



LUDWIG-
MAXIMILIANS-
UNIVERSITÄT
MÜNCHEN

Chair of Metaphysics

What Goes into a Causal Model of EPR Experiments?

Mario Hubert

<https://www.mario-hubert.com>

Model Choice Workshop
Center for Advanced Studies
24 March, 2026



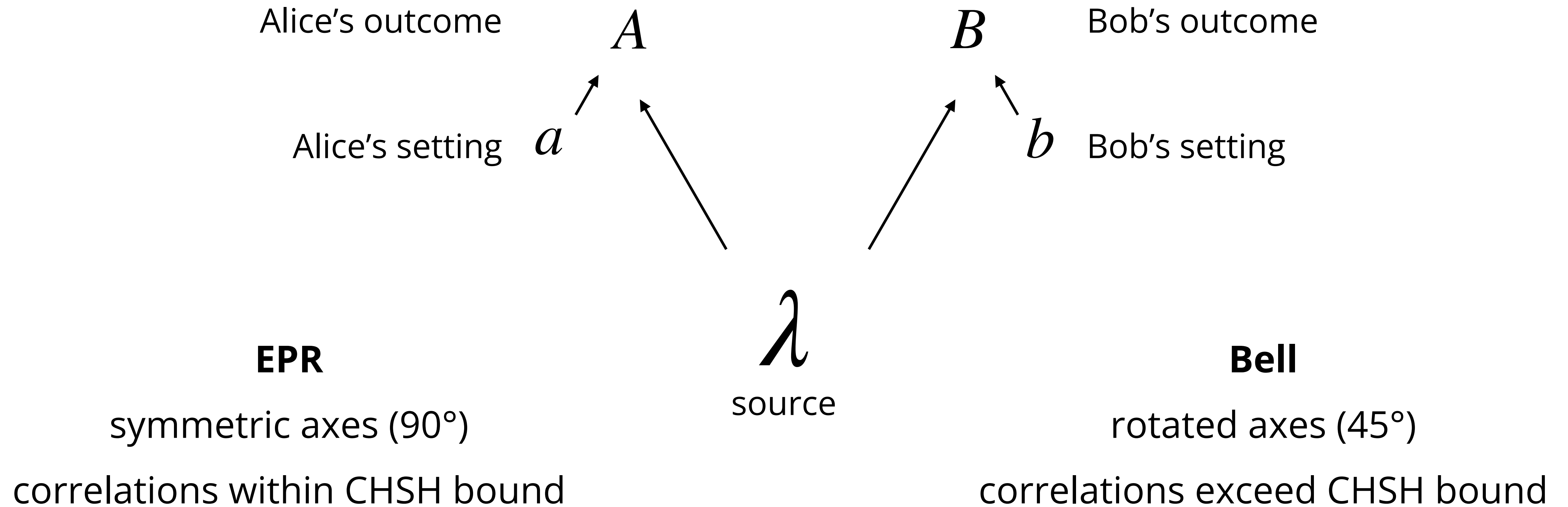
Two entangled particles are measured far apart
and show correlated outcomes.

What is the causal story behind these correlations?

Causal explanations:

1. We want to know how the correlations are generated.
2. What the underlying causal structure of the world is.
3. Ways of intervention.

The Set Up: Measurement of Entangled Particles



a small physical change produces a different statistical situation

Both experiments share the **same independence relations**:

$a \perp b$ (settings are independent)

$A \perp b | a$ (no signaling left to right)

$B \perp a | b$ (no signaling right to left)

Causal discovery algorithms work by reading off independence relations.

*Since EPR and Bell have identical independence relations,
the algorithms return the same causal structure for both (Wood & Spekkens 2015).*

The Missing Ingredient To Distinguish EPR from Bell

The difference between EPR and Bell relies on specific conditional probabilities
given **particular angles**.

This is what Bell inequalities measure.

Any adequate causal model must incorporate not just the independence
structure but the **quantitative constraints** on correlations.

How to Select a Model?

