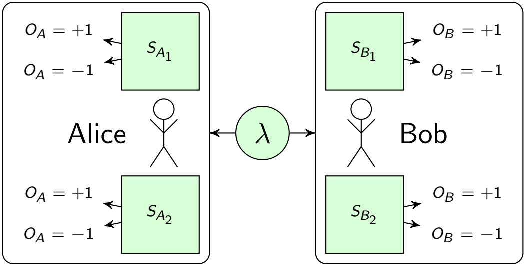
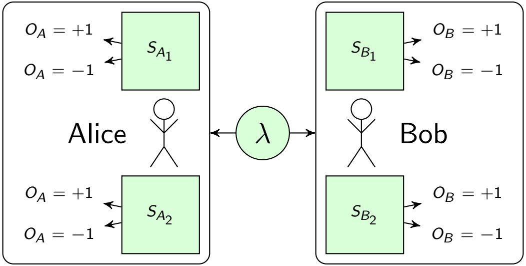
An Operationalist Perspective on Setting Dependence

Utrecht University

Ronnie Hermens

Introduction





Logical structure of Bell's Theorem:

- Local causality $\implies$ Bell inequality
- QM/experiments $\implies$ $\neg$(Bell inequality)

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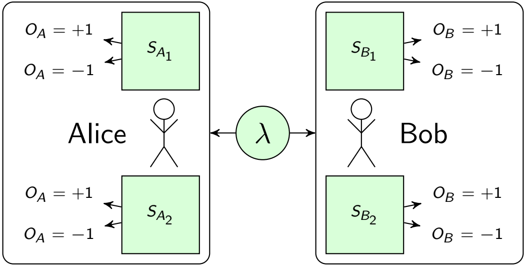

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Common loophole: What if settings depend on λ?

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How to think about setting dependence?

- Superdeterminism: the settings depend on λ.
- Retrocauslity: λ depends on the settings.

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- Superdeterminism: the settings depend on λ.
- Retrocauslity: λ depends on the settings.

More generally:

- What remains of Bell's theorem if we exploit the loophole?
- How can we incorporate setting dependence in a formal framework for possible theories?

Outline

Wood & Spekkens: No Fine-Tuning Theorem

Crash-Course in Causal Networks

Causal Networks

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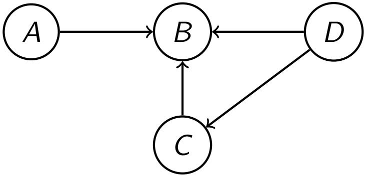

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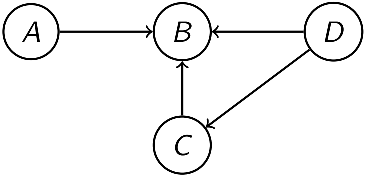

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$$A \perp\!\!\!\perp D,$$

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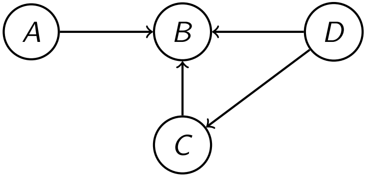

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Joint Distribution

$$P(A, B, C, D) = P(B|A, C, D)P(C|D)P(D)P(A)$$

Causal Discovery Algorithms

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- Input: Conditional Independencies
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- The causal network should be minimal

  Out of two faithful networks, the one with the smallest set of compatible probability distributions is preferred.

Causal Discovery Applied to EPRB (without HV)

For a (non-maximally) entangled state

- Independent settings: $S_A \perp\!\!\!\perp S_B$,
- No-signaling: $S_B \perp\!\!\!\perp O_A | S_A$, $S_A \perp\!\!\!\perp O_B | S_B$,

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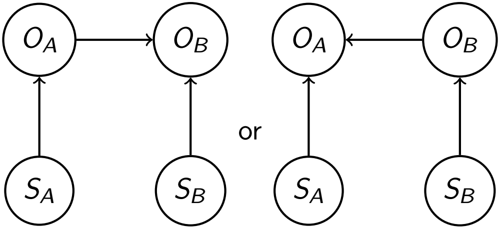

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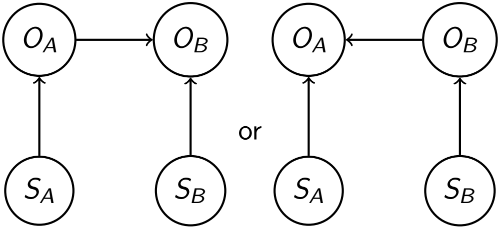

