Title: Relating Wigner's Friend Scenarios to Nonclassical Causal Compatibility, Monogamy Relations, and Fine Tuning

Speakers: YÃ¬lÃ¨Â YÄ«ng

Series: Quantum Foundations

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Abstract: Nonclassical causal modeling was developed in order to explain violations of Bell inequalities while adhering to relativistic causal structure and faithfulness -- that is, avoiding fine-tuned causal explanations. Recently, a no-go theorem stronger than Bell's theorem has been derived, based on extensions of Wigner's friend thought experiment: the Local Friendliness (LF) no-go theorem. Here we show that the LF no-go theorem poses formidable challenges for the field of causal modeling, even when nonclassical and/or cyclic causal explanations are considered. We first recast the LF inequalities, one of the key elements of the LF no-go theorem, as special cases of monogamy relations stemming from a statistical marginal problem; we then further recast LF inequalities as causal compatibility inequalities stemming from a nonclassical causal marginal problem, for a causal structure implied by well-motivated causal-metaphysical assumptions. We find that the LF inequalities emerge from the causal modeling perspective even when allowing the latent causes of observed events to admit post-quantum descriptions, such as Generalised Probabilistic Theories (GPT) or even more exotic theories. We further prove that no nonclassical causal model can explain violations of LF inequalities without violating the No Fine-Tuning principle. Finally, we note that these obstacles cannot be overcome even if one were to appeal to cyclic causal models.

Zoom link

Nonclassical causal models and Wigner's Friend experiments

Yìlè Yīng

with Marina Maciel Ansanelli, Andrea Di Biagio, Elie Wolfe, Eric Gama Cavalcanti

arXiv:2309.12987

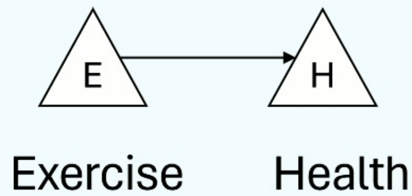
Classical causal models and Bell experiments

Explain correlations through causation

Classical Causal Models

Causal structure:

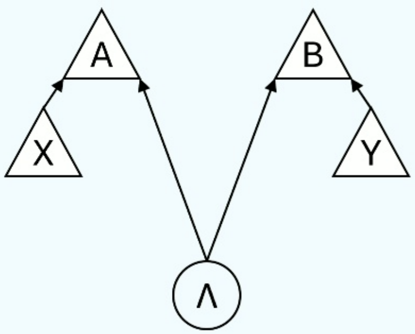
- Directed Acyclic Graph (DAG)
  - Nodes: random variables
  - Arrows: cause-effect relations

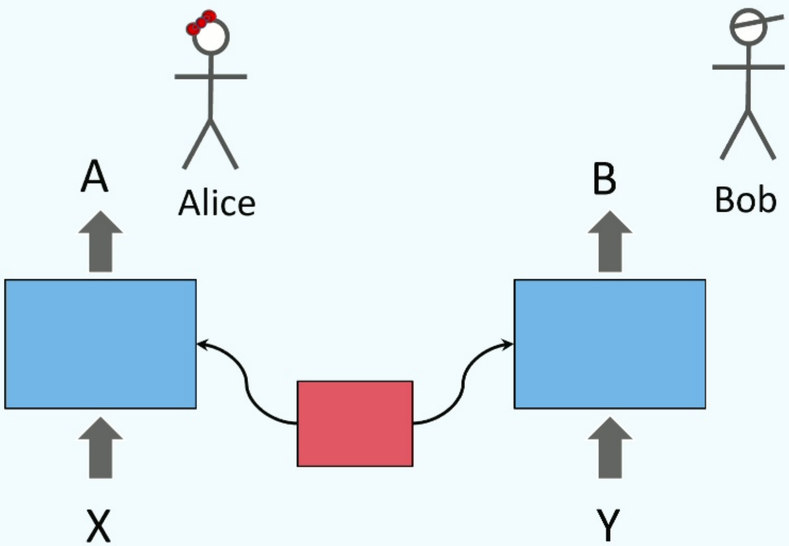


Classical causal models and Bell experiments

Causal structure:

- Directed Acyclic Graph (DAG)

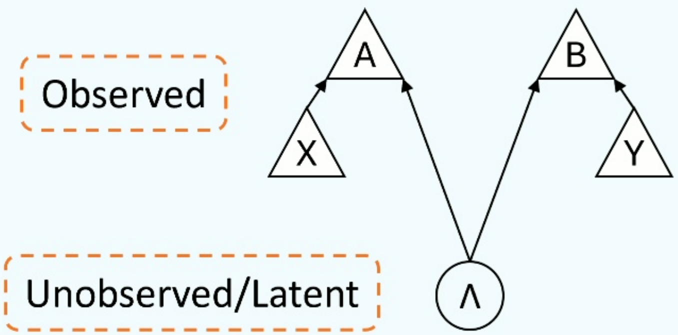


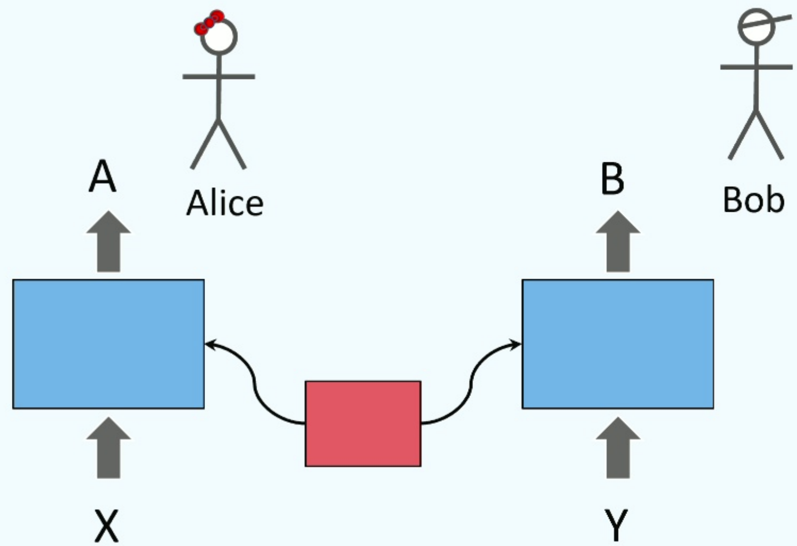


Classical causal models and Bell experiments

Causal structure:

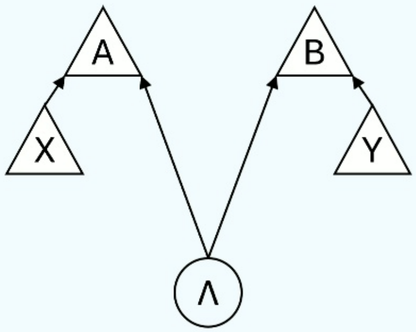
- Directed Acyclic Graph (DAG)





Classical Causal Models

Causal structure:



$\Rightarrow$

Compatible probabilities

- The d-separation rule:

