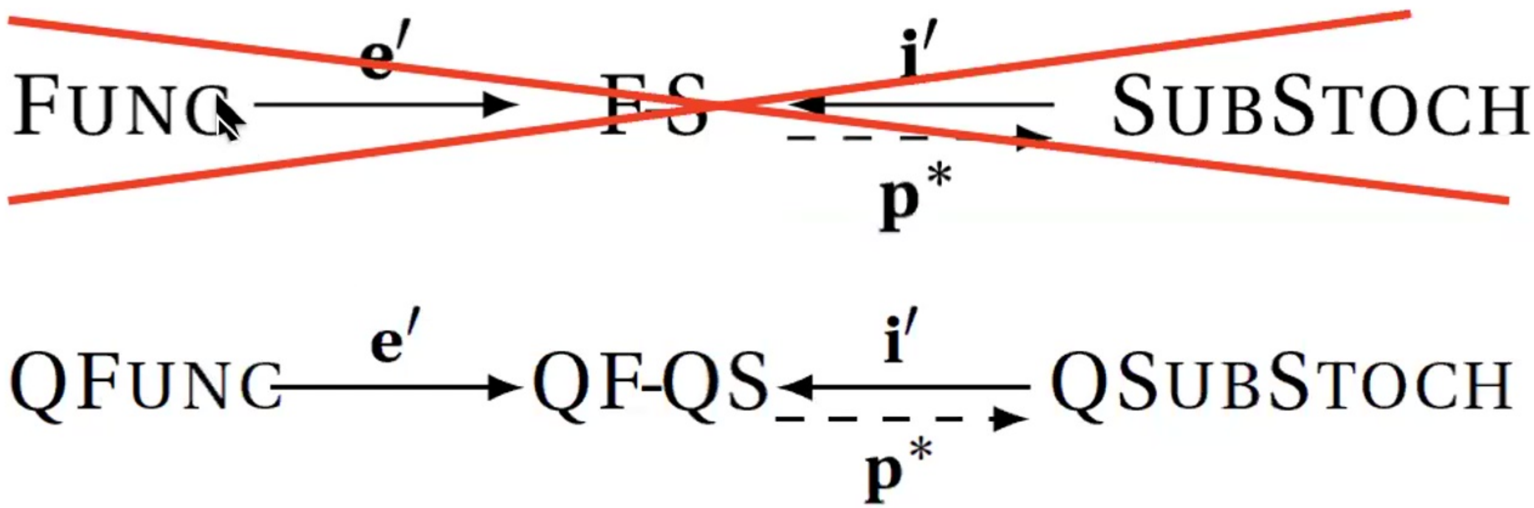
While FUNC specifies **actual** causal relations
PROC specifies **potential** causal relations