Bell's inequalities and their violations give us a **hypothesis space** of possible causal models by violating the assumptions that go into the derivation (Näger 2016).

This is all pre-theoretical.

Subset of the Hypothesis Space

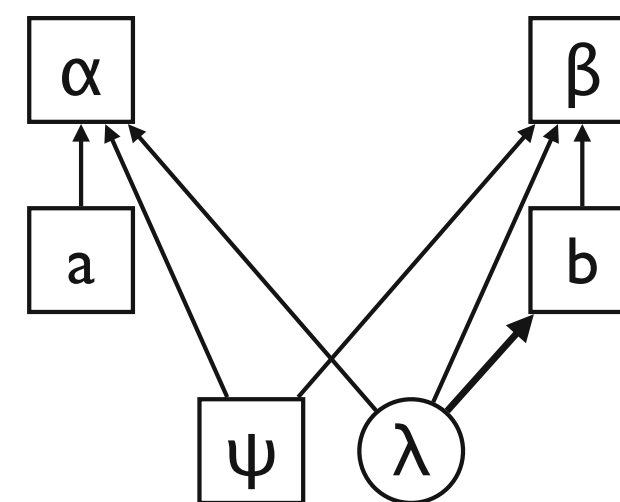
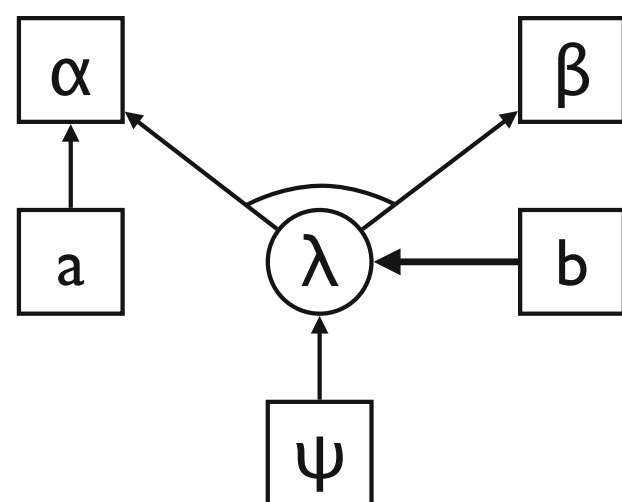
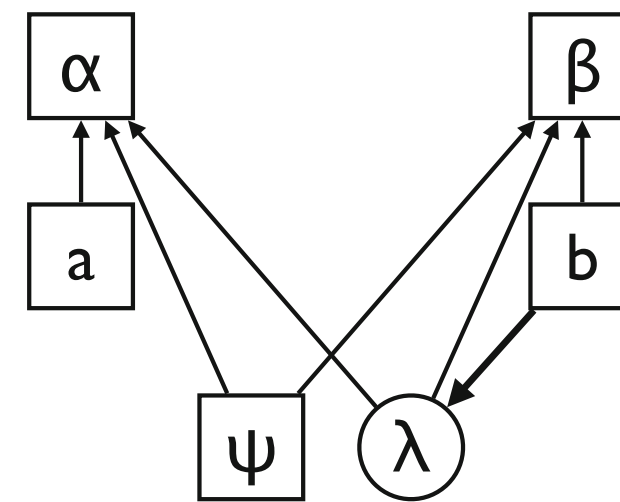
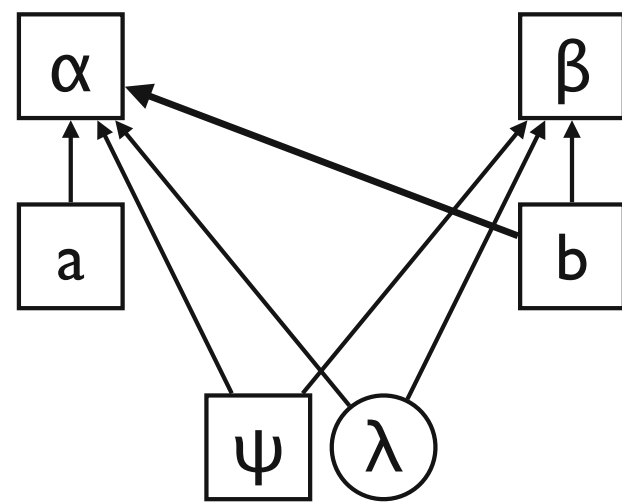
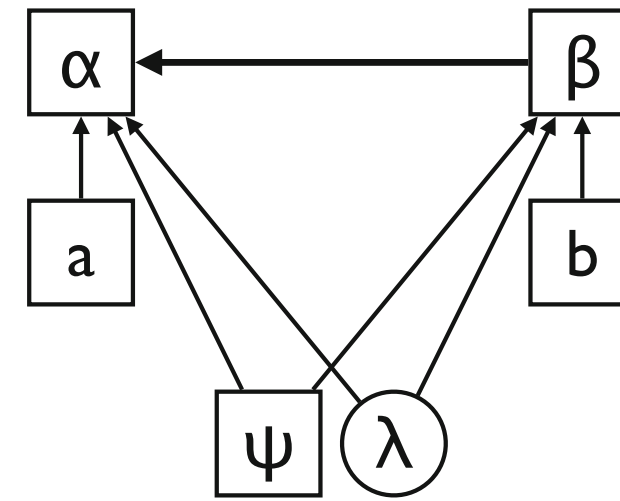
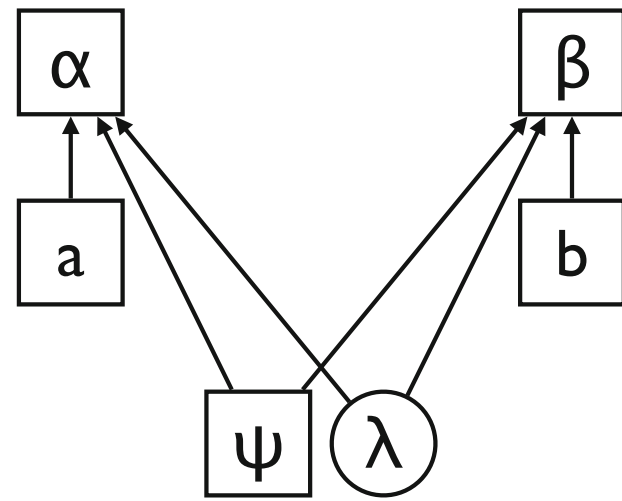
1138