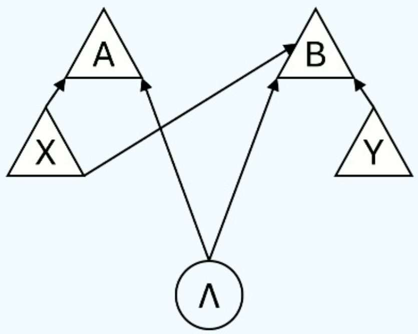
d-separation relation of the graph $\Rightarrow$ (conditional) independence in any compatible P

$$\Lambda \perp_d XY \qquad P(\Lambda XY) = P(\Lambda)P(XY)$$

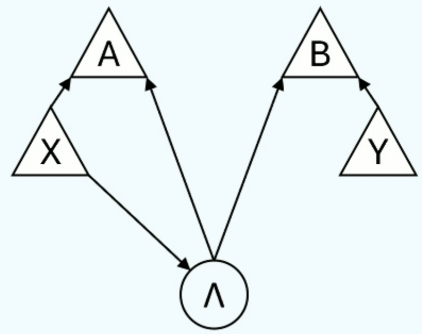
$$AX \perp_d BY|\Lambda \qquad P(AXBY|\Lambda) = P(AX|\Lambda)P(BY|\Lambda)$$

Bell inequalities on P(AB|XY)

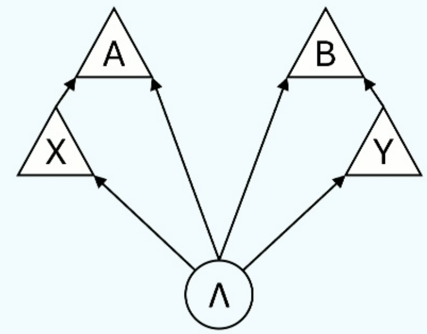
Problems with classical causal explanations



Superluminality

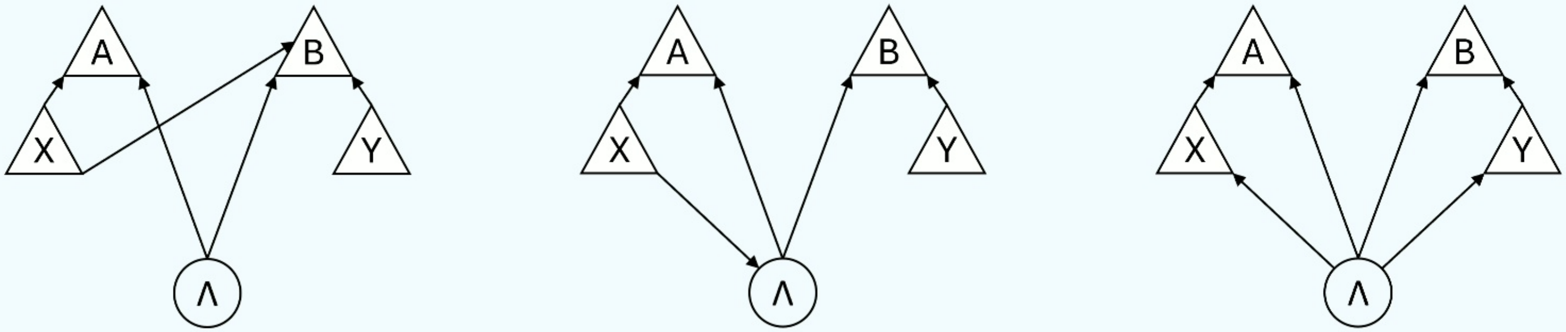


Retrocausality



Superdeterminism

Problems with classical causal explanations



Need **fine-tuning** to explain no-superluminal-signaling

$$P(A|XY) = P(A|X)$$

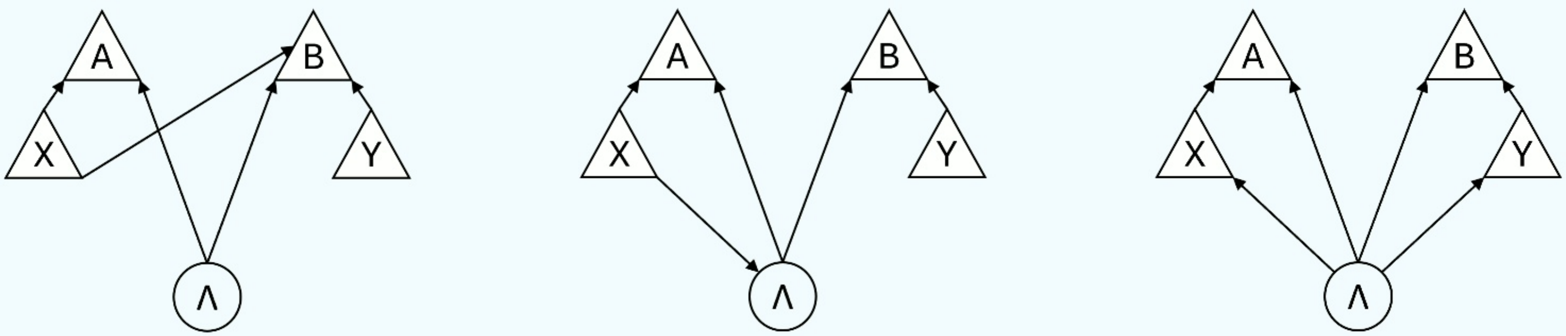
$$P(B|XY) = P(B|Y)$$

C. J. Wood and R. W. Spekkens, New Journal of Physics, 17, 08 **2012**.

No Fine-tuning:
the converse of the d-separation rule

conditional independence $\Rightarrow$ d-separation relation

no superluminal signaling	$P(A\|XY) = P(A\|X)$	$A \perp_d Y\|X$
	$P(B\|XY) = P(B\|Y)$	$B \perp_d X\|Y$



No Fine-tuning: the converse of the d-separation rule

conditional independence $\Rightarrow$ d-separation relation

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$$P(A|XY) = P(A|X) \qquad A \perp_d Y|X$$