How operational CI theories differ from realist CI theories

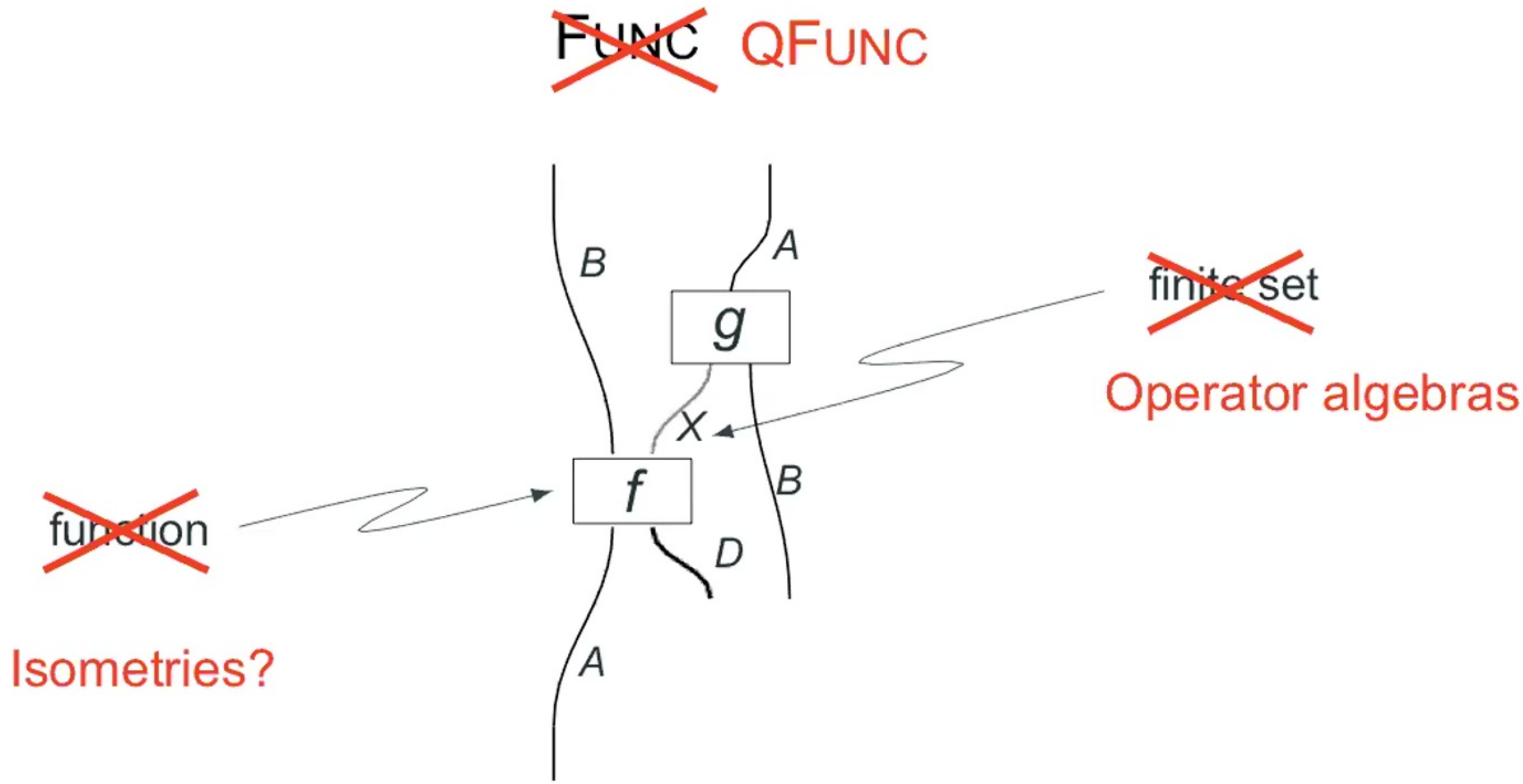
No unique prediction map



The rule for obtaining predictions is not fixed
E.g. Quantum vs. Boxworld

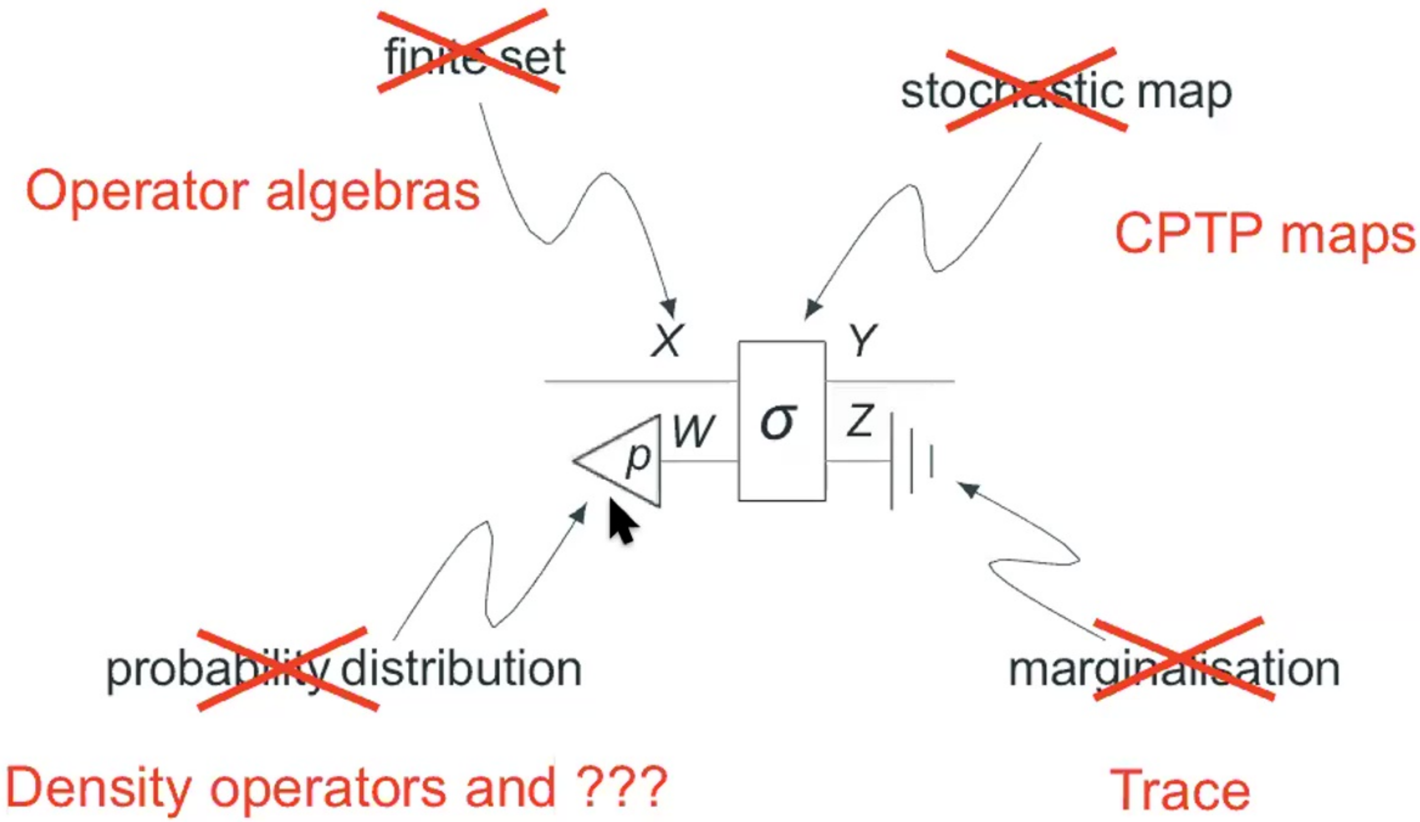

FUNC
e′
FS
i′
SUBSTOCH
p*
QFUNC
e′
QF-QS
i′
QSUBSTOCH
p*

Causal theory