But these are not faithful: signaling is allowed.

$$O_B \not\perp\!\!\!\perp S_A | S_B \text{ or } O_A \not\perp\!\!\!\perp S_B | S_A,$$

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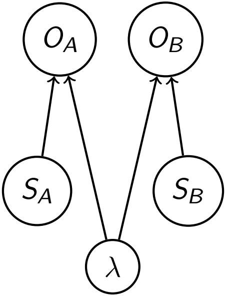

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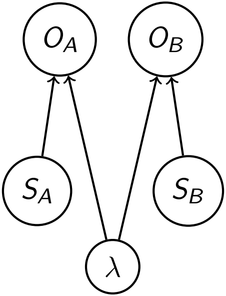
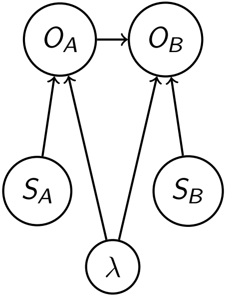


But satisfies Bell locality:

$$O_A \perp\!\!\!\perp O_B S_B | S_A \lambda \text{ and } O_B \perp\!\!\!\perp O_A S_A | S_B \lambda$$

Causal Networks Compatible with QM

Nonlocality



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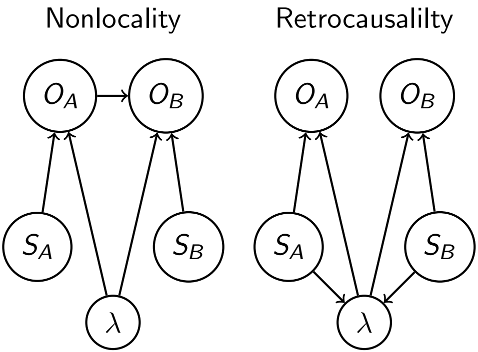

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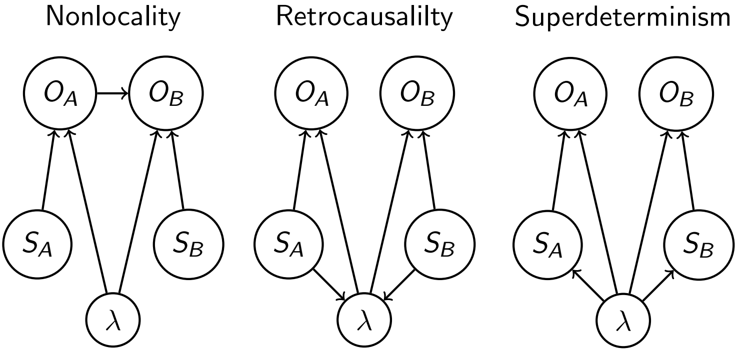

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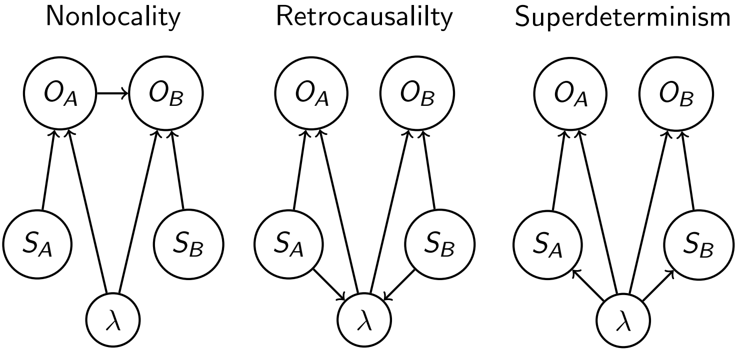

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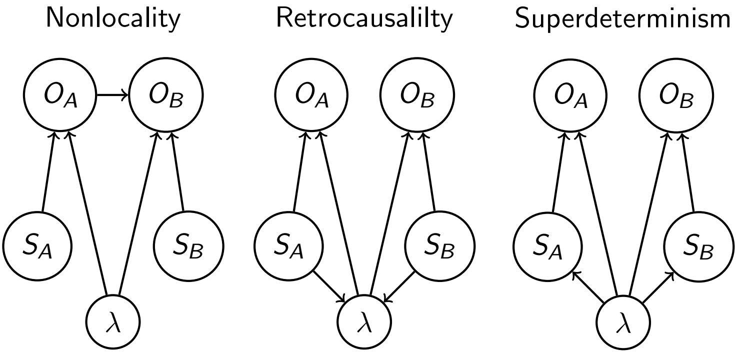
Causal Networks Compatible with QM