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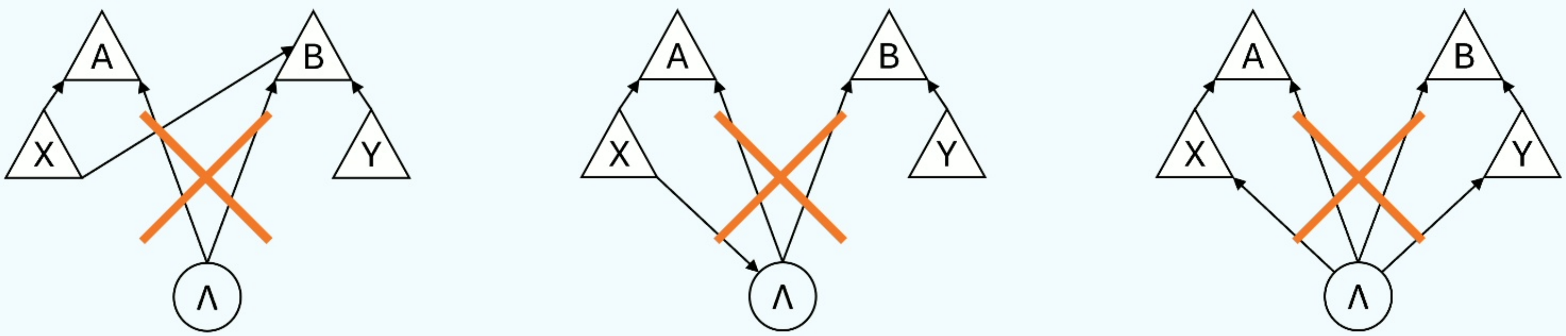
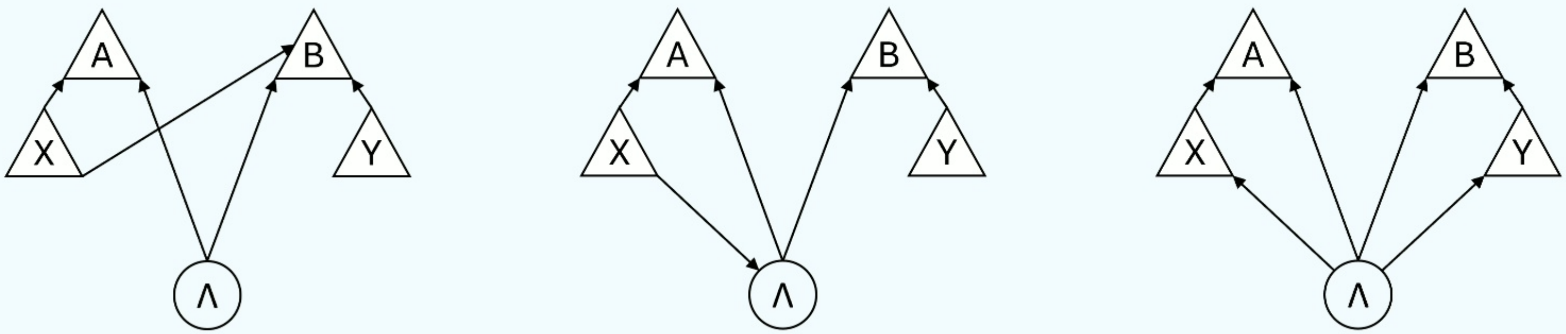


Problems with classical causal explanations

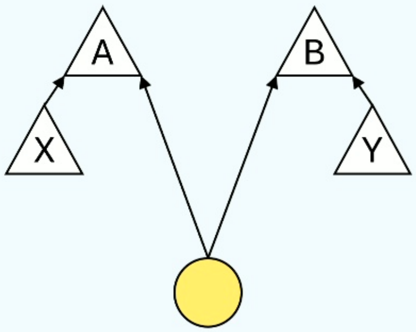


Superluminality　　Retrocausality　　Superdeterminism

Need **fine-tuning** to explain no-superluminal-signaling

Nonclassical Causal Models

Causal structure:



Compatible probabilities

- The d-separation rule:

d-separation relation of the graph $\Rightarrow$ (conditional) independence in the compatible P

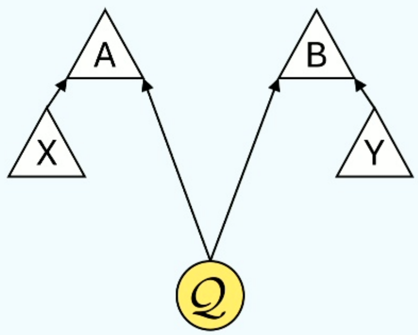
$$\Lambda \perp_d XY \qquad P(\Lambda XY) \cancel{=} P(\Lambda)P(XY)$$

$$AX \perp_d BY|\Lambda \qquad P(AXBY|\Lambda) \cancel{=} P(AX|\Lambda)P(BY|\Lambda)$$

Bell ~~inequalities~~ on P(AB|XY)

Quantum Causal Models

Causal structure:



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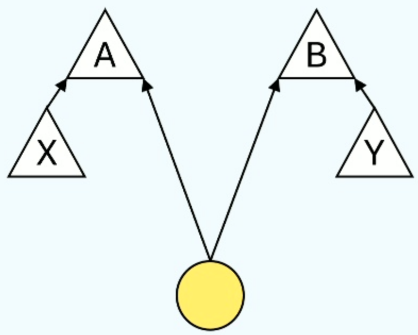
Quantum bound on P(AB|XY)

(e.g., Tsirelson's bound for CHSH)

Generalized Probabilistic Theory

GPT Causal Models

Causal structure:



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No-superluminal-signaling bound on P(AB|XY)

Generalized Probabilistic Theory

GPT Causal Models

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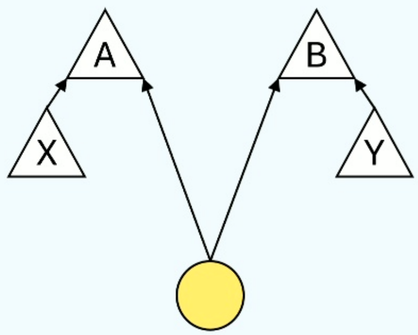


Compatible probabilities

- The d-separation rule **for observed nodes**

$$A \perp_d Y|X \qquad \Rightarrow P(A|XY) = P(A|X)$$

$$B \perp_d X|Y \qquad \Rightarrow P(B|XY) = P(B|Y)$$

No-superluminal-signaling bound on P(AB|XY)

J. Henson, R. Lal, and M. F. Pusey, New Journal of Physics 16, 113043 (2014)

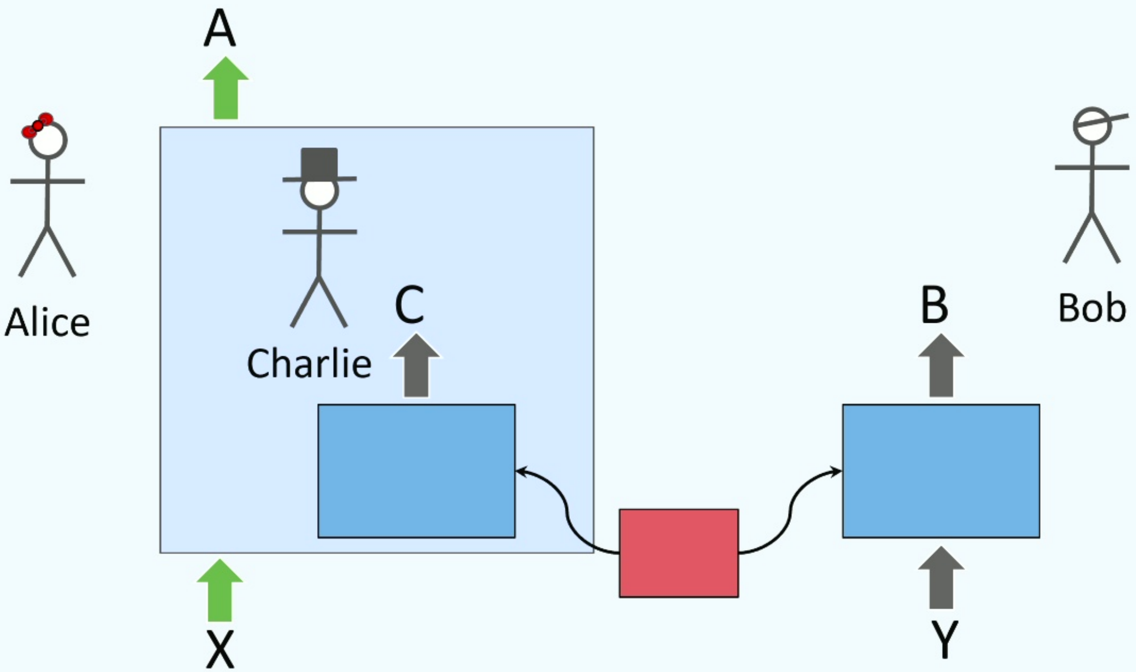
However…here comes Wigner's friend

D. Schmid, Y. Ying, and M. Leifer, A review and analysis of six extended Wigner's friend arguments (2023), arXiv:2308.16220

