Causal Inference: Classical and Quantum

Lecturer: Robert Spekkens
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Journeys,
SAIFR, ICTP, Brazil

Causarum Investigatio
“Investigate the causes”

Simpson's paradox
in statistics
and its causal resolution

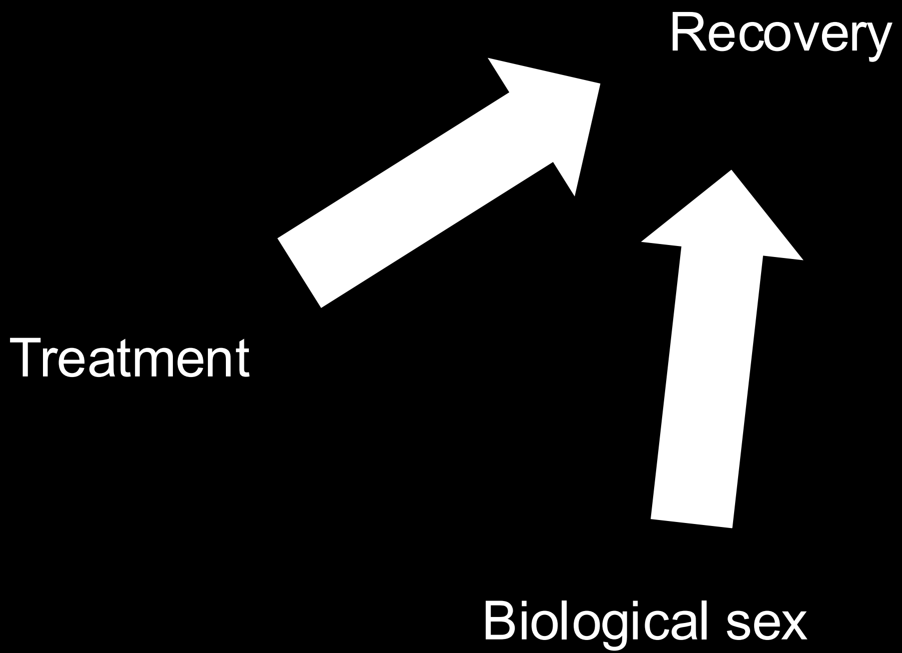
$$P(\text{recovery} \mid \text{drug}) > P(\text{recovery} \mid \text{no drug})$$

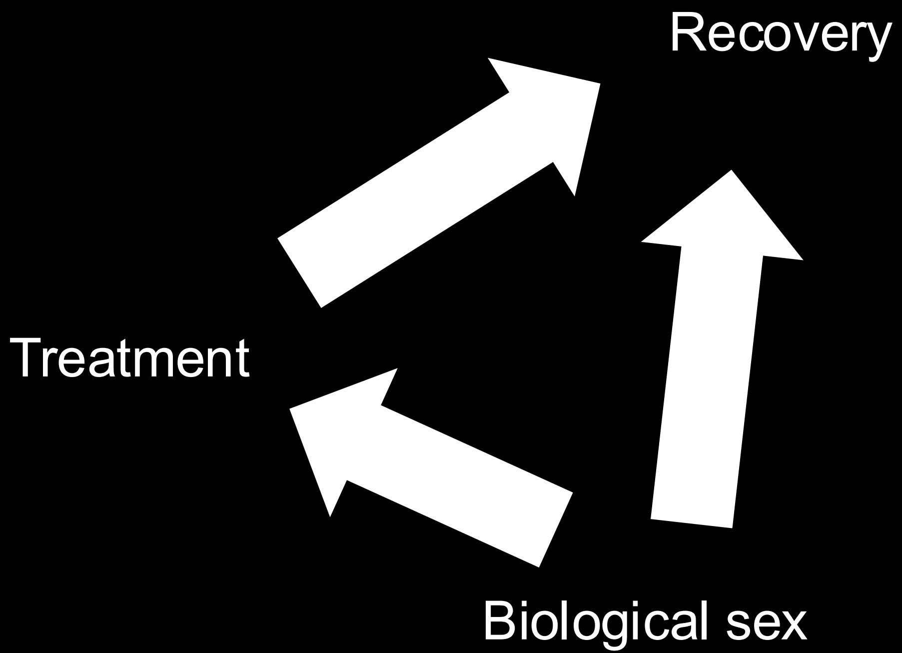
$$P(\text{recovery} \mid \text{drug, male}) < P(\text{recovery} \mid \text{no drug, male})$$

$$P(\text{recovery} \mid \text{drug, female}) < P(\text{recovery} \mid \text{no drug, female})$$

Recovery probability

	drug	**no drug**
male	180/300 = 60%	70/100 = 70%
female	20/100 = 20%	90/300 = 30%
combined	200/400 = 50%	160/400 = 40%


Recovery
Treatment
Biological sex



Recovery
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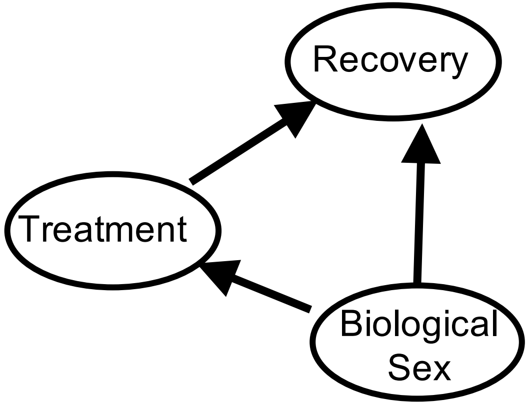
Biological sex

$$P(\text{recovery} \mid \text{drug}) > P(\text{recovery} \mid \text{no drug})$$

$$P(\text{recovery} \mid \text{drug, male}) < P(\text{recovery} \mid \text{no drug, male})$$ ✓

$$P(\text{recovery} \mid \text{drug, female}) < P(\text{recovery} \mid \text{no drug, female})$$ ✓



Therefore: stratify the data by the common cause “statisticians are invariably motivated by causal questions but the peculiar nature of these questions is that they cannot be answered, or even articulated, in the traditional language of statistics.

[…]

causation is not merely an aspect of statistics; it is an addition to statistics, an enrichment that allows statistics to uncover workings of the world that traditional methods cannot”

From: J. Pearl, M. Glymour and N. Jewell, ‘Causal Inference in Statistics’

Statistical paradigm

Causal paradigm

Operational paradigm

Realist paradigm

Causal structures with hidden variables

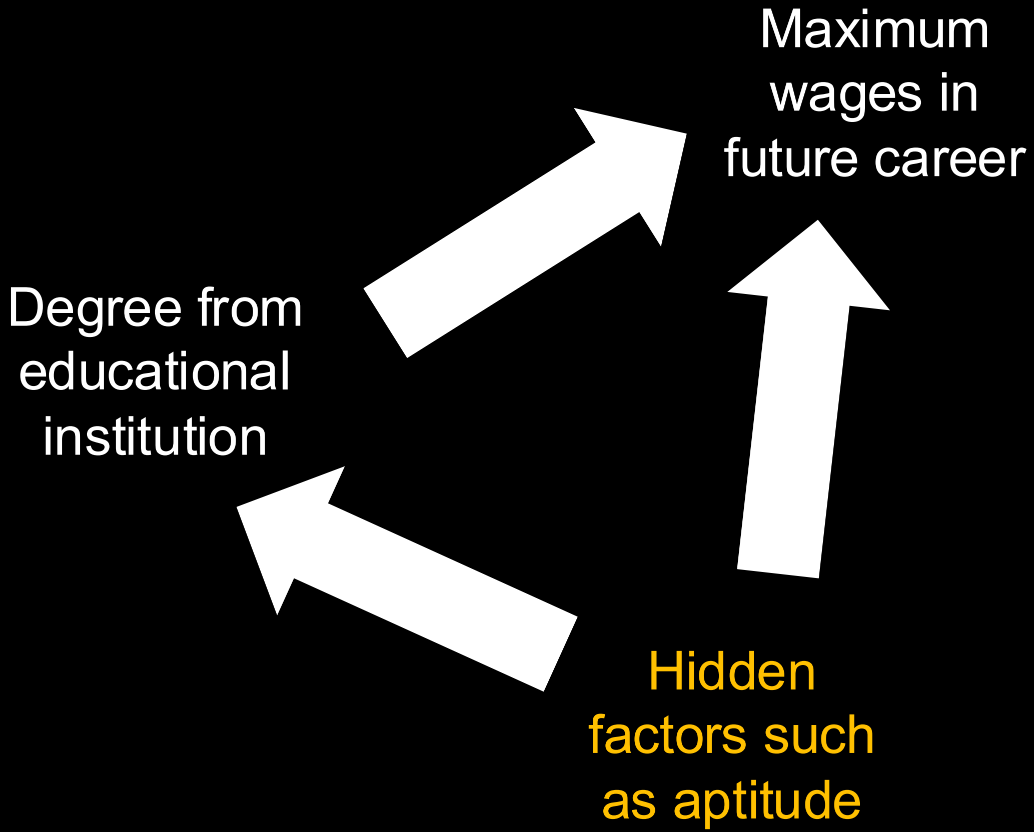
Maximum wages in future career above some threshold?

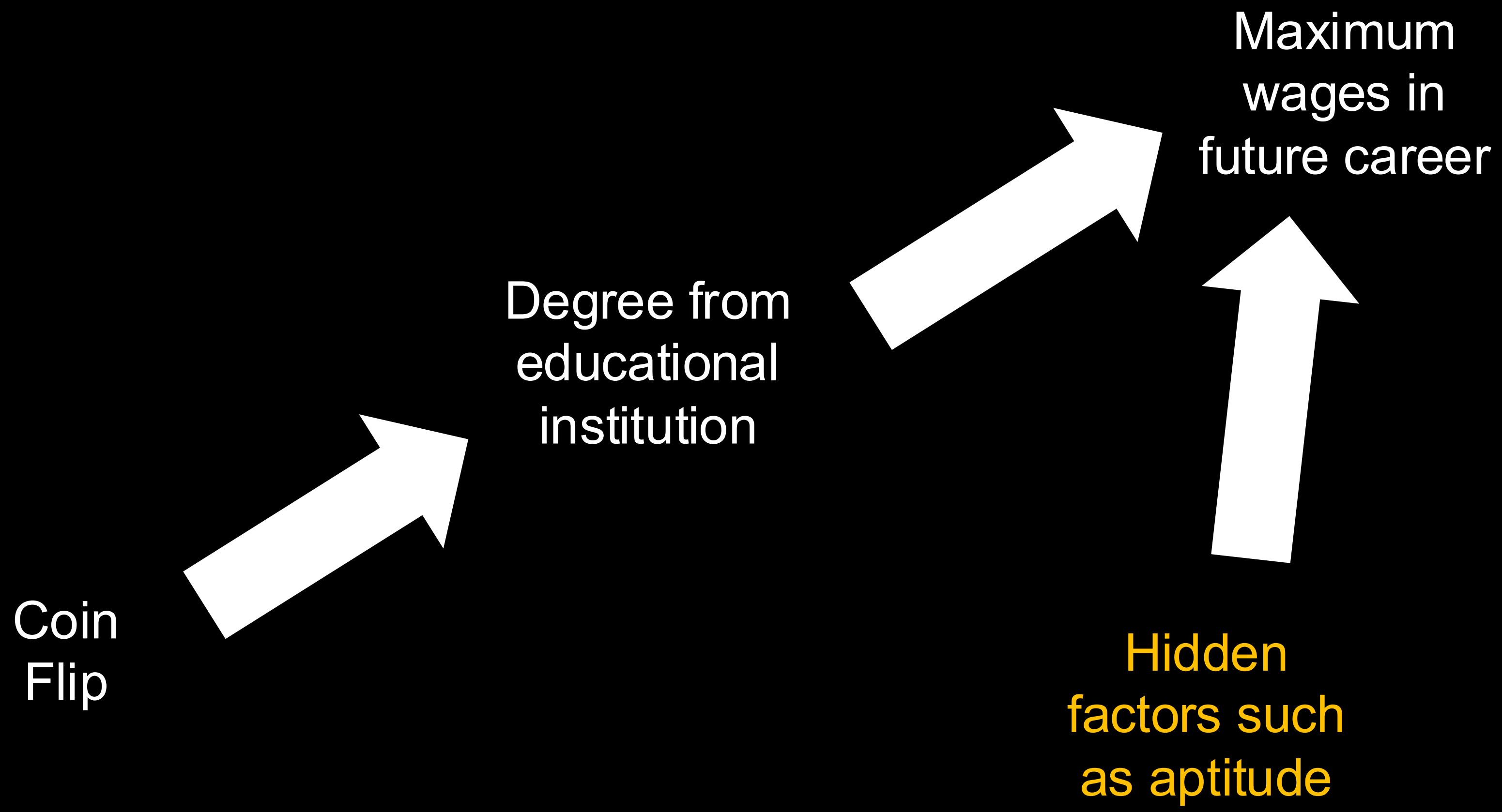
Degree from educational institution?