Nonlocality | Retrocausalilty | Superdeterminism



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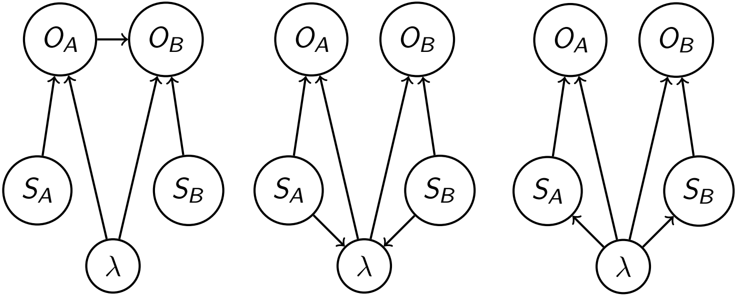

$O_B \not\perp\!\!\!\perp S_A | S_B$ | $O_A \not\perp\!\!\!\perp S_B | S_A$ | $S_A \not\perp\!\!\!\perp S_B$

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Alternative reading:

- Causal networks are inadequate for identifying physically meaningful correlations.
- We can take SD and RC seriously.

Seevinck & Uffink

Motto

Now it is precisely in cleaning up intuitive ideas for mathematics that one is likely to throw out the baby with the bathwater. – J.S. Bell 1990

Settings and Outcomes 1

It is common, like in the work of Wood & Spekkens, to treat settings as random variables. . .

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> *this means that the candidate theory in question would have to specify how probable it is that Alice will choose one setting a_1 rather than a_2, and similarly for Bob and for their joint choices. But that would be a remarkable feat for any physical theory. Even quantum mechanics leaves the question what measurement is going to be performed on a system as one that is decided outside the theory, and does not specify how much more probable one measurement is than another. It thus seems reasonable not to require from the candidate theories that they describe such probabilities.*

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Solution: settings are indices for probability distributions instead of random variables.

Settings and Outcomes 2

Slightly sloppy motivation:

> *if one treats the settings a and b as conditioning arguments in a probability distribution, this implies, at least in Kolmogorovian probability theory, that they are random variables, and thus a probability distribution over their possible values is defined within the model: one cannot write $p(x|y)$ unless $p(y)$ is also defined.*

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- Wood & Spekkens: $P(O_A, O_B, S_A, S_B, \lambda)$,
- Seevinck & Uffink: $P_{S_A,S_B}(O_A, O_B, \lambda)$,
- Ontic models: $P_{S_A,S_B}(O_A, O_B|\lambda)$.

Cleaning up intuitions

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> *There is, however, also a very important difference between settings and outcomes that breaks the symmetry described above. This is a consequence of the fact that, in contradistinction to the outcomes, the settings are supposed to be uncorrelated to the beables λ. [...]*
> *This 'free variables' assumption has the important repercussion that, despite the fact that from a physical point of view outcomes and settings are nothing but beables, they do have a completely different theoretical role to play in the candidate theories in question.*

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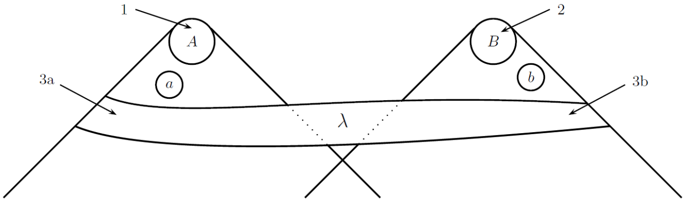
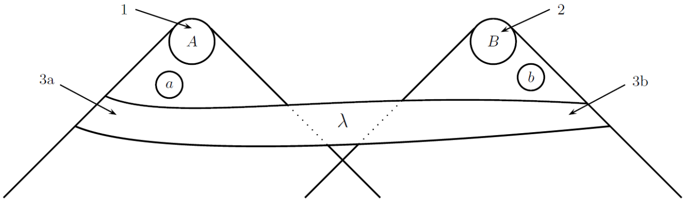
- $P_{S_A,S_B}(O_A, O_B, \lambda)$ instead of $P(O_A, O_B, S_A, S_B, \lambda)$,

as a consequence of **Setting Independence**

- $\rho_{S_A,S_B}(\lambda) = \rho(\lambda)$?