Local Friendliness (LF) experiment

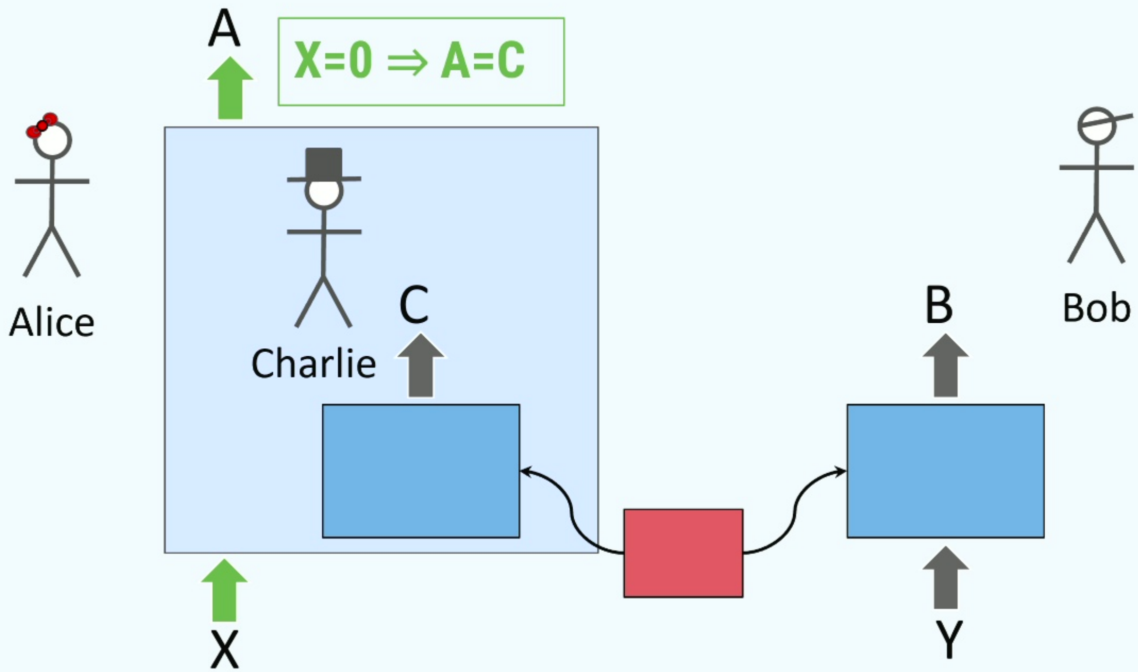
Bong et al, Nature Physics 16, 1199 (2020)

Local Friendliness (LF) experiment

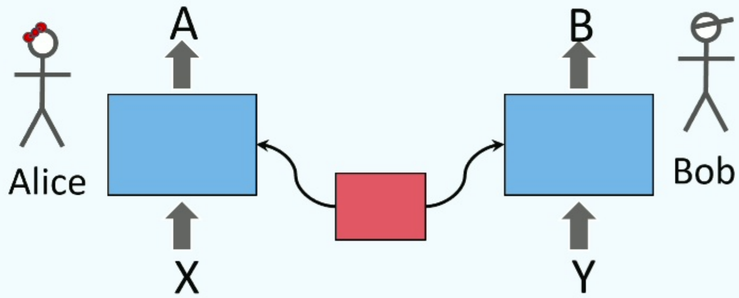


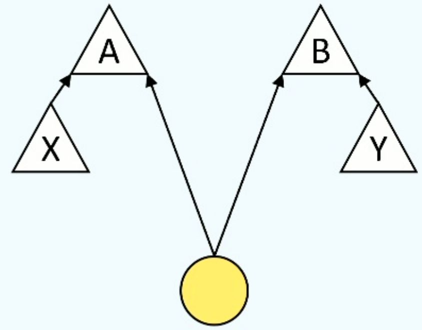
Bong et al, Nature Physics 16, 1199 (2020)