Synthese (2016) 193:1127–1155

Notation:

$A = \alpha$

$B = \beta$



Näger (2016)

What a Model Needs Before Probabilities

- **The causal structure** (which variables influence which)
- **The (physical) independence constraints** (what must be screened off)
- **The quantitative Bell constraints** (not just independence but correlation strength)
- Possibly: **the no fine-tuning principle** (structural independences should be robust)

Getting the causal structure right is a precondition for any meaningful probabilistic model.

How to choose from the hypothesis space?

1. Theory or informed choice of model
 - Determines interpretation of probabilities
2. Theory of causation:
 - a. To specify causal arrows
 - b. Possibly many models for the same theory

Non-Local Causation

Joint work with Frederick Eberhardt (Caltech)

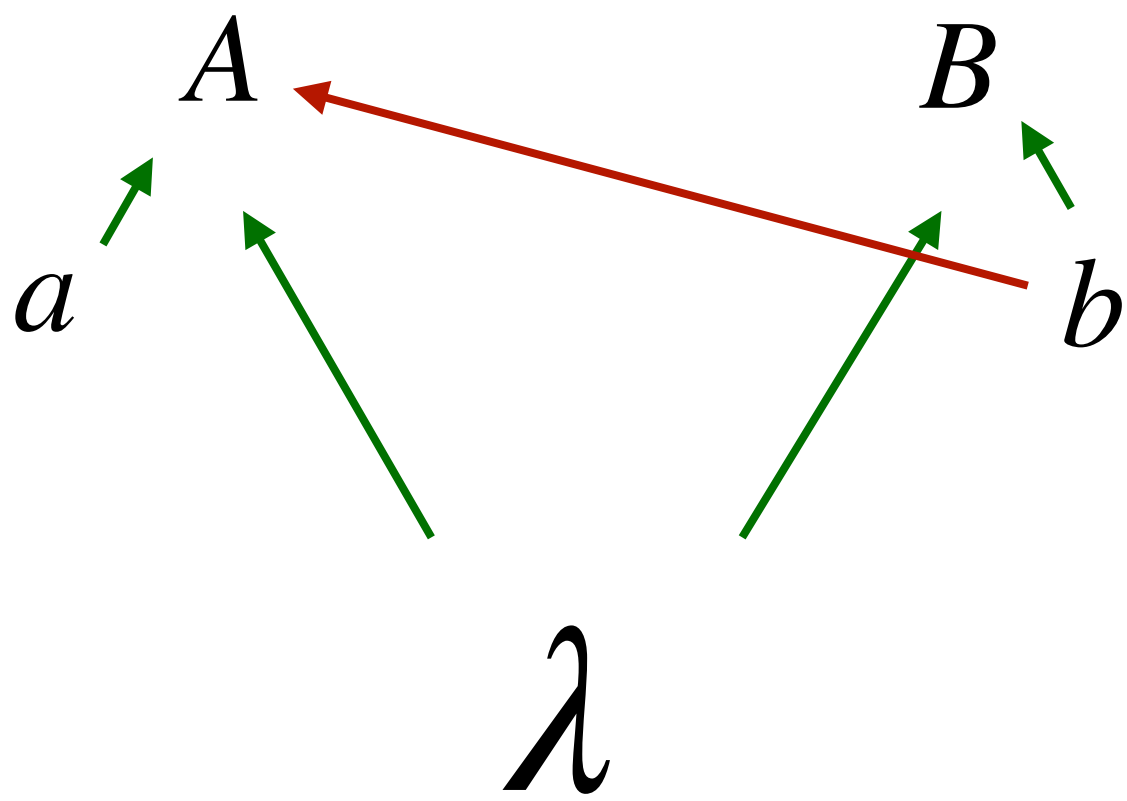
Theory: de Broglie-Bohm

Causation: Counterfactual Theory

Some causal arrows may be also justified with other causal theories

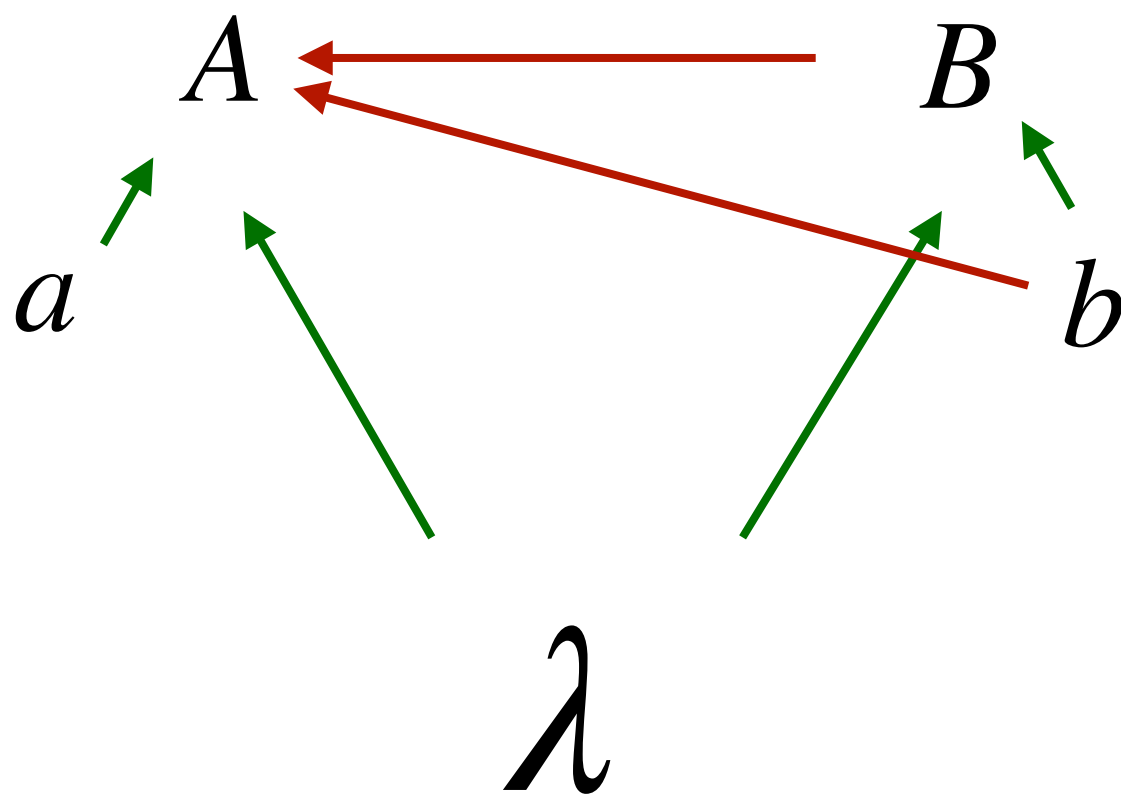
Three Candidate Non-Local Structures:

B measured first, $\lambda = \{\psi, Q_A, Q_B\}$



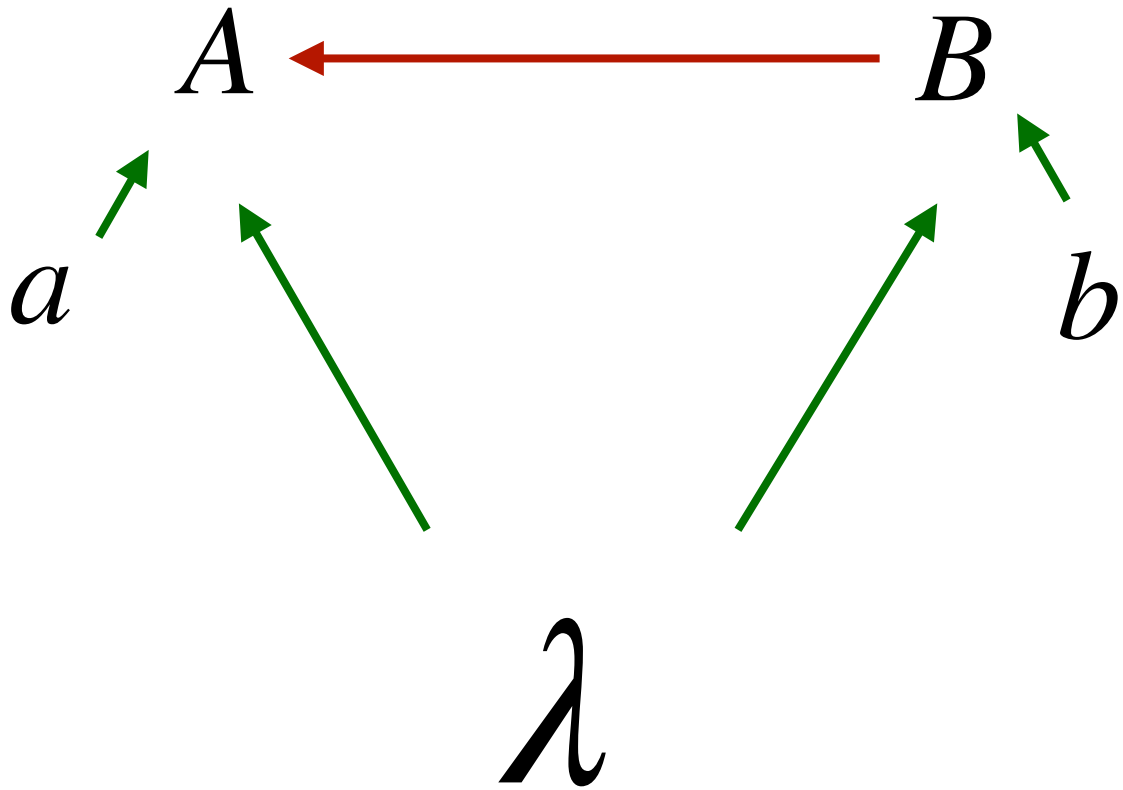
Problem:

$b \rightarrow A$ triggered by measurement



Problem:

$b \rightarrow A$ not a difference maker



Problem:

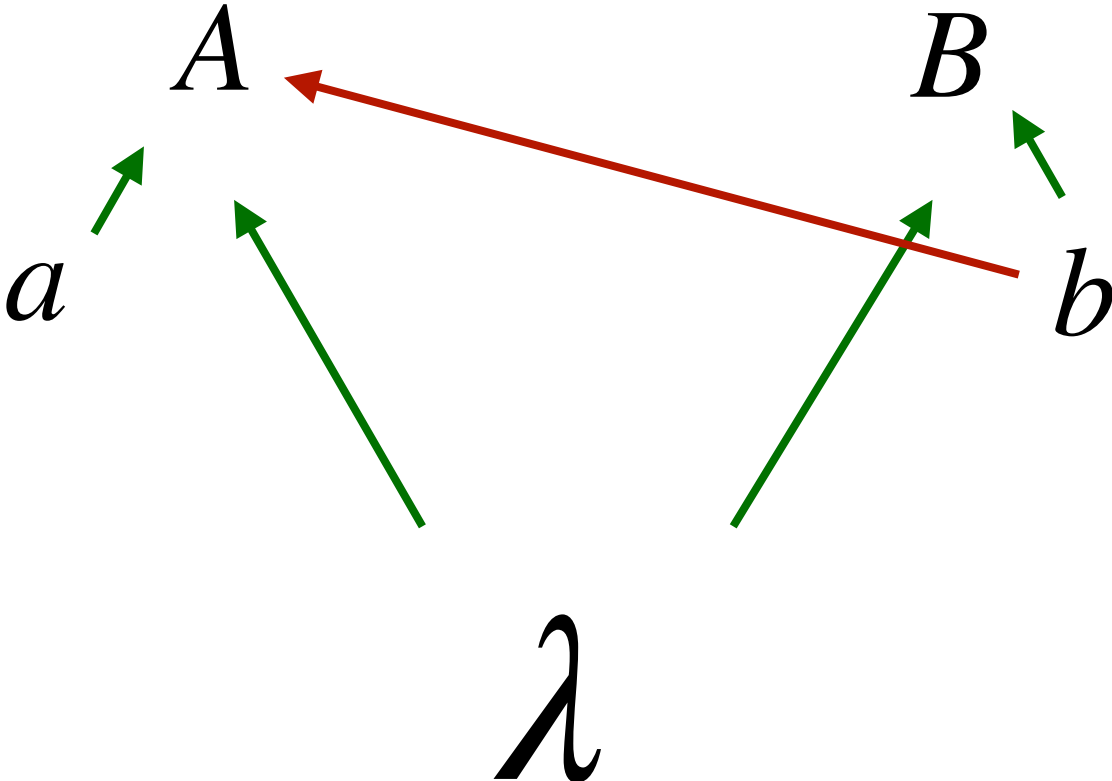
What is the right state space?

We work on this.

Red arrows are fine-tuned. Even though fine-tuned, they need to support counterfactuals.