λ: Sufficient and/or Complete?





Bell's Conflicting Assumptions

- *"the resultant values for a and b do not give any information about λ. So the probability distribution over λ does not depend on a or b".*
- *"it is important that events 3 be specified completely."*

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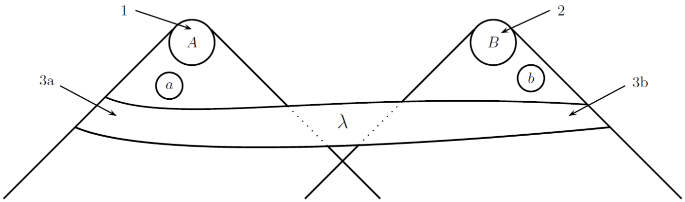
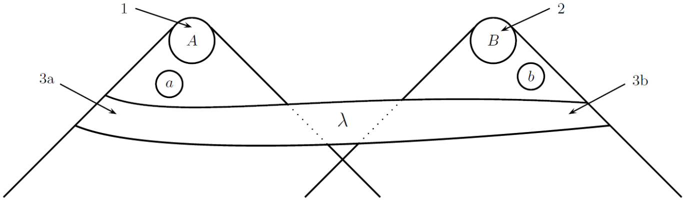


Seevinck & Uffink Solution to Bell's Dilemma

- *"the resultant values for a and b do not give any information about λ. So the probability distribution over λ does not depend on a or b".*
- *"λ should be sufficient for rendering B and b redundant for the task of specifying the probability of outcome A occurring."*



Bell's Dilemma

- *"the resultant values for a and b do not give any information about λ. So the probability distribution over λ does not depend on a or b".*
- *"it is important that events 3 be specified completely."*

This is a false dilemma conflating λ with a probability distribution over λ.

An operationalist approach to setting dependence

User Friendly

- $P_{S_A,S_B}(O_A, O_B, \lambda)$ instead of $P(O_A, O_B, S_A, S_B, \lambda)$, because of $\rho_{S_A,S_B}(\lambda) = \rho(\lambda)$?
- λ is sufficient instead of complete, because of $\rho_{S_A,S_B}(\lambda) = \rho(\lambda)$?

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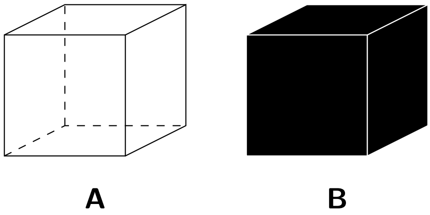
The idea of Setting Independence is entwined in the crucial arguments of Seevinck & Uffink. But the idea that settings and outcomes have a different theoretical role, what this means, and what it implies is quite independent of SI.

$\Longrightarrow$ The theory should be operationally applicable; it should be "user friendly".

Newcomb's Problem



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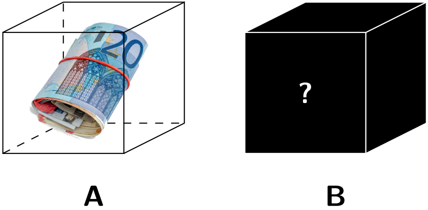

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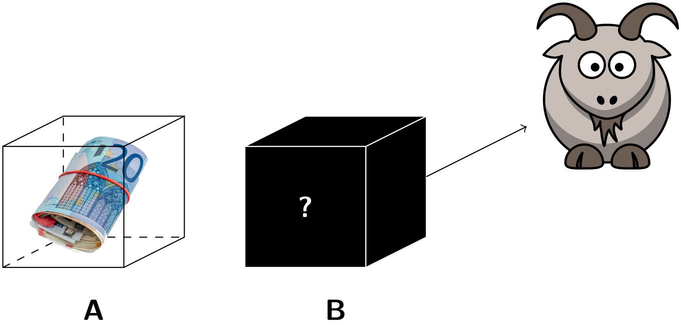

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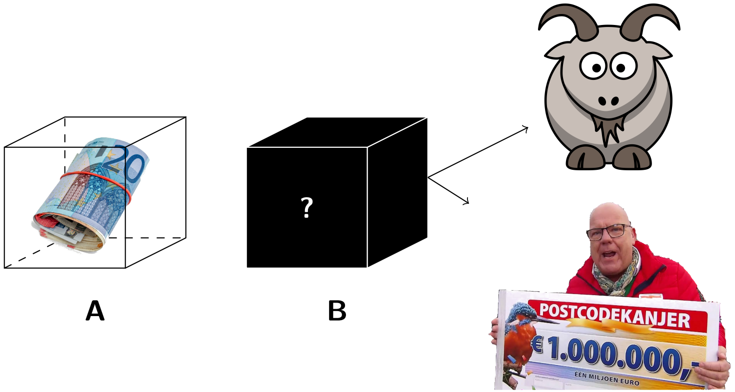