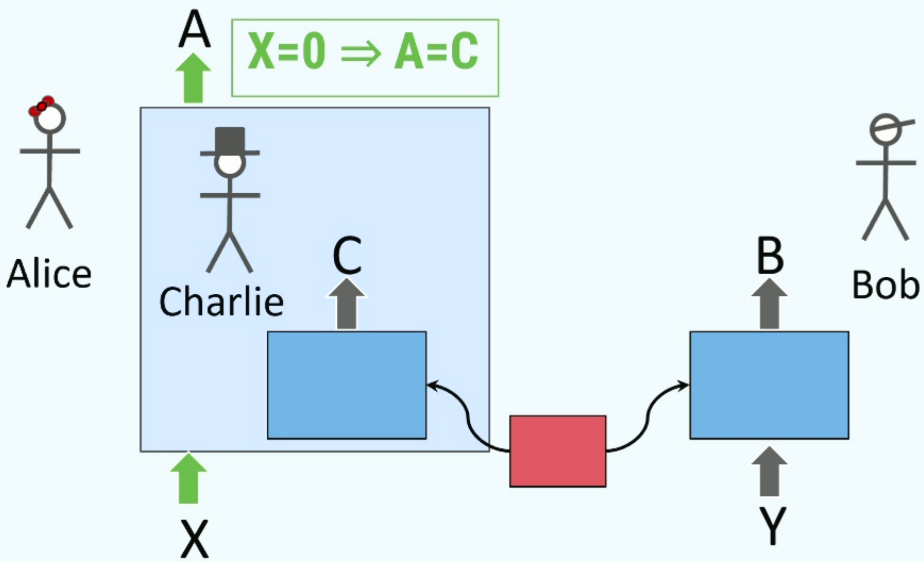
Local Friendliness (LF) experiment



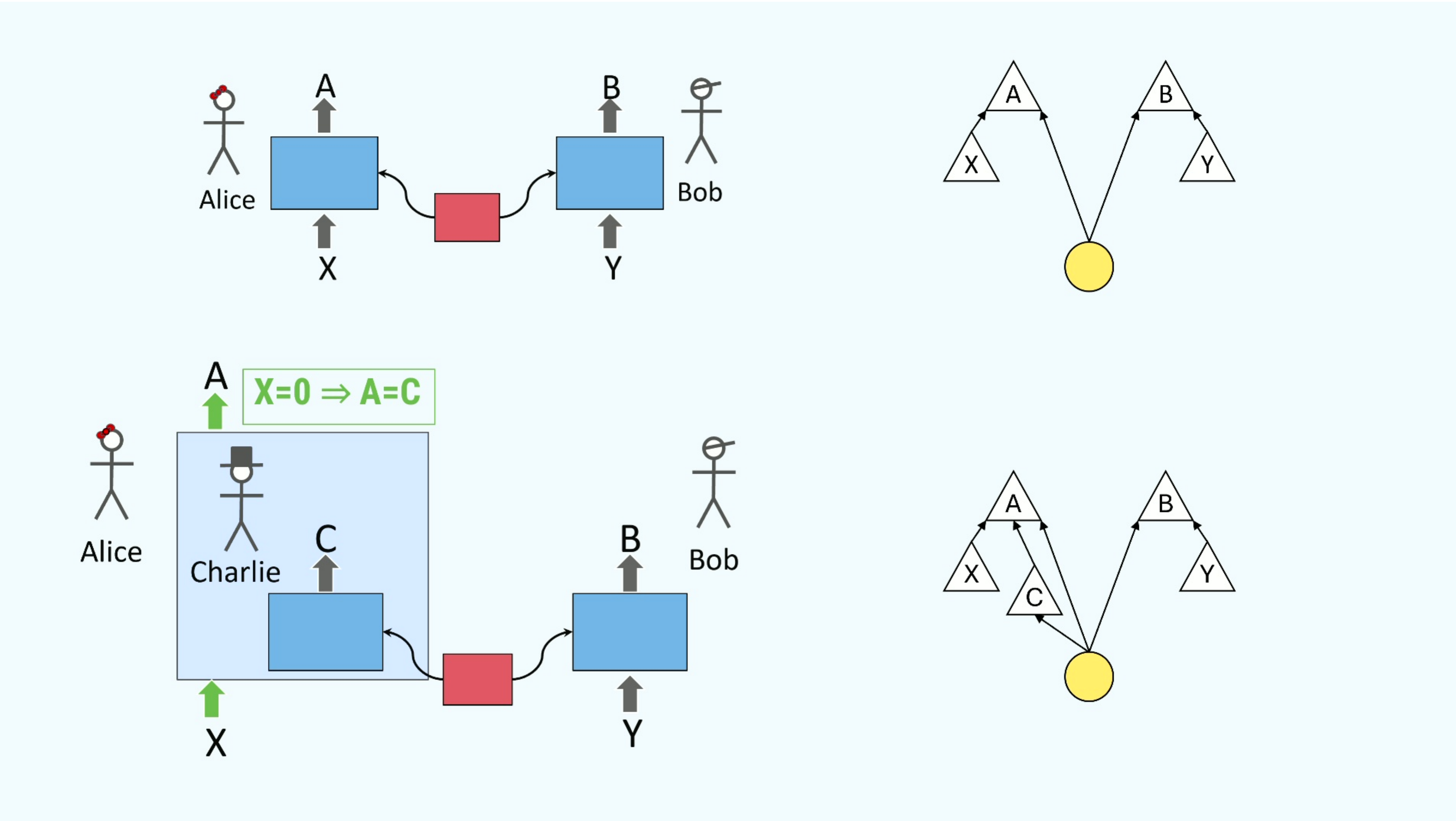
Bong et al, Nature Physics 16, 1199 (2020)


A
B
Alice
Bob
X
Y


A
B
X
Y


A
X=0 ⇒ A=C
Alice
Charlie
C
B
Bob
X
Y

?

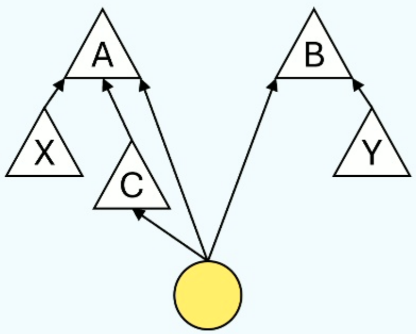


Alice
A
X
B
Bob
Y
A
B
X
Y
A
X=0 ⇒ A=C
Alice
Charlie
C
X
B
Bob
Y
A
B
X
C
Y

Generalized Probabilistic Theory

GPT Causal Models

Causal structure:



Compatible probabilities

- The d-separation rule for observed nodes

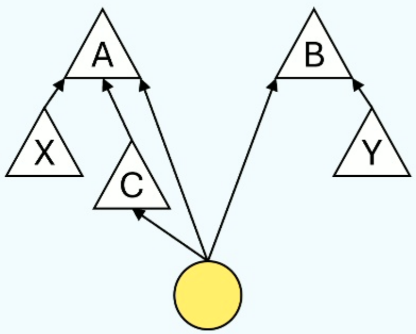
$$AC \perp_d Y|X \qquad \Rightarrow P(AC|XY) = P(A|X)$$

$$BC \perp_d X|Y \qquad \Rightarrow P(BC|XY) = P(B|Y)$$

Generalized Probabilistic Theory

GPT Causal Models

Causal structure:



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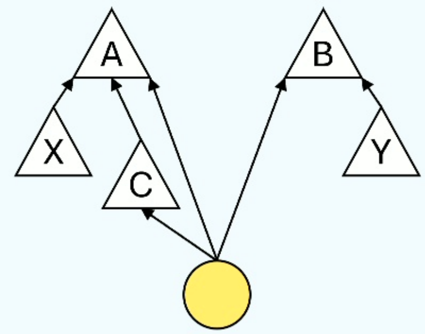
Monogamy relations on P(ABC|XY)!

P(AB|XY), P(AC|XY) and P(BC|XY) constrain each other

R. Augusiak, M. Demianowicz, M. Pawlowski, J. Tura, and A. Acin, Physical Review A 90, 052323 (2014)

Monogamy relations on P(abc|xy)



Example:

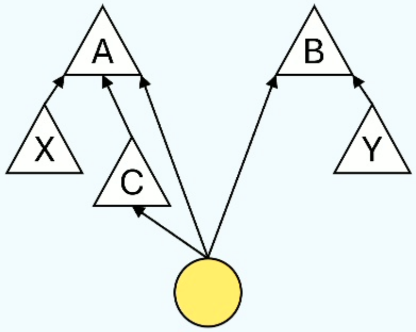
$$\overbrace{\mathrm{CHSH}_{P(AB|XY)}}^{\leq 1} + \overbrace{\sum_{A=C} P(AC|X{=}0)}^{\leq 1} \leq \frac{7}{4}$$

$$\frac{1}{4}\left[\sum_{A=B} P(AB|00)+\sum_{A=B} P(AB|01)+\sum_{A=B} P(AB|10)+\sum_{A\neq B} P(AB|11)\right]$$

$$\boxed{\mathbf{X{=}0 \Rightarrow A{=}C} \Rightarrow \mathrm{CHSH}_{P(AB|XY)} \leq \frac{3}{4}}$$

Local Friendliness (LF) inequalities

Local Friendliness (LF) Inequalities



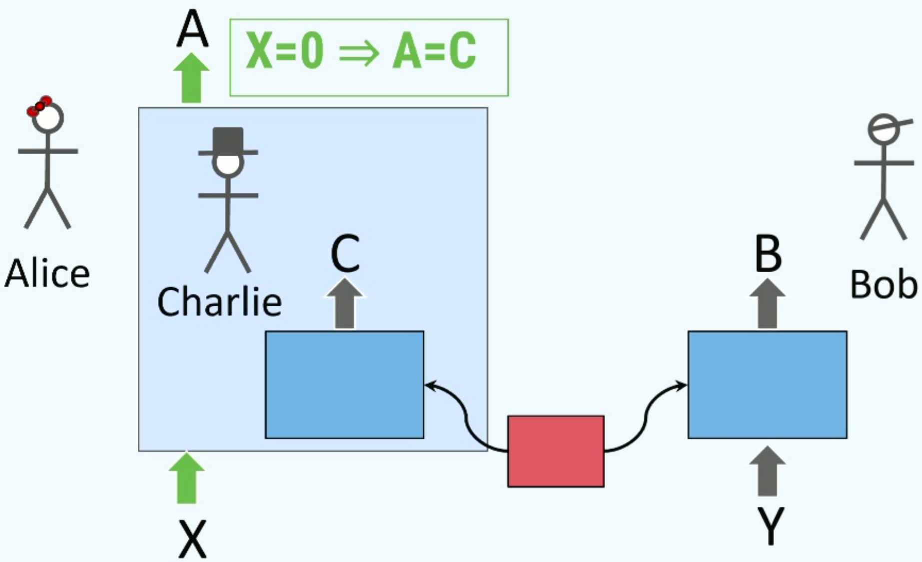
Monogamy relations

$\boxed{X=0 \Rightarrow A=C}$

In general, LF inequalities are strictly weaker than Bell inequalities.