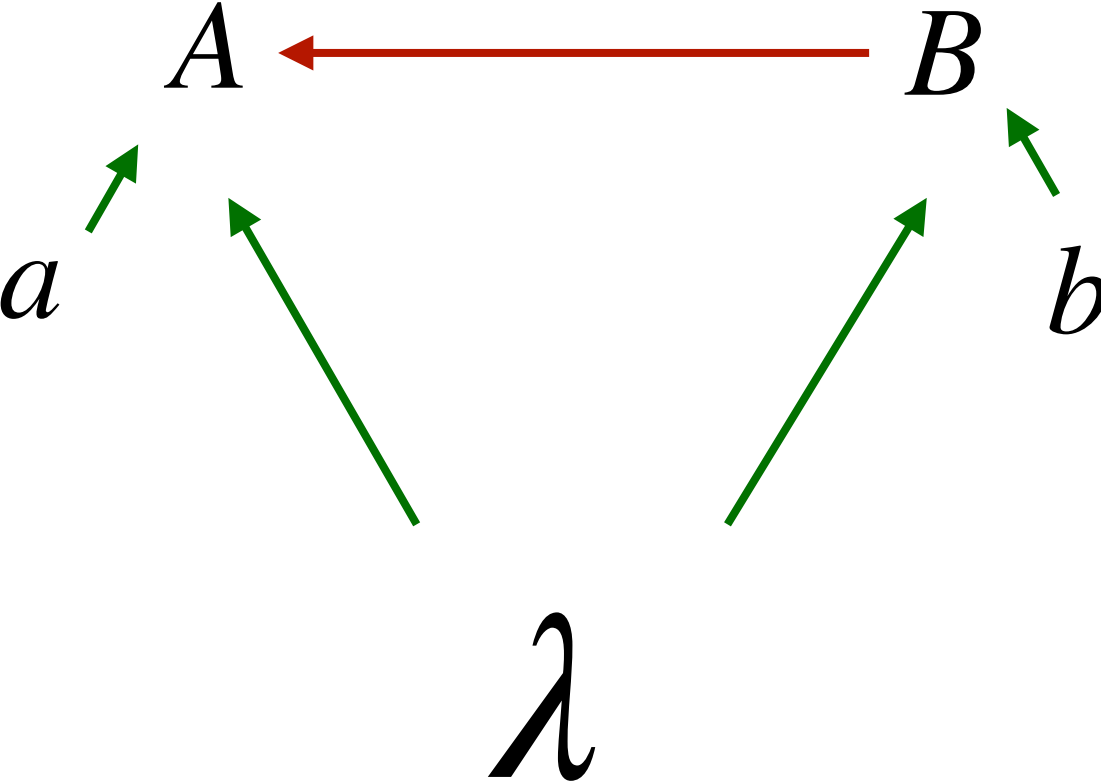
The Deeper Issue – Justifying the Arrows (Adequacy Criteria):

B measured first, $\lambda = \{\psi, Q_A, Q_B\}$



Functional dependencies:

The model is adequate if it correctly encodes which variables depend on which (here: particles and wave-function).



A causal model should represent the **physical processes** by which causal influence is transmitted. Getting the functional dependencies right is necessary but not sufficient. You also need to get the process right, including what triggers the influence, what mediates it, and in what order things happen.

Conclusion



1. You can't get an appropriate causal model for EPR correlations by applying the causal discovery algorithm to the correlations.
2. Violations of Bell's inequalities provide a hypothesis space for possible causal models.
3. Selecting a causal model of the hypothesis space requires choice of physical theory and causal theory. And even then the model may be underdetermined (causal adequacy criteria).

References

Hubert, M. and Eberhardt, F. (2026). Direct Causal Links in EPR-Experiments. Manuscript.

Näger, P. M. (2016). The causal problem of entanglement. *Synthese*, 193(4):1127–55.

Wood, C. J. and Spekkens, R. W. (2015). The lesson of causal discovery algorithms for quantum correlations: Causal explanations of Bell-inequality violations require fine-tuning. *New Journal of Physics*, 17. Adlam, E. (2022). Laws of nature as constraints. *Foundations of Physics*, 52(1):28.