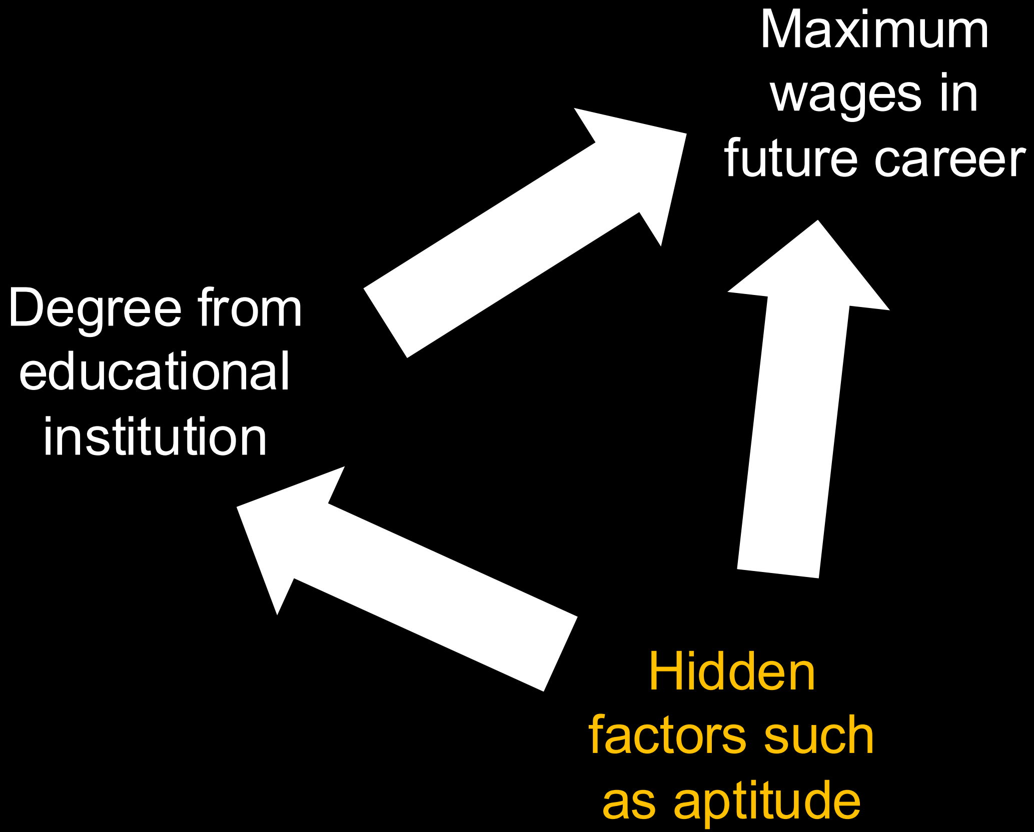
	Yes	No
Yes	79%	21%
No	43%	57%

Maximum
wages in
future career

Degree from
educational
institution


Maximum wages in future career
Degree from educational institution
Hidden factors such as aptitude


Maximum wages in future career
Degree from educational institution
Coin Flip
Hidden factors such as aptitude


Maximum wages in future career
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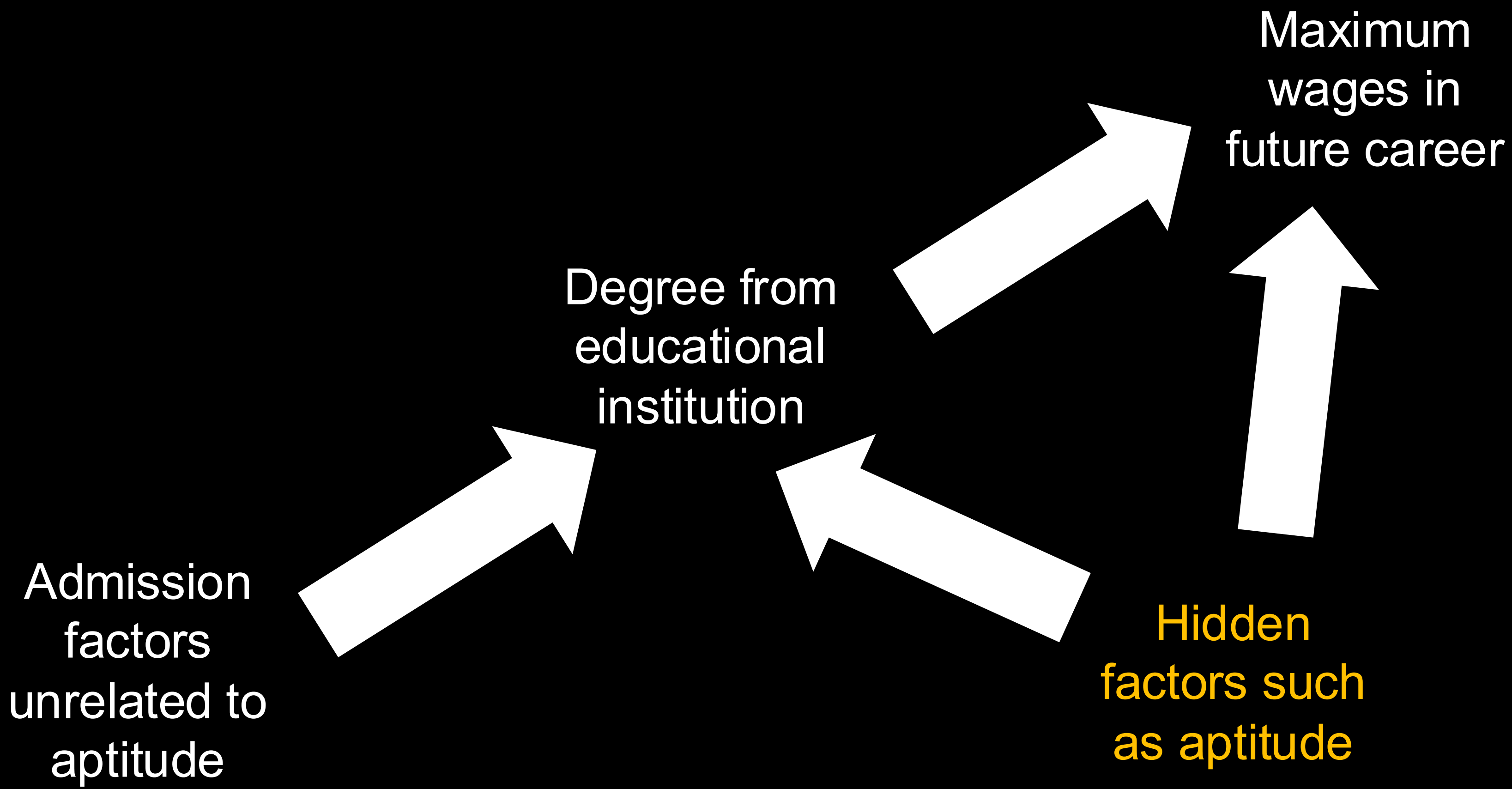
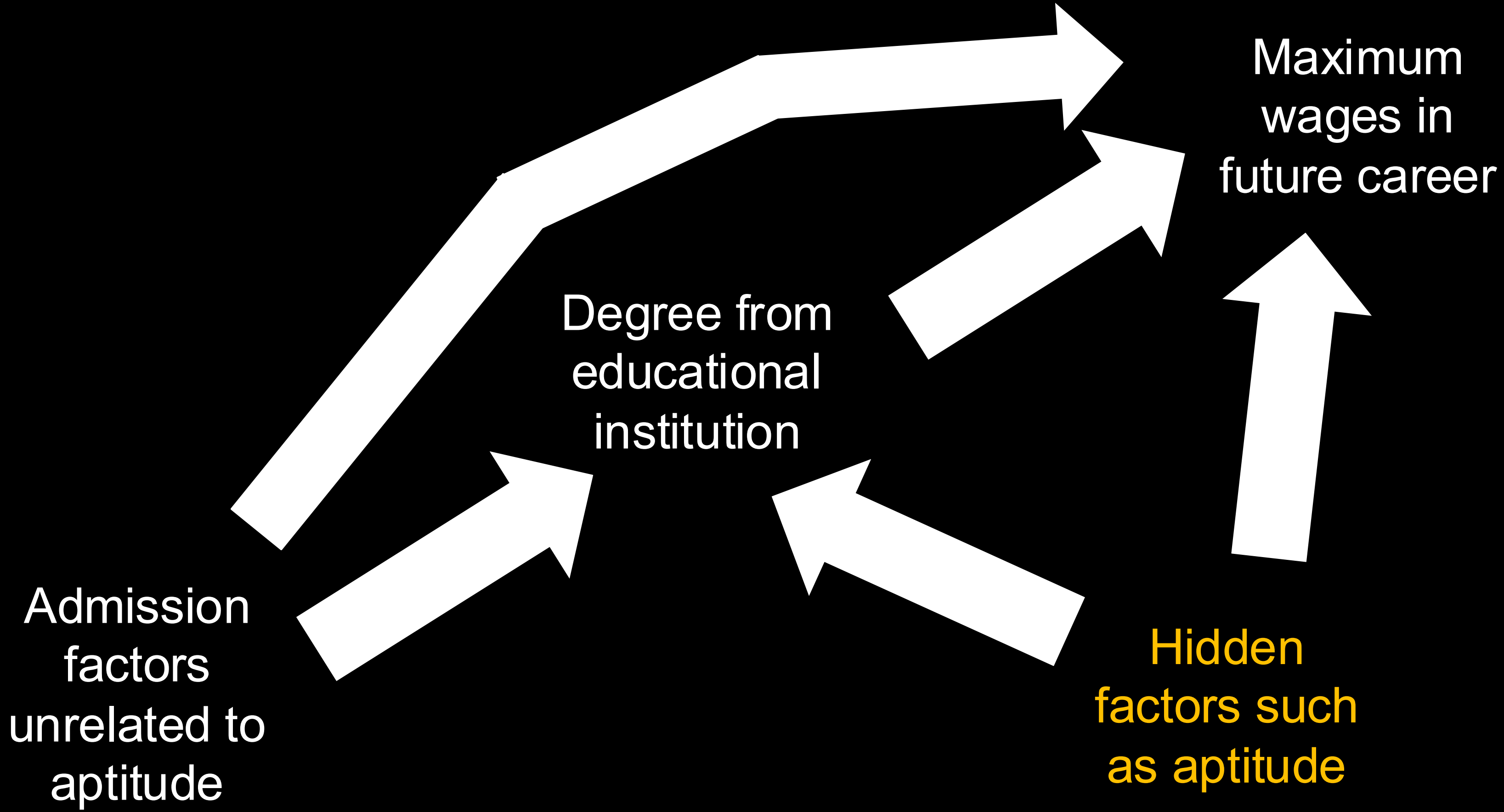