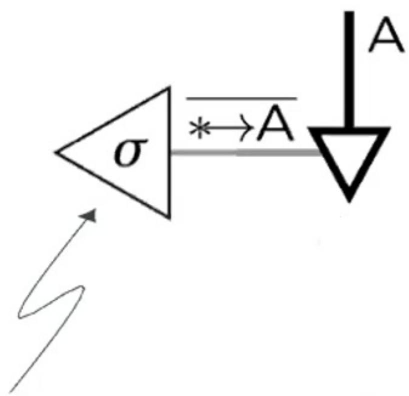
Bayesian probability theory

~~BAYES~~ QBAYES



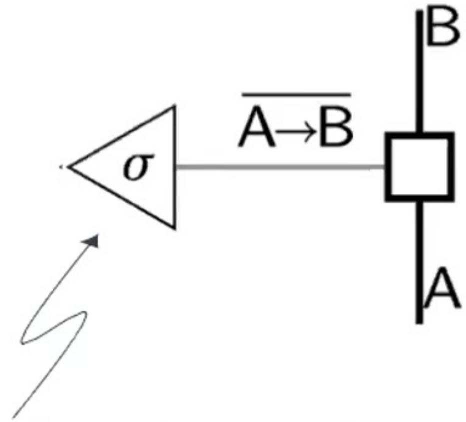
Bayesian probability theory

~~BAYES~~ QBAYES



~~probability distribution Over A~~

Density operator



~~probability distribution over functions from A to B~~

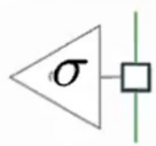
???