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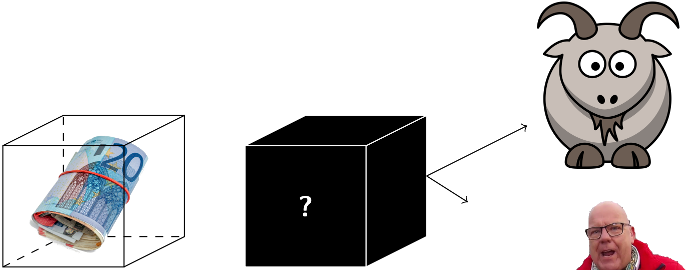

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1. Choose box B, or
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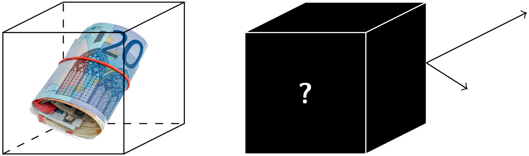

A **B**

1. Choose box B, or
2. Choose both boxes.

- If you choose both boxes, box B contains a goat,
- If you choose only box B, it contains Gaston with a check.

Relaxing Setting Independence 1

- $P_{S_A,S_B}(O_A, O_B|\lambda)$ instead of $P(O_A, O_B, S_A, S_B, \lambda)$

Because we should not demand that the theory defines probabilities over settings.

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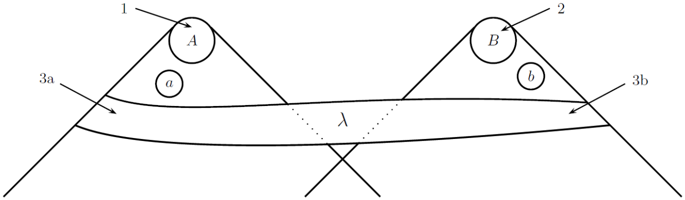

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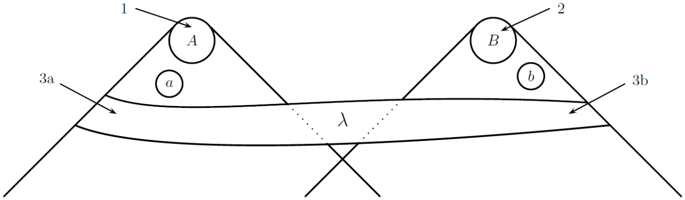

But what if such probabilities are part of the ontology and λ specifies them?
Then $P_{S_A,S_B}(O_A, O_B|\lambda)$ is only meaningful for settings that are possible given λ.

Relaxing Setting Independence 2

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What exactly is the role of $\rho_{S_A,S_B}(\lambda)$?

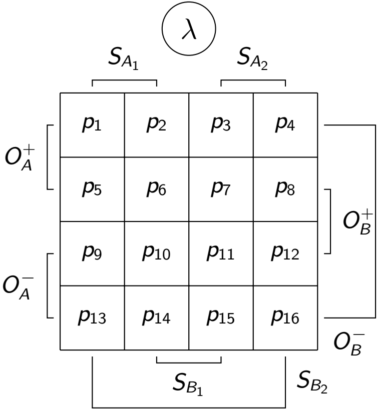
- $\rho_{S_A,S_B}(\lambda)$ bridges the gap between the ontology and the phenomena.
- User-friendliness: the theory should make predictions for all possible settings, $\forall S_A, S_B \; \exists \rho_{S_A,S_B}$ such that

$$\int_{\Lambda_{S_A,S_B}} P_{S_A,S_B}(O_A = A, O_B = B|\lambda)\rho_{S_A,S_B}(\lambda)\,\mathrm{d}\lambda$$

  yields well-defined predictions.

Every λ yields an epistemic state in which these things make sense.