Maximum wages in future career
Degree from educational institution
Admission factors unrelated to aptitude
Hidden factors such as aptitude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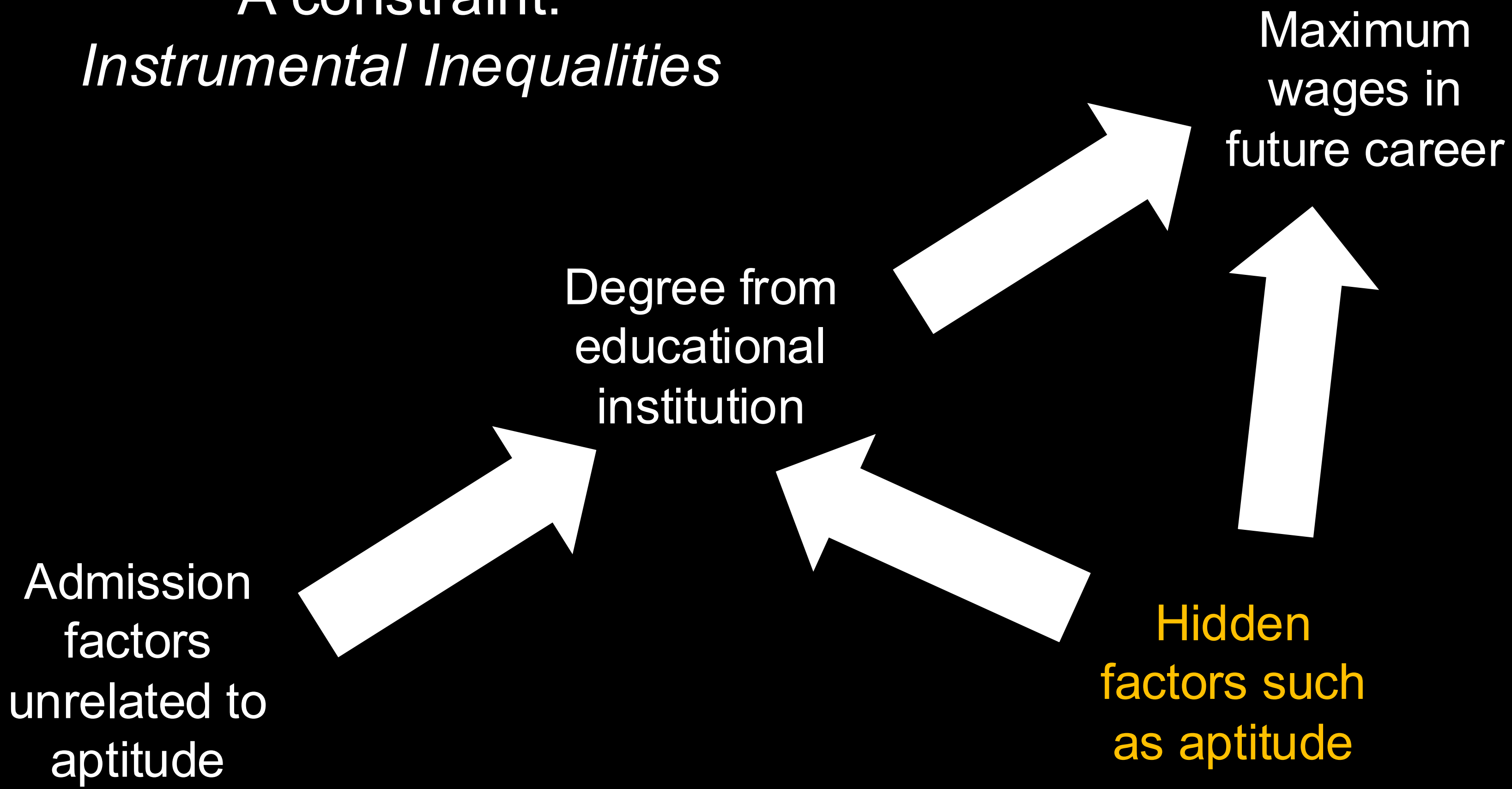
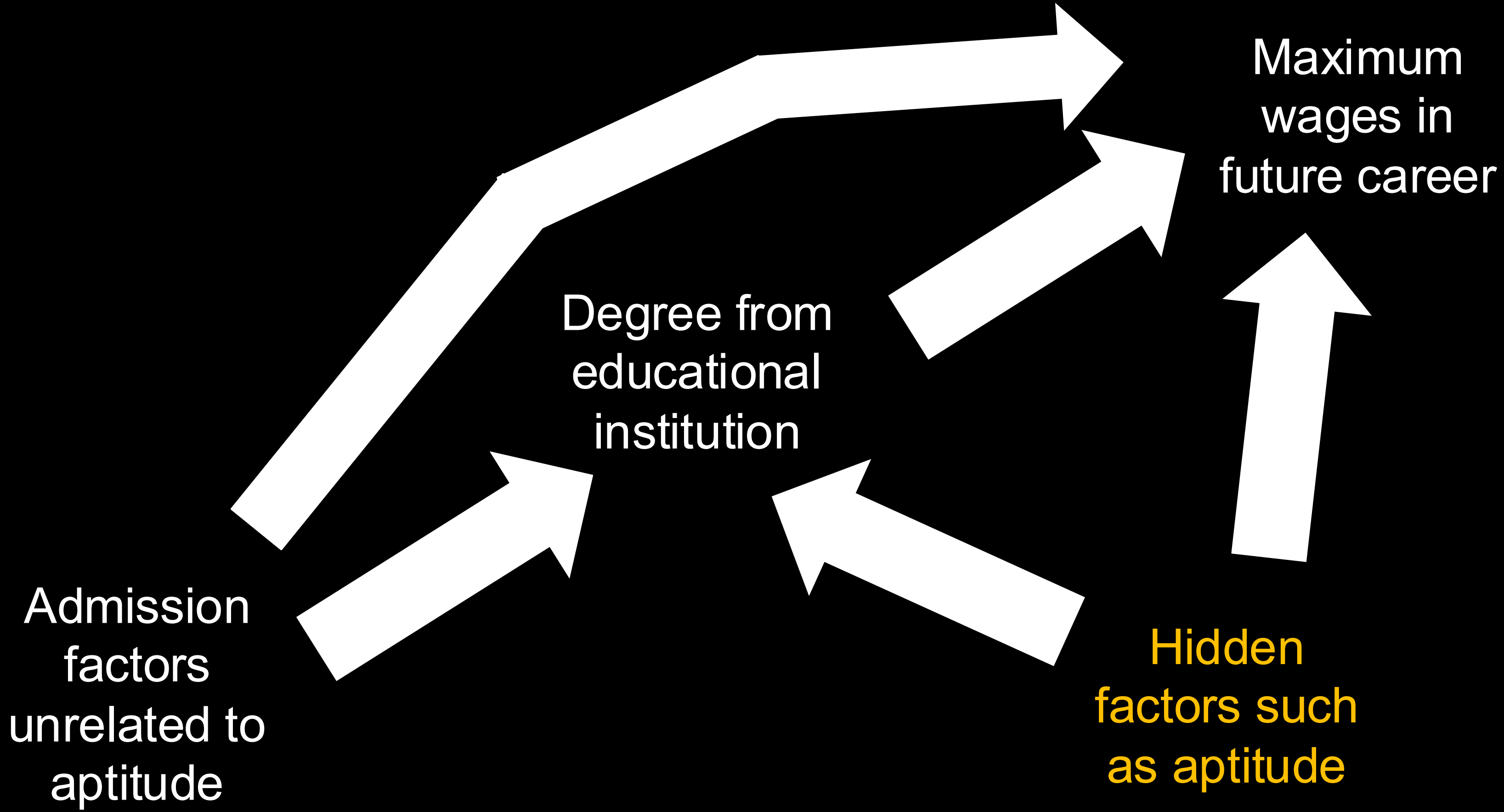
A constraint: *Instrumental Inequalities*




Maximum wages in future career
Degree from educational institution
Admission factors unrelated to aptitude
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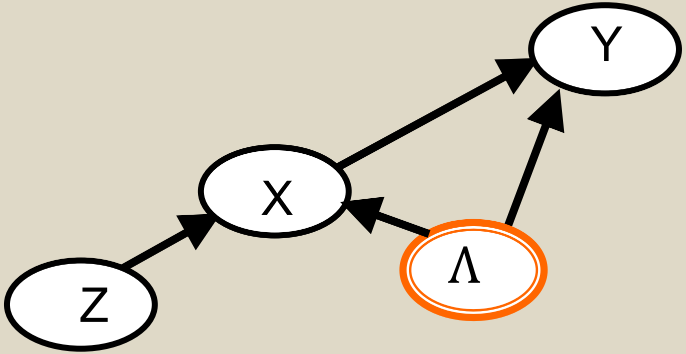
Causal structure

Parameters



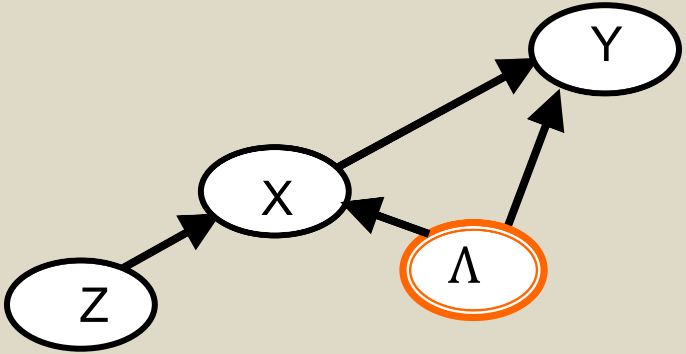
$P_{X|\Lambda Z}$

$P_{Y|\Lambda X}$

P_{Λ}

P_Z

Causal structure



Parameters

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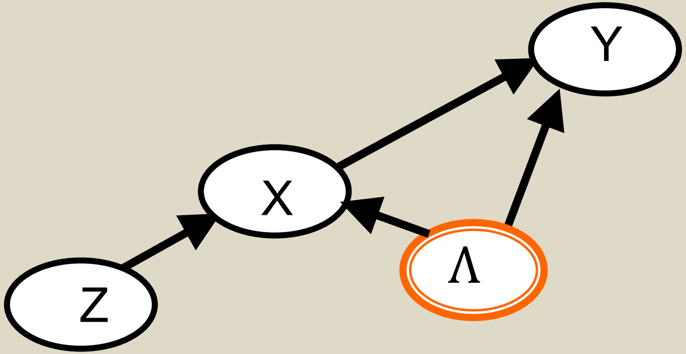
P_{Z}

$$P_{XYZ} = \sum_{\Lambda} P_{Y|X\Lambda} P_{X|Z\Lambda} P_{\Lambda} P_{Z}$$

Causal structure



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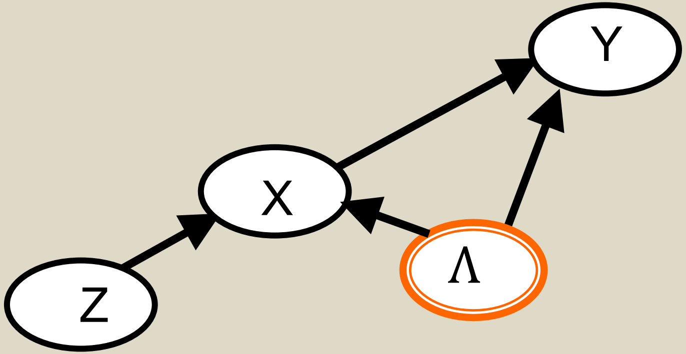
A distribution is said to be compatible with a given causal structure if there are parameters that yield it

Causal structure



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$P_{Y|\Lambda X}$

P_{Λ}

P_{Z}

$$P_{XYZ} = \sum_{\Lambda} P_{Y|X\Lambda} P_{X|Z\Lambda} P_{\Lambda} P_{Z}$$

Example of causal compatibility constraint:

$$\boxed{P_{XY|Z}(00|0) + P_{XY|Z}(01|1) \leq 1}$$

Pearl, 1993

The evidence

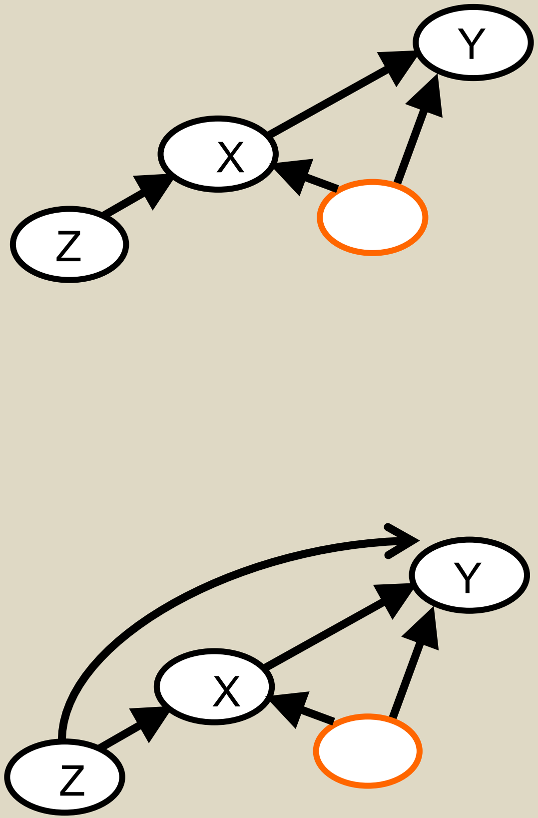
Z=0

	Y=0	Y=1
X=0	0.79	0.21
X=1	0.43	0.57

Z=1

	Y=0	Y=1
X=0	0.59	0.41
X=1	0.39	0.61

The hypotheses



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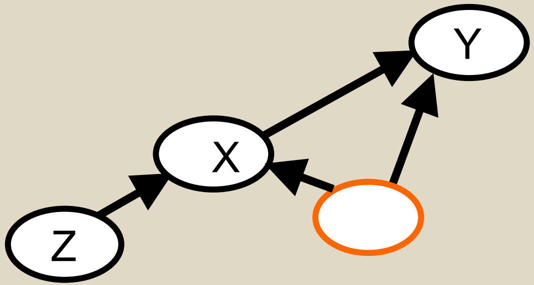
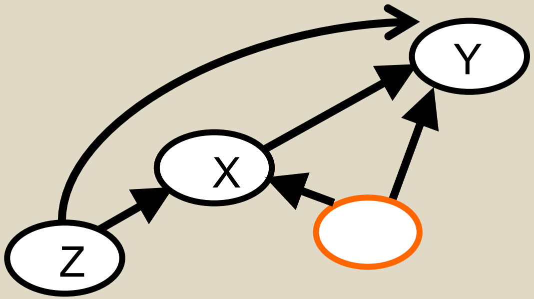
Violates the instrumental inequality!