In the binary case, they coincide: $\mathrm{CHSH}_{P(AB|XY)} \leq \frac{3}{4}$

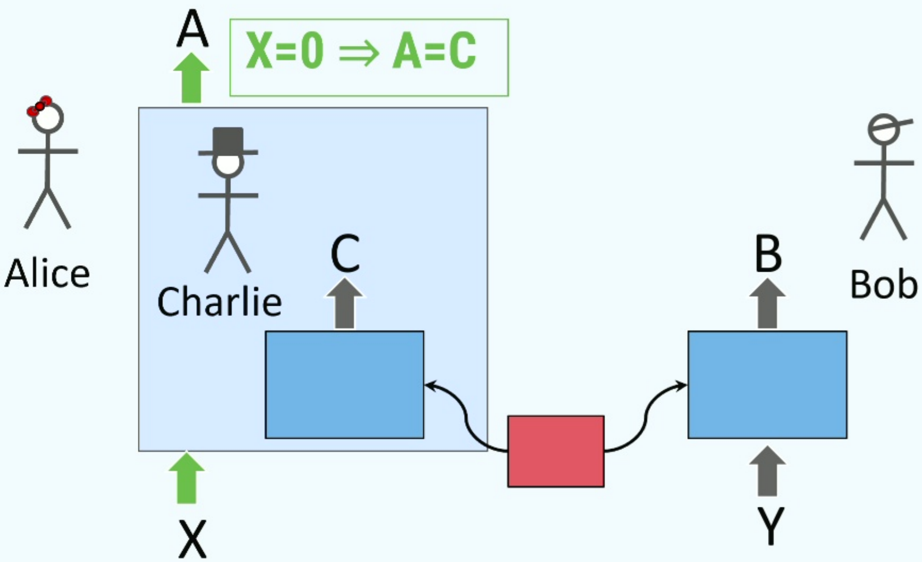
Quantum violations of LF inequalities

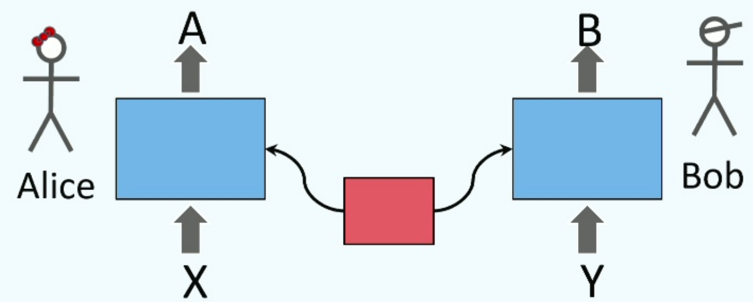


Bong et al, Nature Physics 16, 1199 (2020)
H. M. Wiseman, E. G. Cavalcanti, and E. G. Rieffel, Quantum 7, 1112 (2023)

Quantum violations of LF inequalities

e.g., $\mathrm{CHSH}_{P(AB|XY)} \leq \frac{3}{4}$

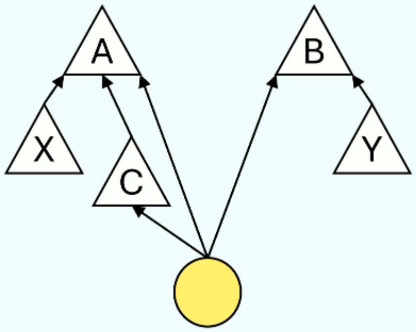




Bong et al, Nature Physics 16, 1199 (2020)
H. M. Wiseman, E. G. Cavalcanti, and E. G. Rieffel, Quantum 7, 1112 (2023)

Any d-sep causal model with the LF DAG cannot explain violations of LF inequalities!

$X=0 \Rightarrow A=C$

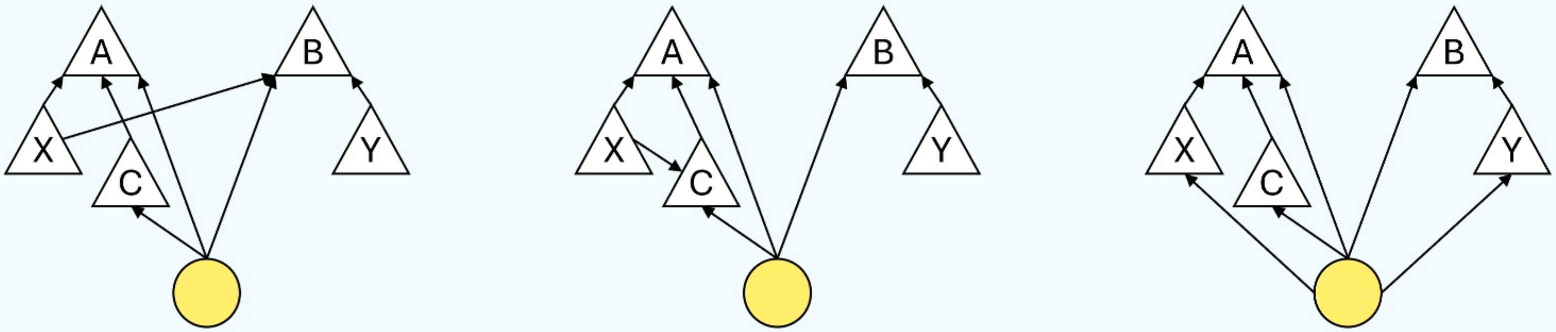


+

d-separation rule
for observed nodes

$\Rightarrow$ Monogamy relations on P(ABC|XY) $\Rightarrow$ LF inequalities

Problems with d-sep causal explanations



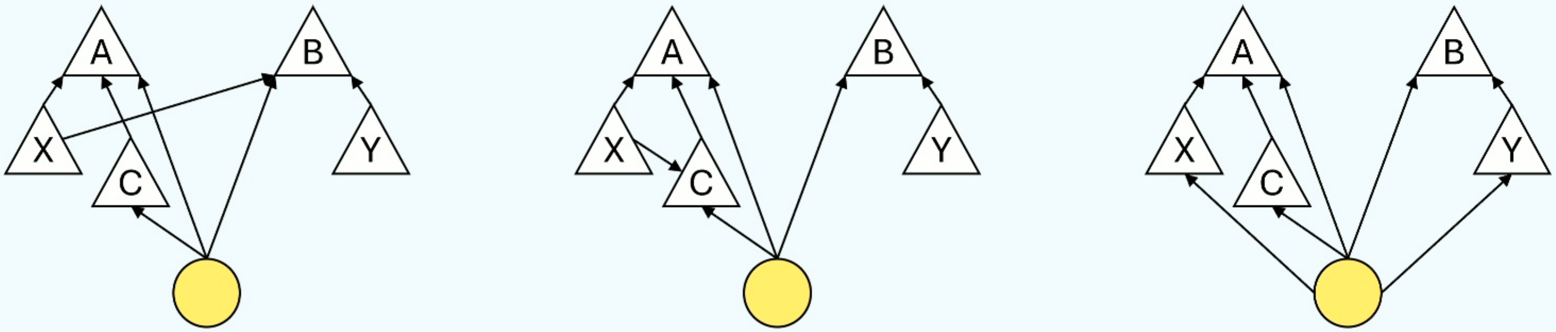
Need **fine-tuning** to explain no-superluminal/retro-signaling!