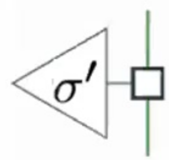
Consider the four functions on the set {0,1}

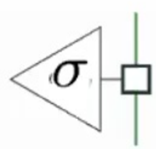
$$f_{\mathrm{id}}, f_{\mathrm{flip}}, f_0, f_1$$

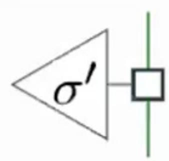
Now, consider two states of knowledge:

$$\sigma = \frac{1}{2}[f_{\mathrm{id}}] + \frac{1}{2}[f_{\mathrm{flip}}] \qquad \sigma' = \frac{1}{2}[f_0] + \frac{1}{2}[f_1]$$

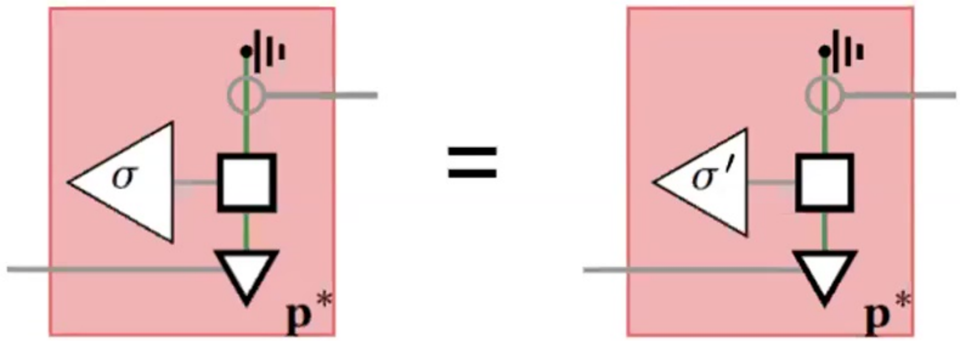


$\neq$


but


$\sim_{\mathbf{p}}$


“inferentially equivalent”



$$\sigma = \tfrac{1}{2}[f_{\mathrm{id}}] + \tfrac{1}{2}[f_{\mathrm{flip}}]$$

$$\sigma' = \tfrac{1}{2}[f_0] + \tfrac{1}{2}[f_1]$$

$$P_{Y|X} = \frac{1}{2}\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} + \frac{1}{2}\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} = \begin{pmatrix} \frac{1}{2} & \frac{1}{2} \\ \frac{1}{2} & \frac{1}{2} \end{pmatrix}$$

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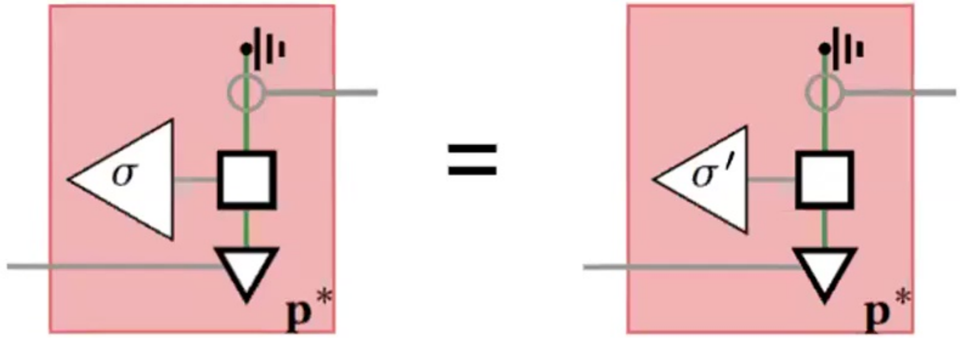