The hypotheses



Implies a constraint:
the instrumental inequality



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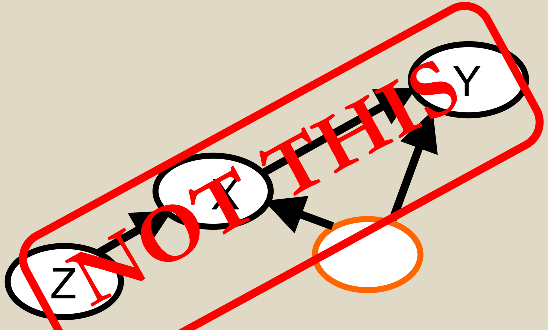

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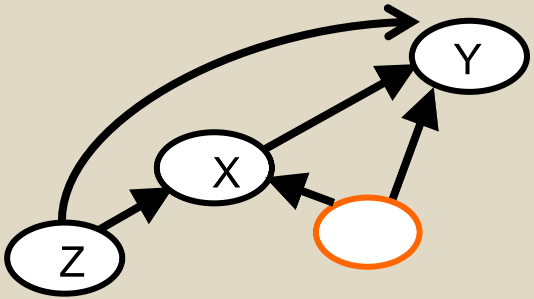

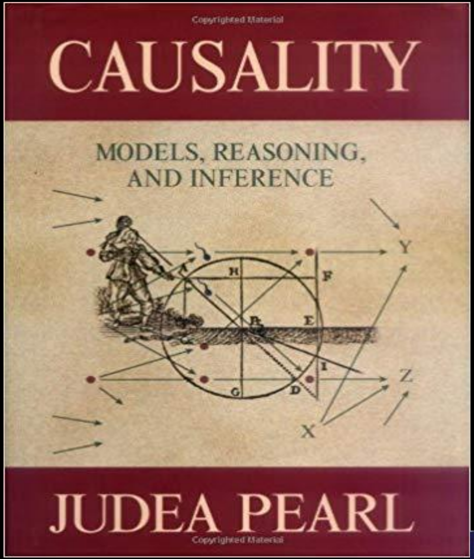
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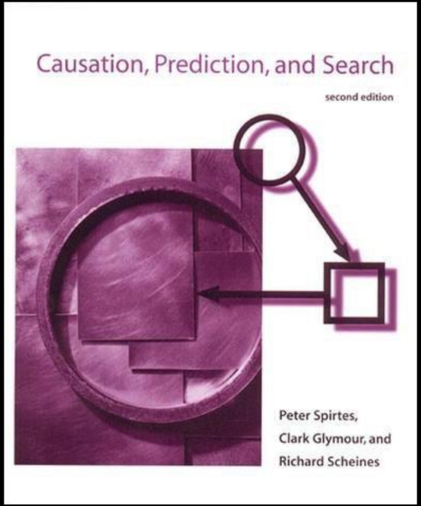
Causation, Prediction, and Search
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Peter Spirtes,
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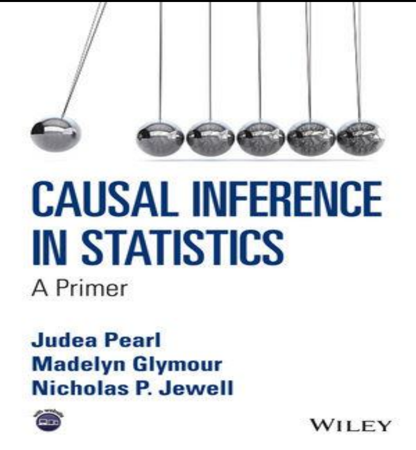
Richard Scheines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A Primer
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Madelyn Glymour
Nicholas P. Jewell
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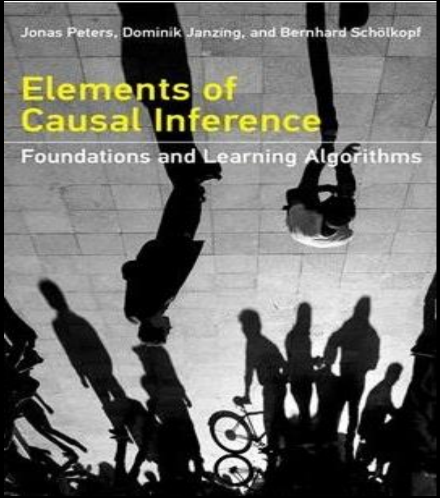
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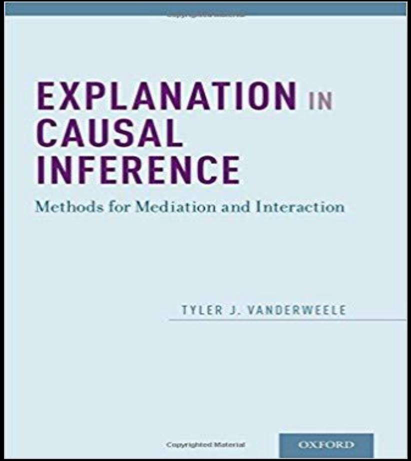
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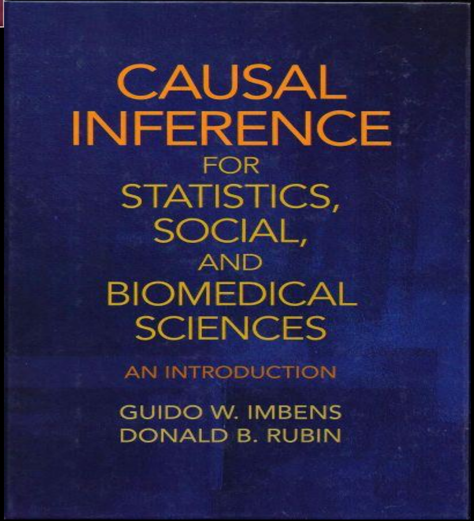
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AN INTRODUCTION
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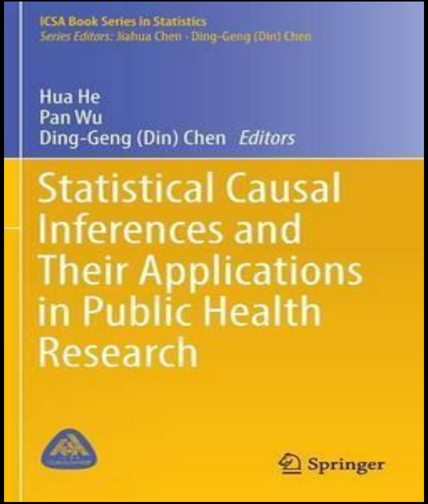
DONALD B. RUBIN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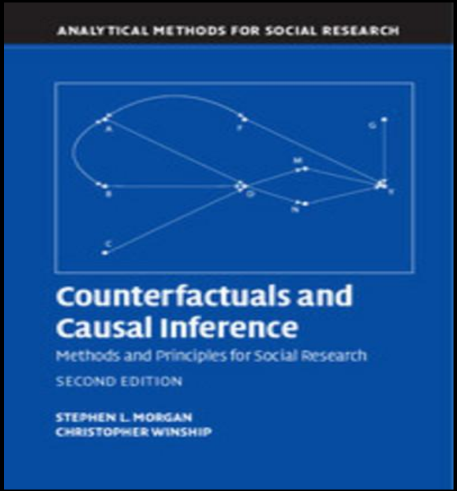
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Counterfactuals and Causal Inference
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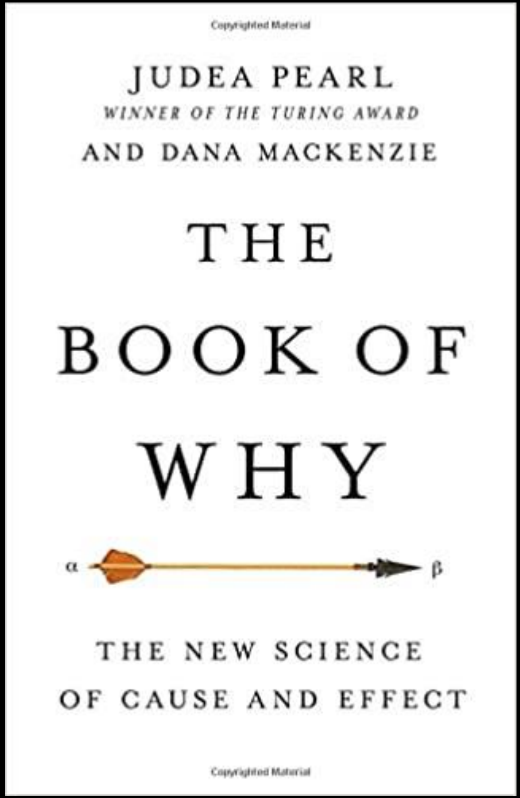
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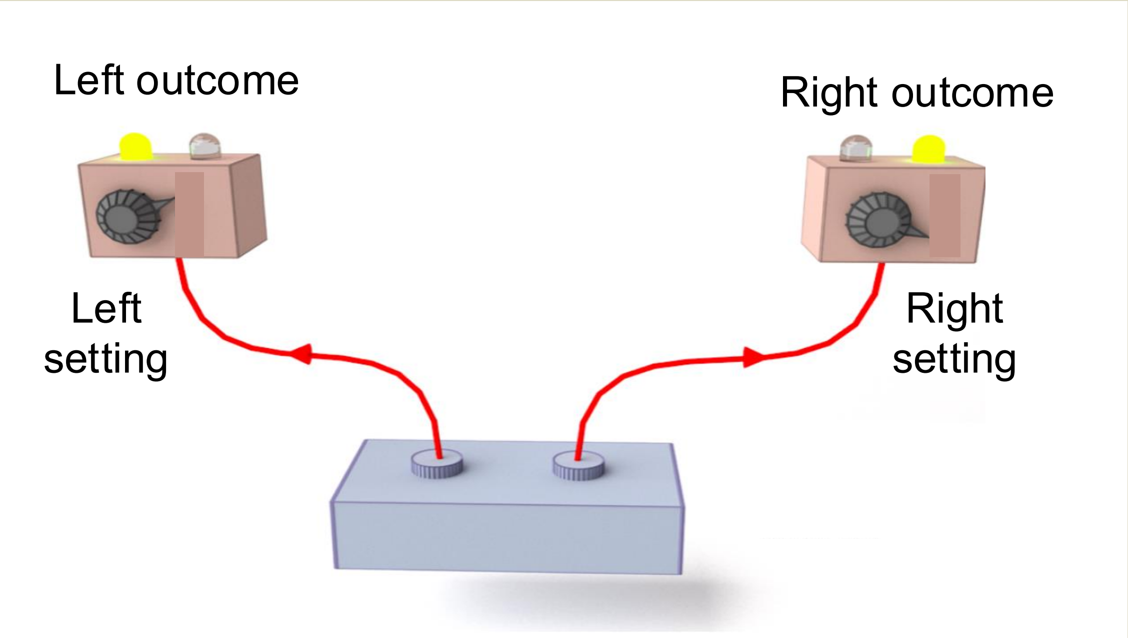
QUANTUM THEORY

John Stuart Bell


Left outcome
Right outcome
Left
setting
Right
setting

Left outcome and Right outcome

Left setting and Right setting	0 and 0	0 and 1	1 and 0	1 and 1
0 and 0	43%	7%	7%	43%
0 and 1	43%	7%	7%	43%
1 and 0	43%	7%	7%	43%
1 and 1	7%	43%	43%	7%