$$P(A|XY) = P(A|X)$$

$$P(B|XY) = P(B|Y)$$

$$P(C|XY) = P(C)$$

Problems with d-sep causal explanations



Need **fine-tuning** to explain no-superluminal/retro-signaling!

$$P(A|XY) = P(A|X)$$

$$P(B|XY) = P(B|Y)$$

$$P(C|XY) = P(C)$$

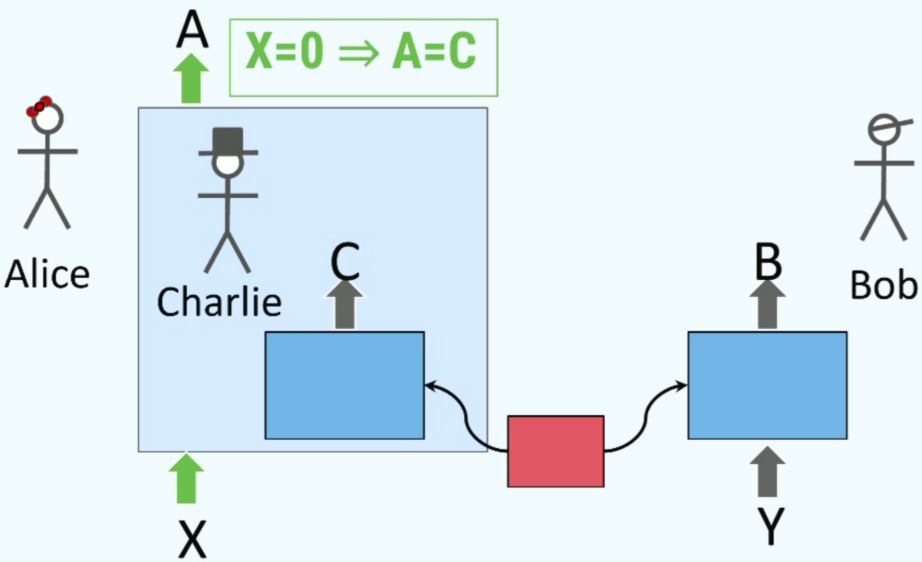
Any d-sep causal model must be fined-tuned to explain violations of LF inequalities!

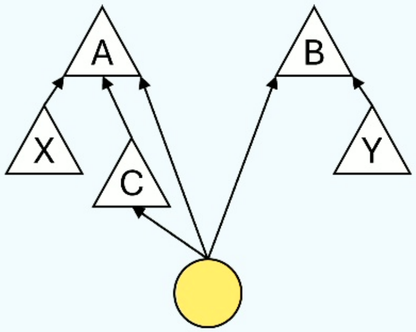
How about cyclic causal models?

Any compositional causal model must be fined-tuned to explain violations of LF inequalities!

even if it is cyclic and violates the d-sep rule for observed events

What's next?

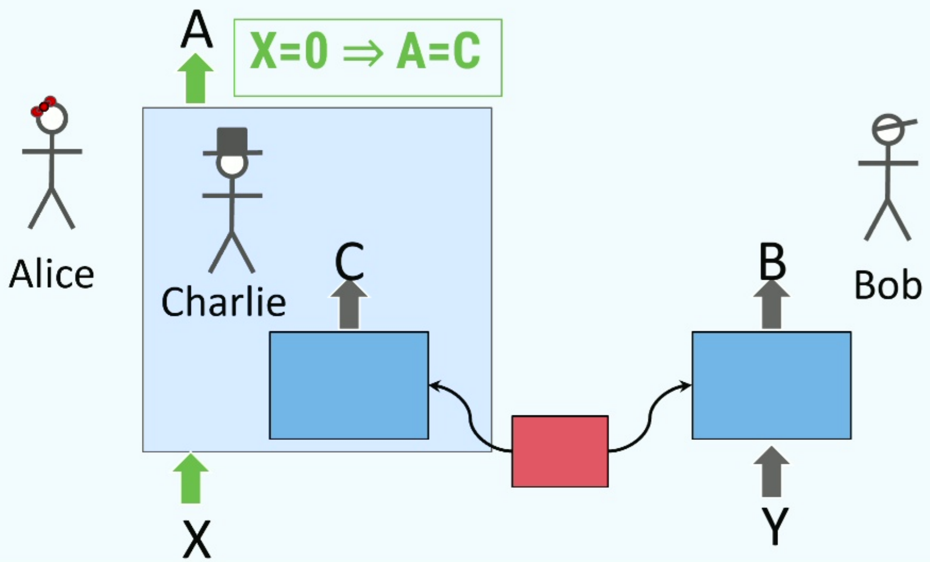


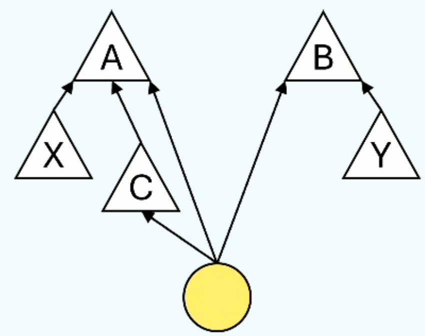


the LF DAG

What's next?

- Does P(ABCXY) really exist?
- Make C less "real" (e.g., Relational QM, QBism)? Or many-worlds?



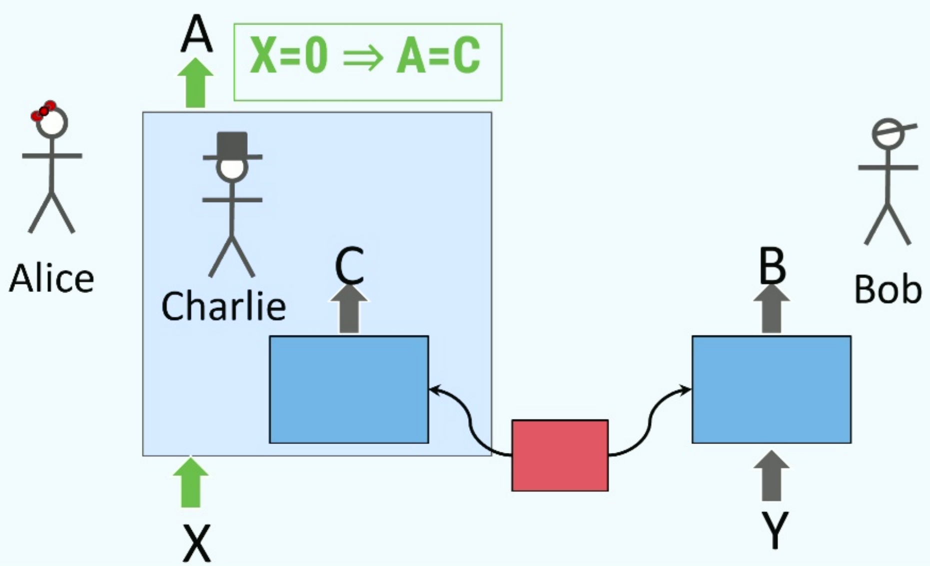


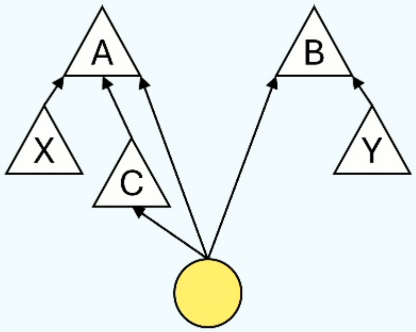
the LF DAG

What's next?