Ontology vs Phenomena



$$\sum_{i=1}^{16} p_i = 1$$

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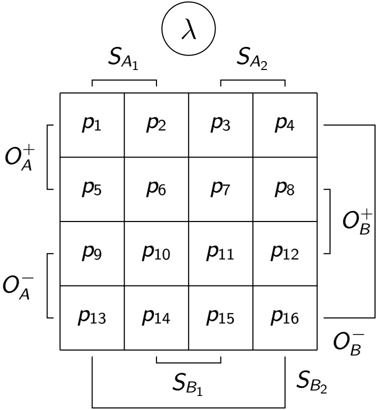

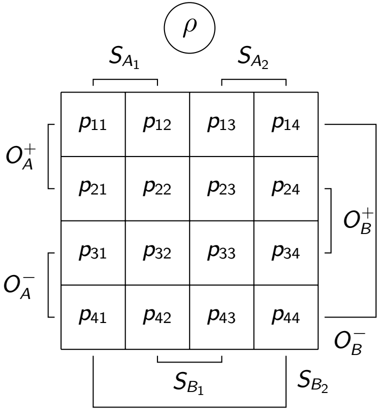

$\sum_{i=1}^{16} p_i = 1$ $\qquad$ $\sum_{i=1}^{4} p_{ij} = 1$

$$p_{23} = \int P(O_A^+, O_B^+ | S_{A_2}, S_{B_1}, \lambda) \rho_{S_{A_2}, S_{B_1}}(\lambda)\, \mathrm{d}\lambda.$$

Bell's Theorem and Setting Dependence

- "User friendliness" implies $\rho \neq \delta_\lambda$.
- Maximal information: $\rho_S(\lambda)$ 0,1-valued.

  "Epistemic Determinism"

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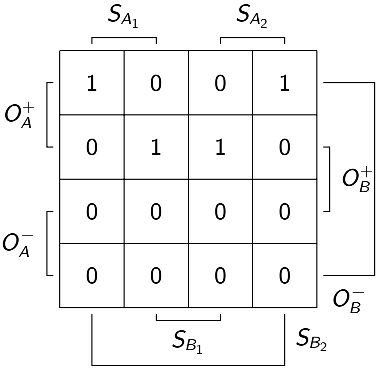
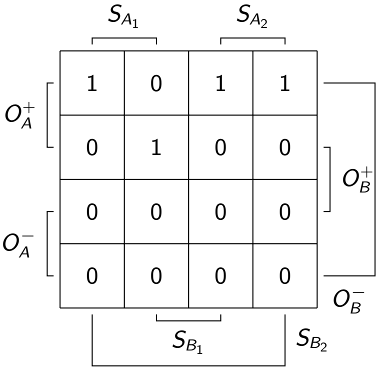
  "Epistemic Determinism"





- "User friendliness" implies $\rho \neq \delta_\lambda$.
- Maximal information: $\rho_S(\lambda)$ 0,1-valued.

  "Epistemic Determinism"

	S_{A_1}		S_{A_2}	
O_A^+	1	0	0	1
	0	1	1	0
O_A^-	0	0	0	0
	0	0	0	0

O_B^+ O_B^- S_{B_1} S_{B_2}

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O_B^+ O_B^- S_{B_1} S_{B_2}

- No-Signaling & Epistemic Determinism $\Longrightarrow$ Bell-inequality

Problems with Setting Dependence

Shimony, Horne and Clauser

In any scientific experiment in which two or more variables are supposed to be randomly selected, one can always conjecture that some factor in the overlap of the backward light cones has controlled the presumably random choices. But, we maintain, skepticism of this sort will essentially dismiss all results of scientific experimentation. Unless we proceed under the assumption that hidden conspiracies of this sort do not occur, we have abandoned in advance the whole enterprise of discovering the laws of nature by experimentation.

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- The way nature behaves should be independent of whether we look at what's going on?

Discovering the Laws by Experimentation

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  $\Lambda_E = \{\lambda_1, \dots, \lambda_N\}$.

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- If λ does not determine joint probabilities, how can we be sure systems always have responses for the actual settings?
- Many mechanisms are possible for selecting settings:
    - Swiss lottery machines,
    - Digits of π,
    - Number of mouse droppings.
- Retro-causal solution: the settings determine the kind of responses λ has. The mechanism is irrelevant.
- New problem: only measurement events have retro-causal power?

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- Given U, all possible outcomes are realized.
- Both the choice $U \in \mathcal{U}$ as well as the actual physical process U' on the system are determined by the the evolution of the universal wave function.

→ Why do U and U' match?

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- Novel argument against Setting Dependence?
- The model is useless?
- Motivation for Copenhagen-esque philosophy?


END