The evidence

Left outcome and Right outcome

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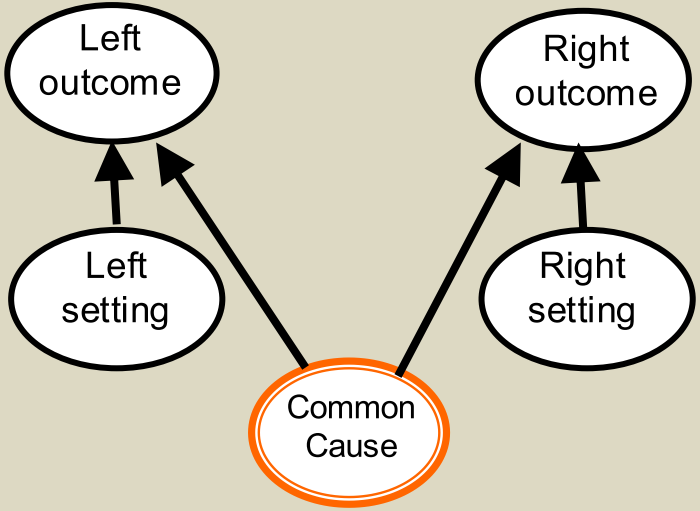
The natural hypothesis



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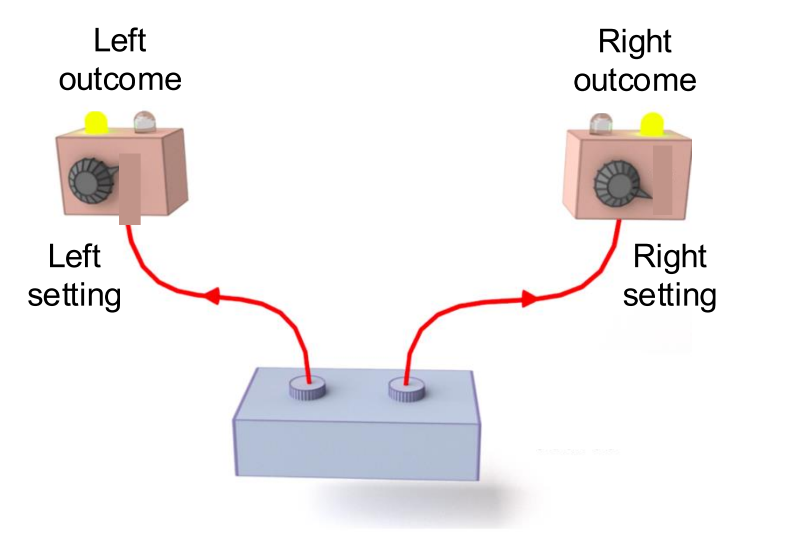
	0 a				
	1 a				
	1 a				



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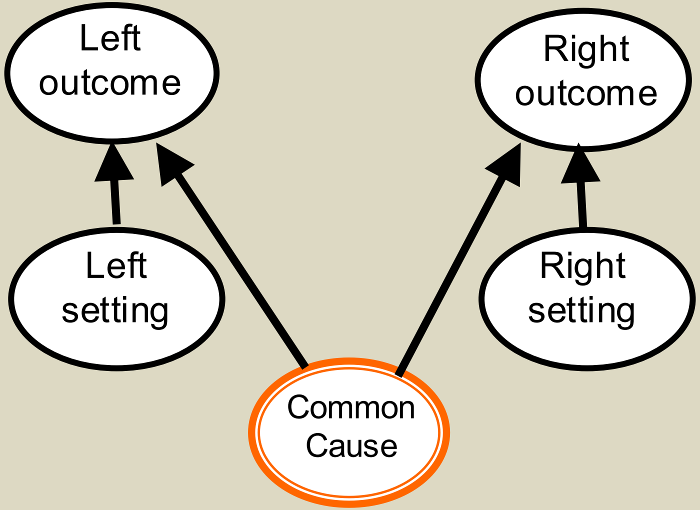

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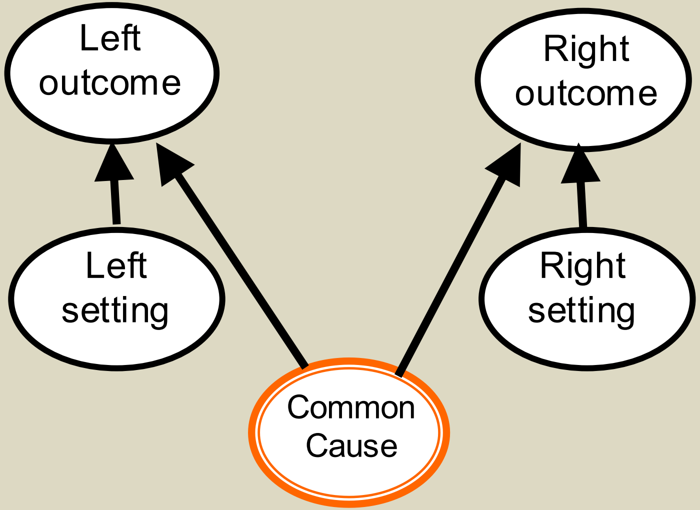

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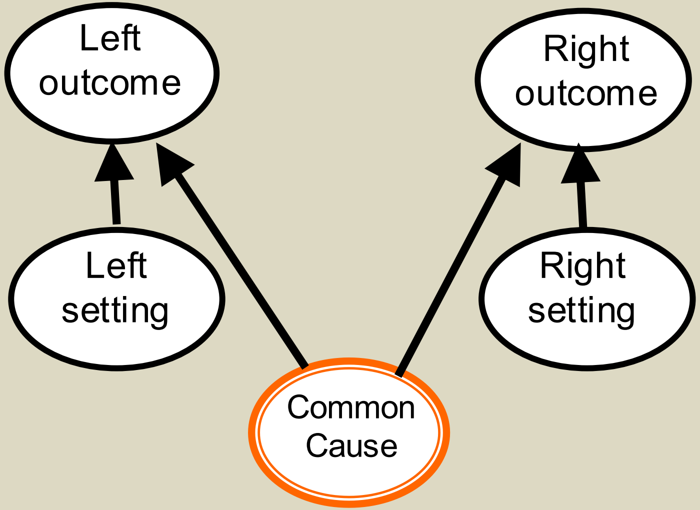

Implies a constraint:
Bell Inequalities

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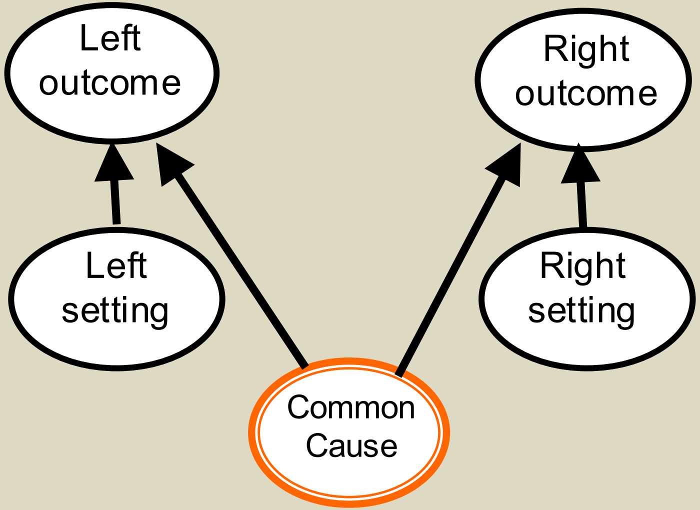
Violates the

Bell Inequalities!

The natural hypothesis



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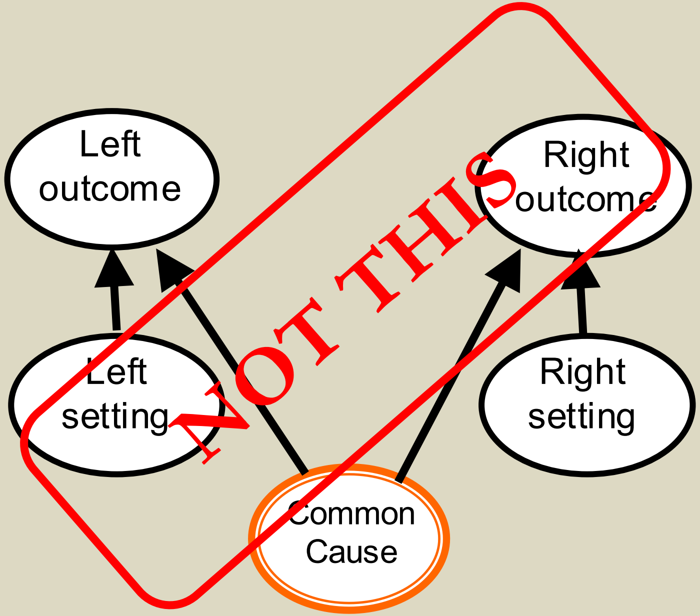
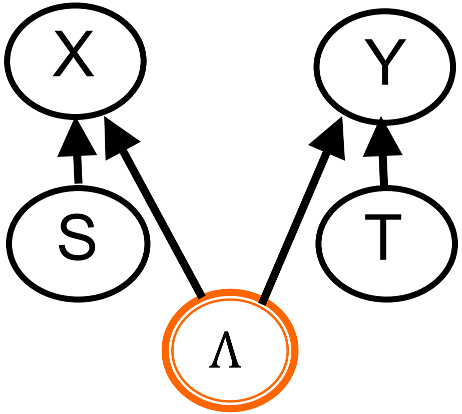


Implies a constraint:
Bell Inequalities

Incompatible

Causal structure



Parameters

$P_{X|S\Lambda}$

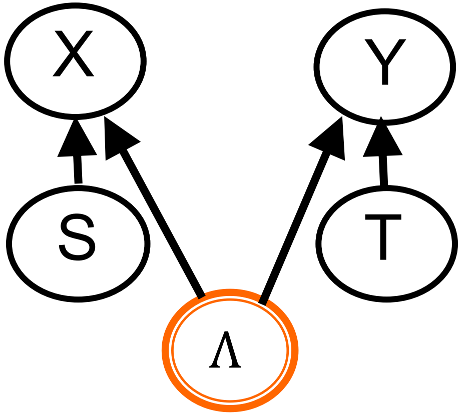
$P_{Y|T\Lambda}$

P_{Λ}

P_S

P_T

Causal structure



Parameters

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$P_{Y|T\Lambda}$

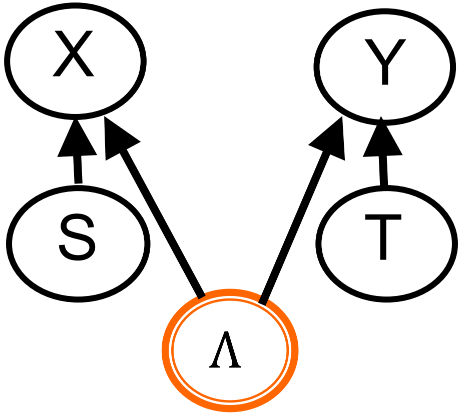
P_{Λ}

P_S

P_T

$$P_{XYST} = \sum_{\Lambda} P_{Y|T\Lambda} P_{X|S\Lambda} P_{\Lambda} P_S P_T$$

Causal structure



Parameters

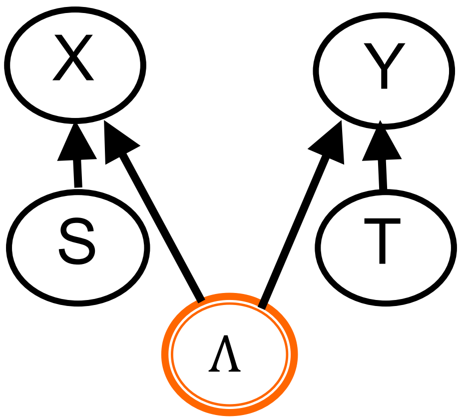
$P_{X|S\Lambda}$

$P_{Y|T\Lambda}$

P_{Λ}

$$P_{XY|ST} = \sum_{\Lambda} P_{Y|T\Lambda} P_{X|S\Lambda} P_{\Lambda}$$

Causal structure



Parameters

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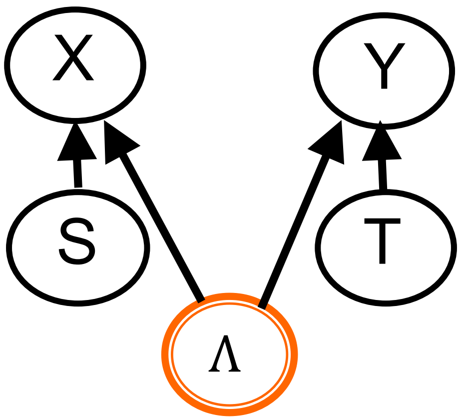
$P_{Y|T\Lambda}$