- Does P(ABCXY) really exist?

Keep the causal structure intact
Update the notion of causality



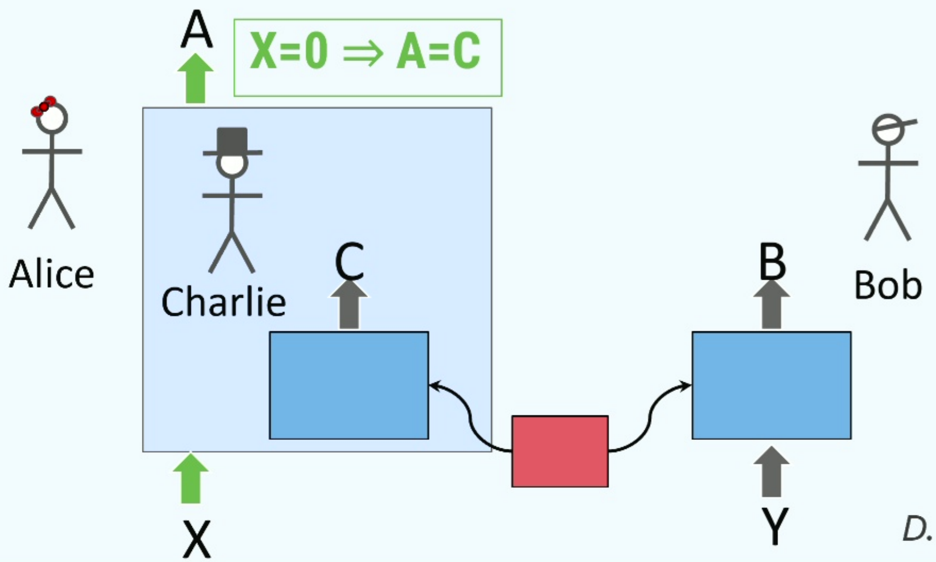


the LF DAG

What's next?

- Does P(ABCXY) really exist?

Keep the causal structure intact
Update notions of causality and inference

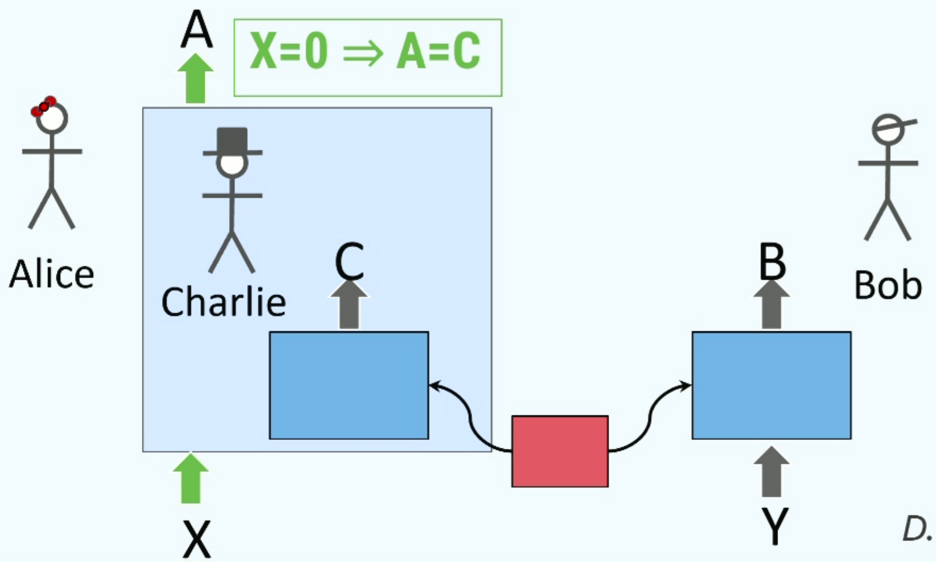


D. Schmid, J. H. Selby, and R. W. Spekkens, arXiv:2009.03297

What's next?

- Does P(ABCXY) really exist?

Keep the causal structure intact
Update notions of causality and inference



Stay tuned ;)

D. Schmid, J. H. Selby, and R. W. Spekkens, arXiv:2009.03297

What’s next?

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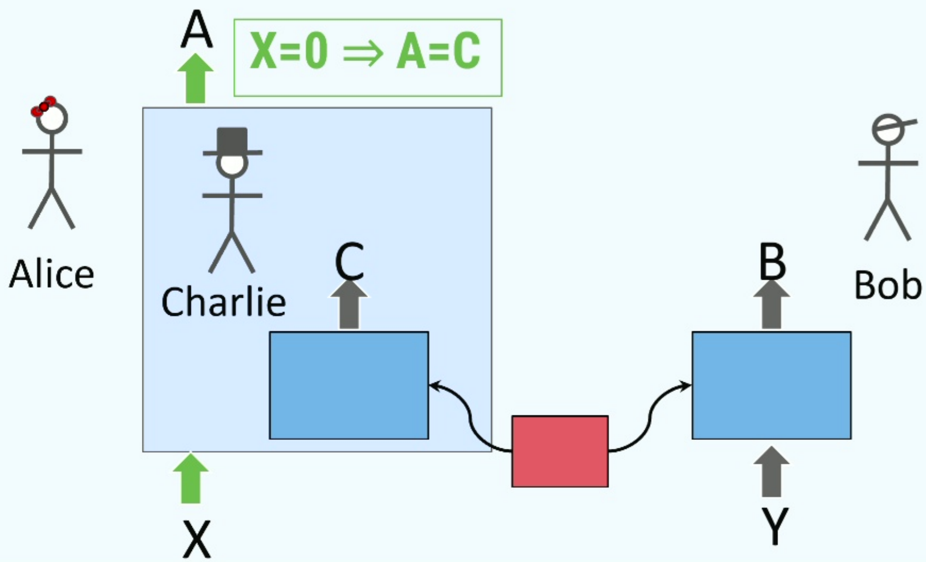
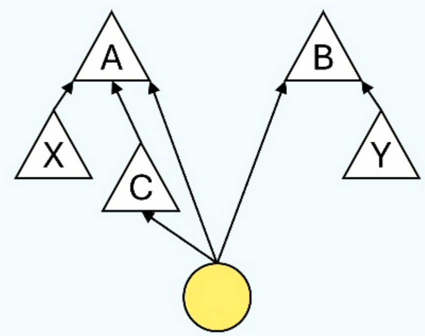
Keep the causal structure intact
Update the notion of causality





the LF DAG