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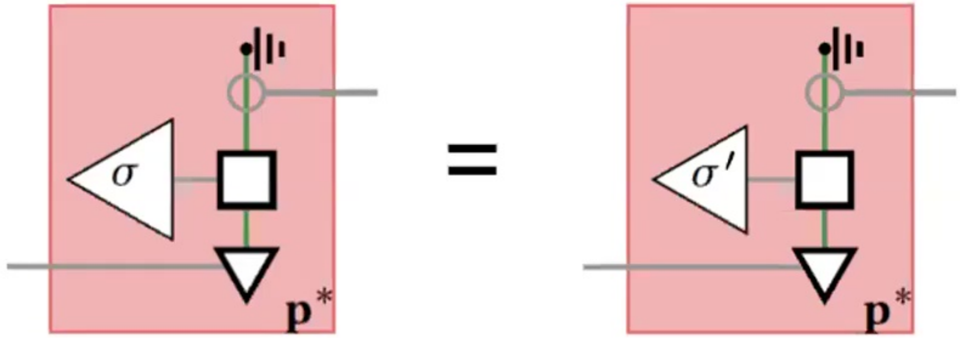
Scrambles causation and inference!



$\sigma = \frac{1}{2}[f_{\text{id}}] + \frac{1}{2}[f_{\text{flip}}]$

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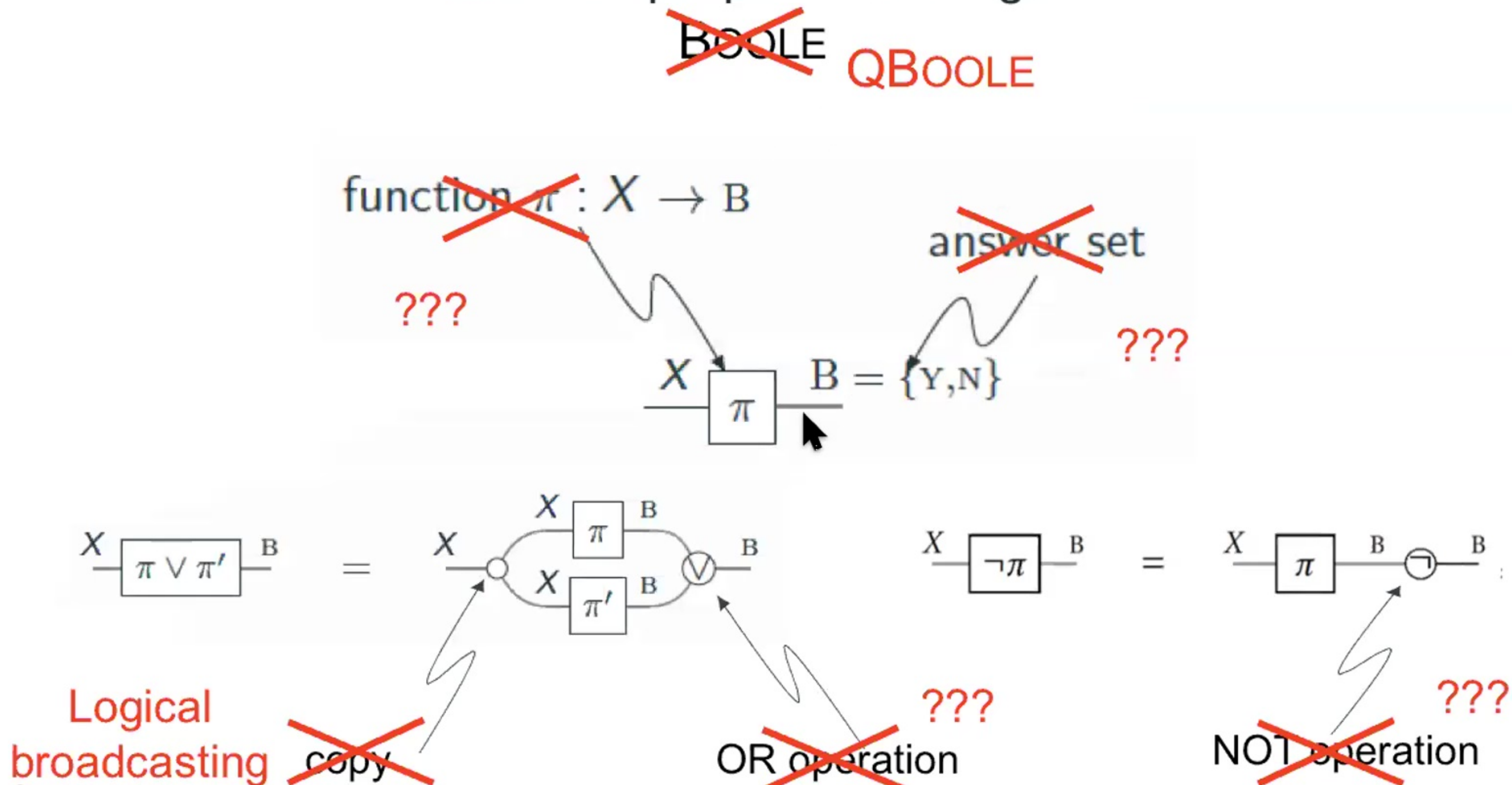
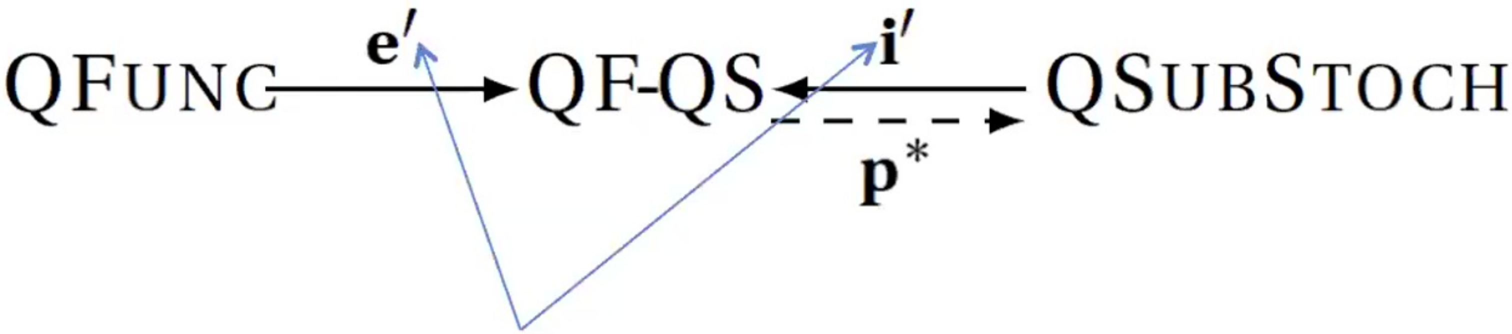
$$P_{Y|X} = \frac{1}{2}\begin{pmatrix} 1 & 1 \\ 0 & 0 \end{pmatrix} + \frac{1}{2}\begin{pmatrix} 0 & 0 \\ 1 & 1 \end{pmatrix} = \begin{pmatrix} \frac{1}{2} & \frac{1}{2} \\ \frac{1}{2} & \frac{1}{2} \end{pmatrix}$$

Scrambles causation and inference!

Boolean propositional logic



The quantum realist causal-inferential theory



Modified to capture an epistemic restriction

The meaning of
causal and inferential
concepts

emerge from

The axioms defining the
causal-inferential theory

What might such a quantum notion of **causation** imply for a quantum notion of **time**?

The meaning of
causal and inferential
concepts

emerge from

The axioms defining the
causal-inferential theory