P_{Λ}

$$P_{XY|ST} = \sum_{\Lambda} P_{Y|T\Lambda} P_{X|S\Lambda} P_{\Lambda}$$

Examples of causal compatiblity constraints:

Causal structure Parameters



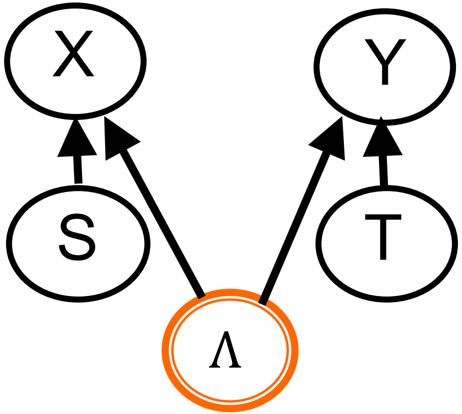
$P_{X|S\Lambda}$
$P_{Y|T\Lambda}$
P_{Λ}

$$P_{XY|ST} = \sum_{\Lambda} P_{Y|T\Lambda} P_{X|S\Lambda} P_{\Lambda}$$

Examples of causal compatiblity constraints:

$$P_{X|ST} = P_{X|S}$$
$$P_{Y|ST} = P_{Y|T}$$

Causal structure



Parameters

$$P_{X|S\Lambda}$$
$$P_{Y|T\Lambda}$$
$$P_{\Lambda}$$

$$P_{XY|ST} = \sum_{\Lambda} P_{Y|T\Lambda} P_{X|S\Lambda} P_{\Lambda}$$

Examples of causal compatiblity constraints:

$$P_{X|ST} = P_{X|S}$$
$$P_{Y|ST} = P_{Y|T}$$

$$\boxed{\begin{aligned} &\tfrac{1}{4}\sum_{x=y} P_{XY|ST}(xy|00) + \tfrac{1}{4}\sum_{x=y} P_{XY|ST}(xy|01) \\ &\quad \tfrac{1}{4}\sum_{x=y} P_{XY|ST}(xy|10) + \tfrac{1}{4}\sum_{x\neq y} P_{XY|ST}(xy|11) \leq \tfrac{3}{4} \end{aligned}}$$

Clauser, Horne, Shimony and Holte, Phys. Rev. Lett.23, 880 (1967)

The evidence

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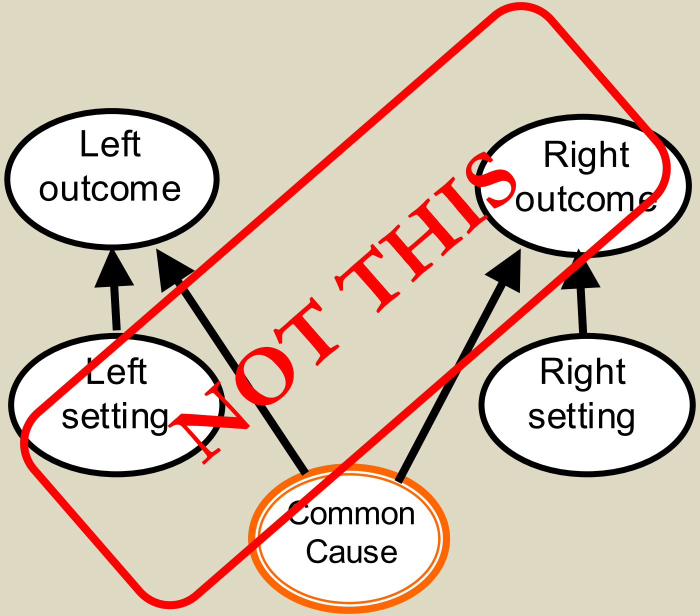
Violates the
Bell Inequalities!

The natural hypothesis



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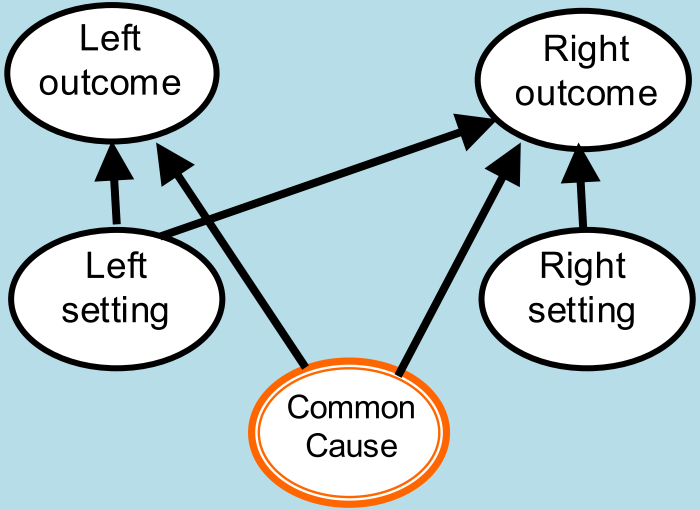
The 2nd possibility

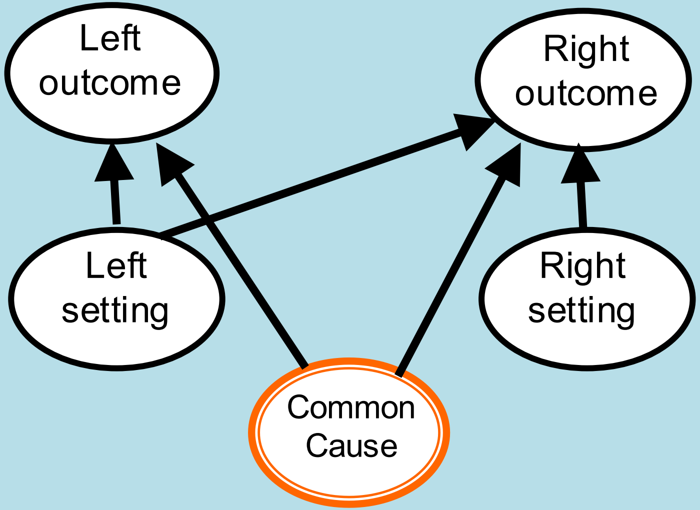


The evidence

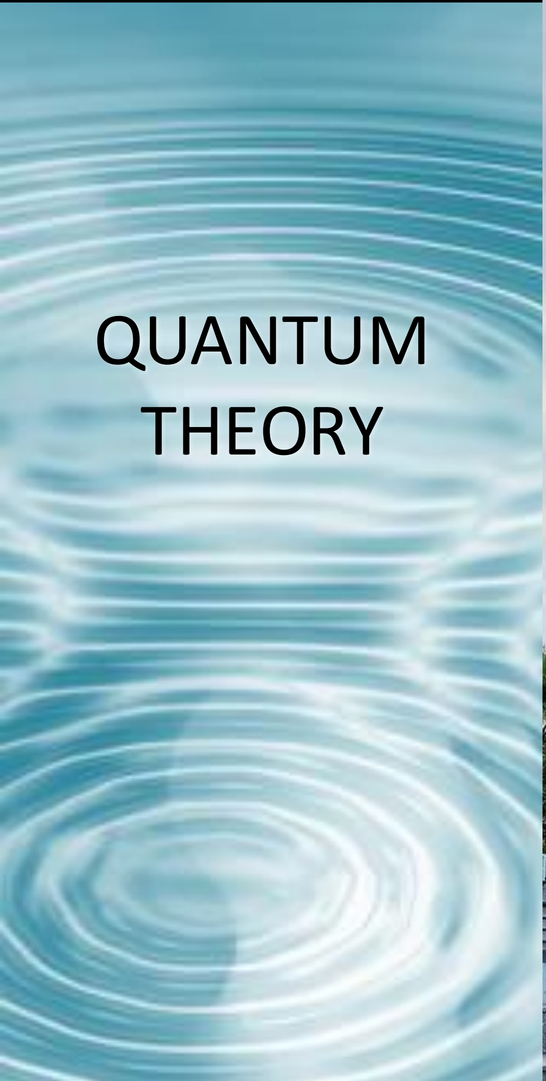
Left outcome and Right outcome

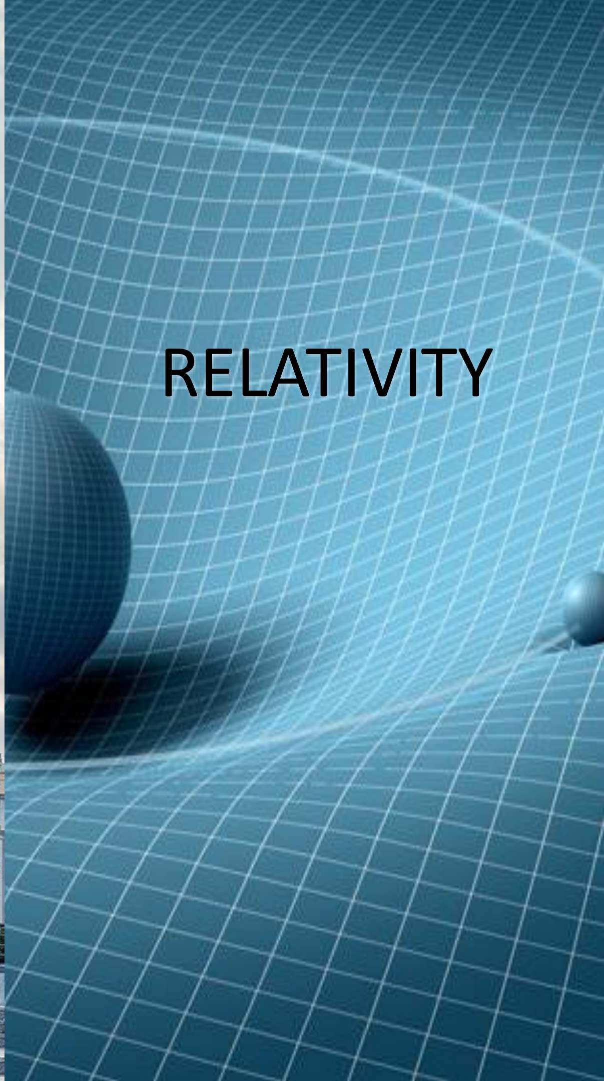
Left setting and Right setting	0 and 0	0 and 1	1 and 0	1 and 1
0 and 0	43%	7%	7%	43%
0 and 1	43%	7%	7%	43%
1 and 0	43%	7%	7%	43%
1 and 1	7%	43%	43%	7%

The 2nd possibility



Compatible


QUANTUM
THEORY

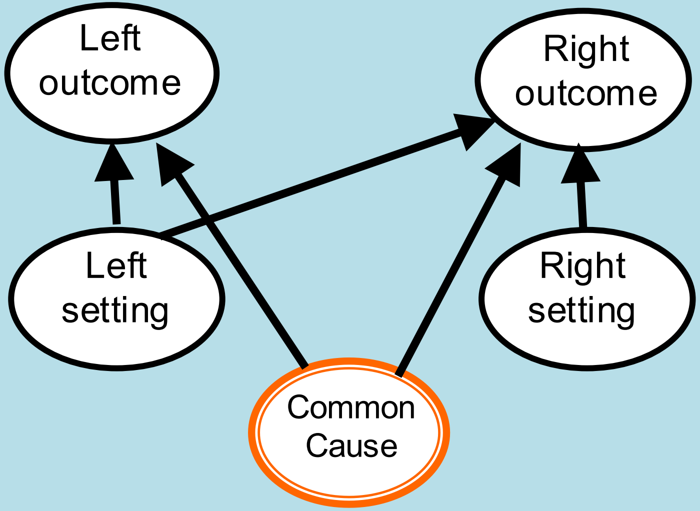

RELATIVITY

The evidence

Left outcome and Right outcome

Left setting and Right setting	0 and 0	0 and 1	1 and 0	1 and 1
0 and 0	43%	7%	7%	43%
0 and 1	43%	7%	7%	43%
1 and 0	43%	7%	7%	43%
1 and 1	7%	43%	43%	7%

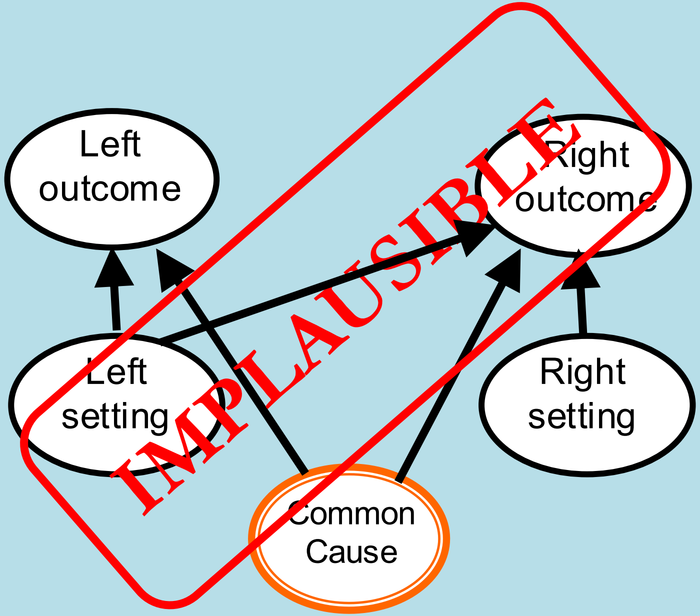
The 2nd possibility



The evidence

Left setting and Right setting	Left outcome and Right outcome: 0 and 0	0 and 1	1 and 0	1 and 1
0 and 0	43%	7%	7%	43%
0 and 1	43%	7%	7%	43%
1 and 0	43%	7%	7%	43%
1 and 1	7%	43%	43%	7%

The 2nd possibility

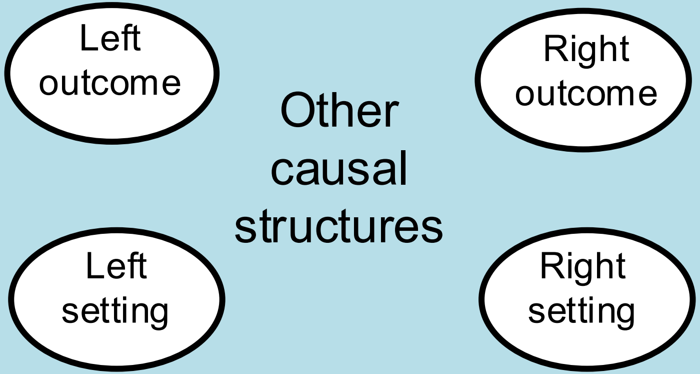


The evidence

Left outcome and Right outcome

Left setting and Right setting		0 and 0	0 and 1	1 and 0	1 and 1
	0 and 0	43%	7%	7%	43%
	0 and 1	43%	7%	7%	43%
	1 and 0	43%	7%	7%	43%
	1 and 1	7%	43%	43%	7%

The usual suspects



The evidence

	Left outcome and Right outcome			
Left setting and Right setting	0 and 0	0 and 1	1 and 0	1 and 1
0 and 0	43%	7%	7%	43%
0 and 1	43%	7%	7%	43%
1 and 0	43%	7%	7%	43%
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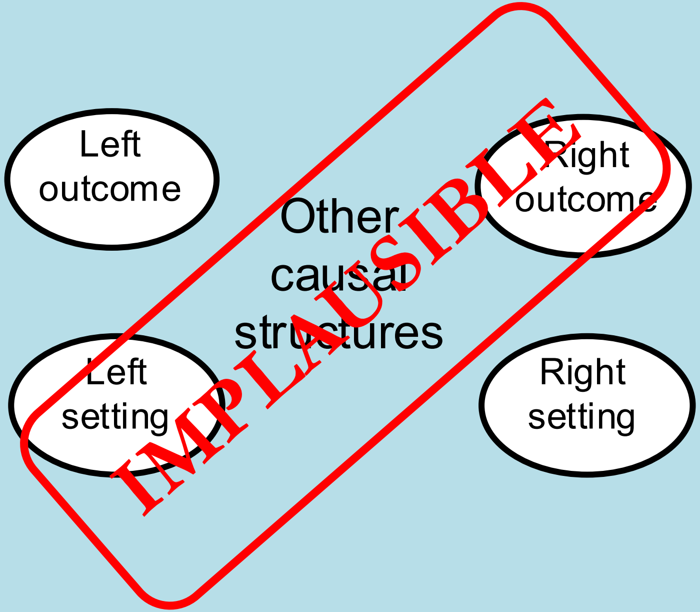
The usual suspects



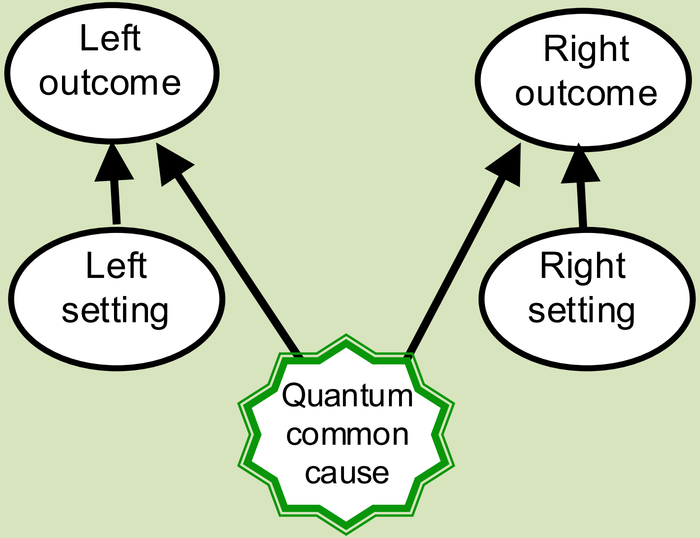
Wood and RWS, New J. Phys. 17, 033002 (2015)

The evidence

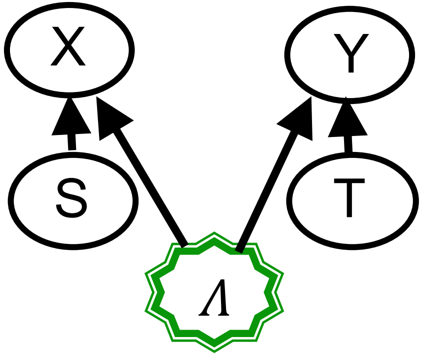
A new possibility

Left outcome and Right outcome

Left setting and Right setting		0 and 0	0 and 1	1 and 0	1 and 1
	0 and 0	43%	7%	7%	43%
	0 and 1	43%	7%	7%	43%
	1 and 0	43%	7%	7%	43%
	1 and 1	7%	43%	43%	7%



Quantum causal model



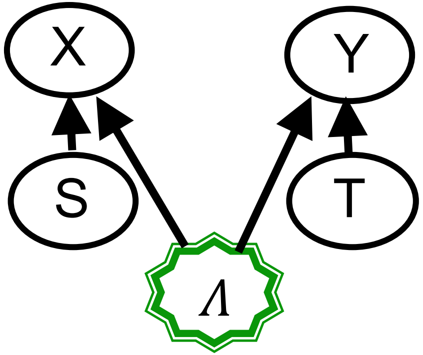
$\rho_{X|S\Lambda}$

$\rho_{Y|T\Lambda}$

ρ_{Λ}

$$[\rho_{X|S\Lambda}, \rho_{Y|T\Lambda}] = 0$$

Quantum causal model

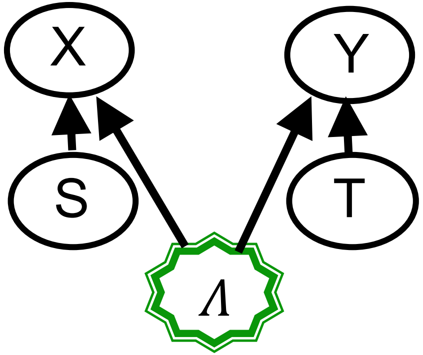


$$\rho_{X|S\Lambda}$$
$$\rho_{Y|T\Lambda}$$
$$\rho_{\Lambda}$$

$$[\rho_{X|S\Lambda}, \rho_{Y|T\Lambda}] = 0$$

$$P_{XY|ST} = \mathrm{Tr}_{\Lambda}(\rho_{X|S\Lambda}\rho_{Y|T\Lambda}\rho_{\Lambda})$$

Quantum causal model



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$$[\rho_{X|S\Lambda}, \rho_{Y|T\Lambda}] = 0$$

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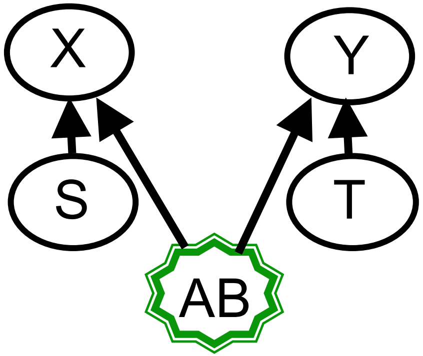
Leifer and RWS, PRA 88, 052130 (2013)
Henson, Lal & Pusey NJP 16, 113043 (2014)
Costa, Shrapnel NJP 18(6) (2016)
Allen, Barrett, Horsman, Lee & RWS, PRX 7, 031021 (2017)
Barrett, Lorenz, Oreshkov, arXiv:1906.10726

Quantum causal model



$\rho_{X|SA}$

$\rho_{Y|TB}$

ρ_{AB}

$$P_{XY|ST} = \mathrm{Tr}_{AB}(\rho_{X|SA}\rho_{Y|TB}\rho_{AB})$$

Leifer and RWS, PRA 88, 052130 (2013)
Henson, Lal & Pusey NJP 16, 113043 (2014)
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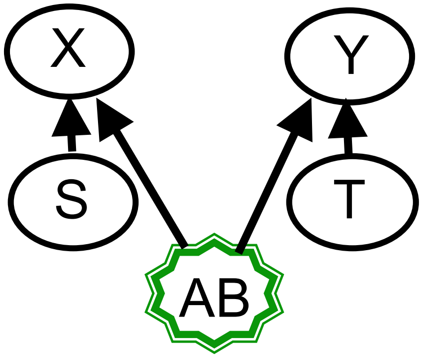
Quantum causal model



$\{E^A_{x|s}\}_x$ for each s

$\{E^B_{y|t}\}_y$ for each t

ρ_{AB}

$$P_{XY|ST}(xy|st) = \mathrm{Tr}_{AB}((E^A_{x|s} \otimes E^B_{y|t})\rho_{AB})$$

Leifer and RWS, PRA 88, 052130 (2013)
Henson, Lal & Pusey NJP 16, 113043 (2014)
Costa, Shrapnel NJP 18(6) (2016)
Allen, Barrett, Horsman, Lee & RWS, PRX 7, 031021 (2017)
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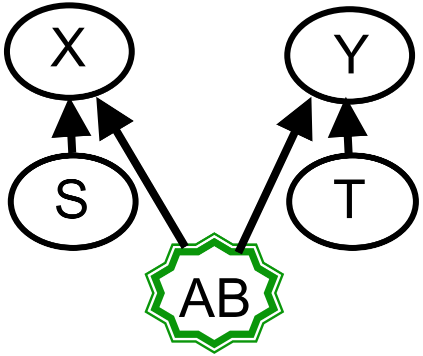
Quantum causal model



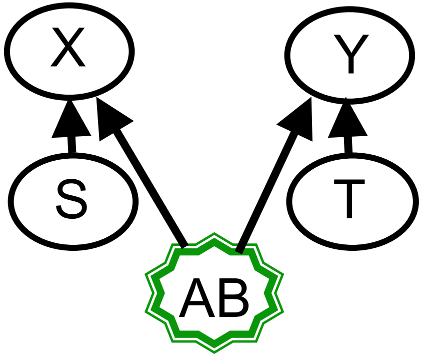
$\rho_{X|SA}$

$\rho_{Y|TB}$

ρ_{AB}

$$P_{XY|ST} = \mathrm{Tr}_{AB}(\rho_{X|SA}\rho_{Y|TB}\rho_{AB})$$

Quantum causal model



$$\rho_{X|SA}$$
$$\rho_{Y|TB}$$
$$\rho_{AB}$$

$$P_{XY|ST} = \mathrm{Tr}_{AB}(\rho_{X|SA}\rho_{Y|TB}\rho_{AB})$$

Causal compatibility constraints:

$$P_{X|ST} = P_{X|S}$$
$$P_{Y|ST} = P_{Y|T}$$

$$\boxed{\begin{aligned}&\tfrac{1}{4}\textstyle\sum_{x=y} P_{XY|ST}(xy|00) + \tfrac{1}{4}\sum_{x=y} P_{XY|ST}(xy|01)\\ &\tfrac{1}{4}\textstyle\sum_{x=y} P_{XY|ST}(xy|10) + \tfrac{1}{4}\sum_{x\neq y} P_{XY|ST}(xy|11) \leq \tfrac{1}{2} + \tfrac{1}{2\sqrt{2}}\end{aligned}}$$

Tsirelson, Lett. Math. Phys. 4, 93 (1980)

The evidence

A new possibility

		Left outcome and Right outcome			
		0 and 0	0 and 1	1 and 0	1 and 1
Left setting and Right setting	0 and 0	43%	7%	7%	43%
	0 and 1	43%	7%	7%	43%
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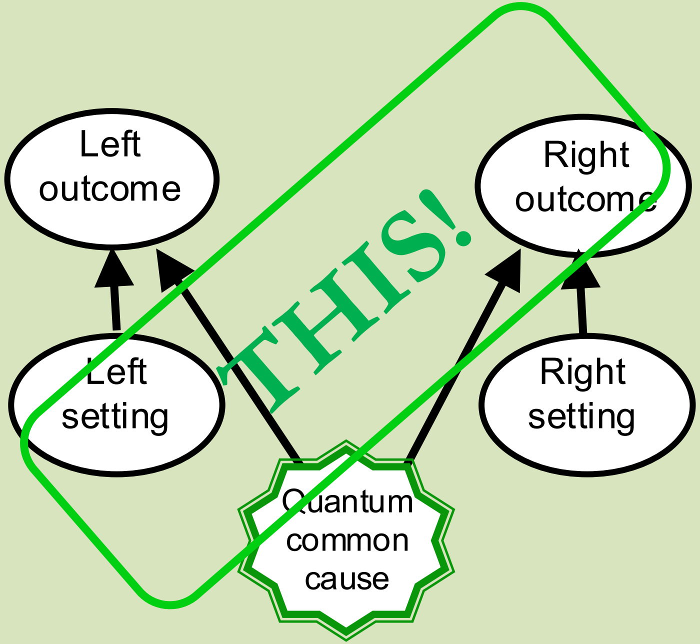
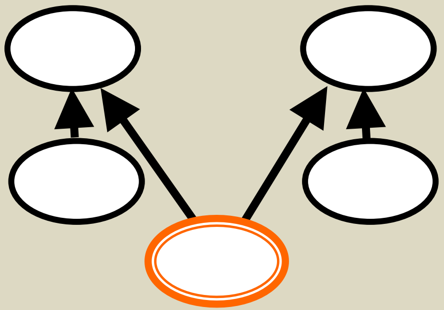
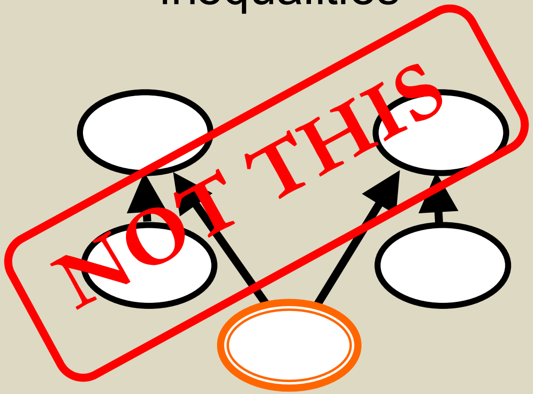


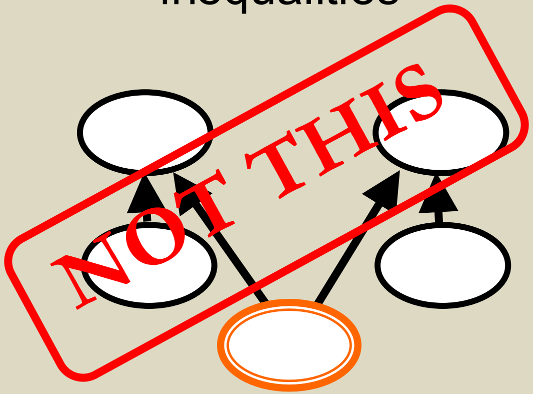
Compatible

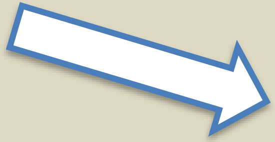


Violation of Bell inequalities

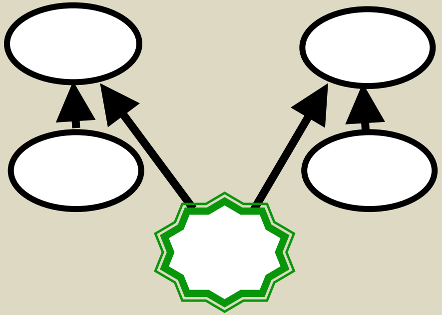


Violation of Bell inequalities

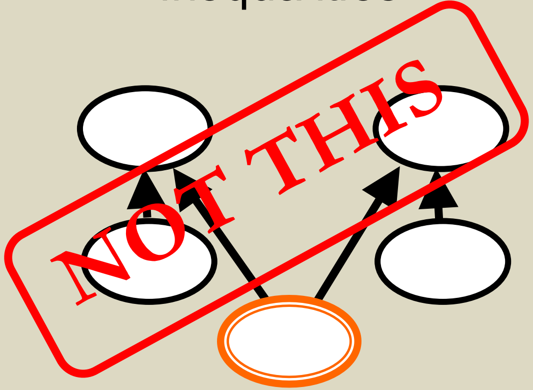




Witnessing quantumness

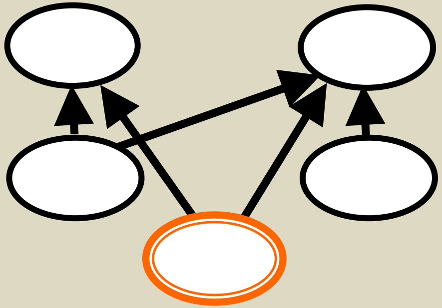


Violation of Bell inequalities

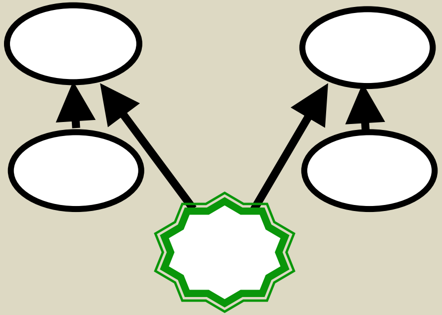


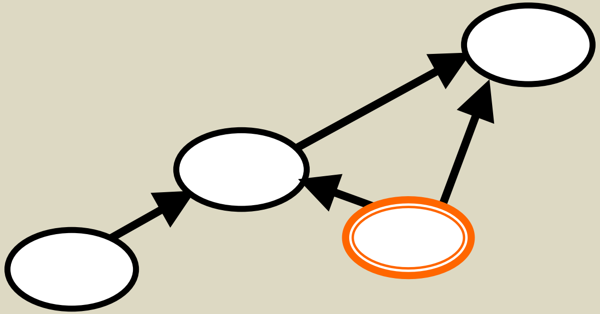
or

Witnessing need for different structure

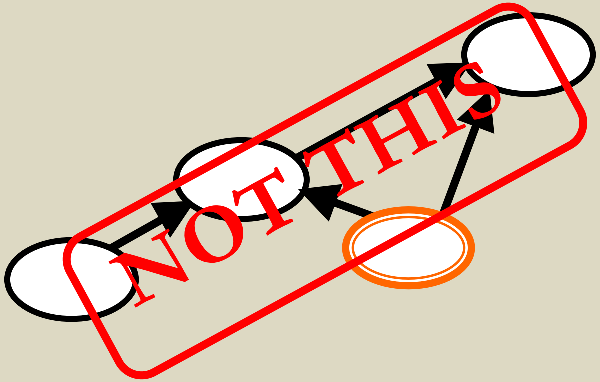


Witnessing quantumness

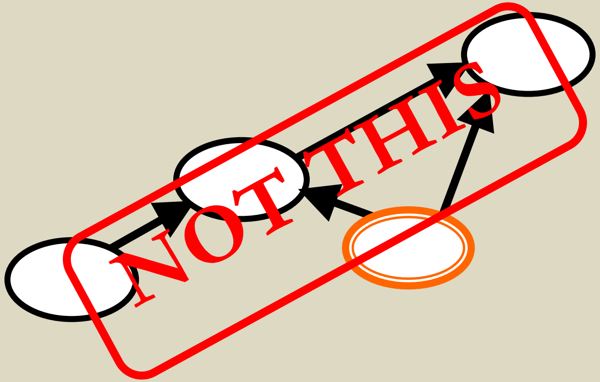




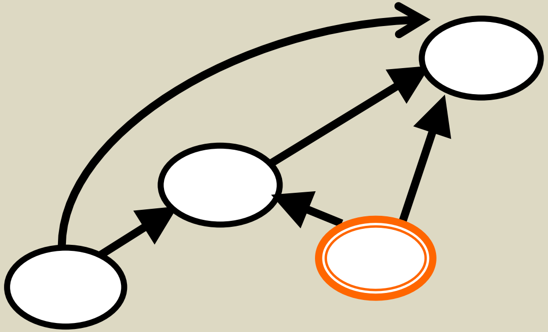
Violation of
Instrumental
Inequalities



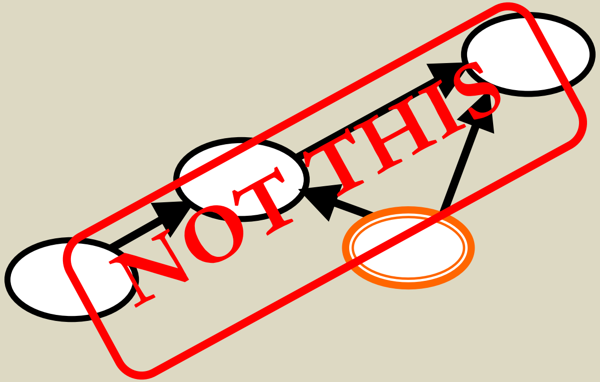
Violation of Instrumental Inequalities



Witnessing need for different structure

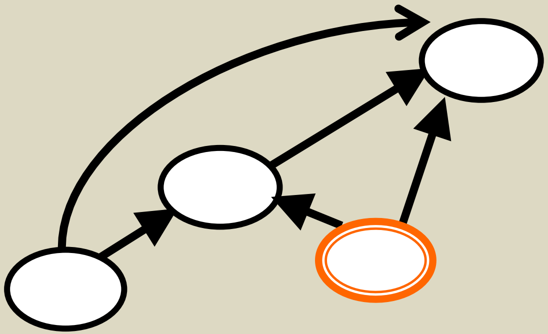


Violation of
Instrumental
Inequalities

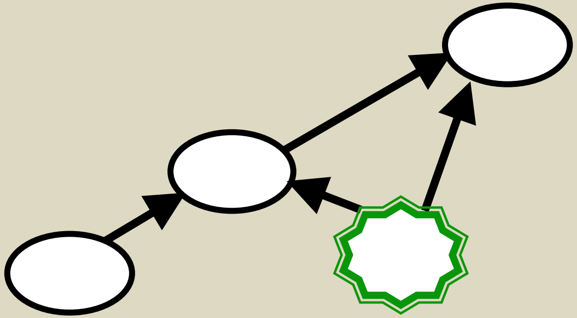


or

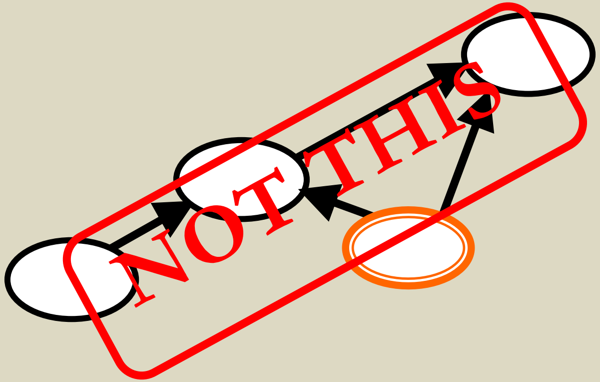
Witnessing need for
different structure



Witnessing
quantumness



Violation of Instrumental Inequalities



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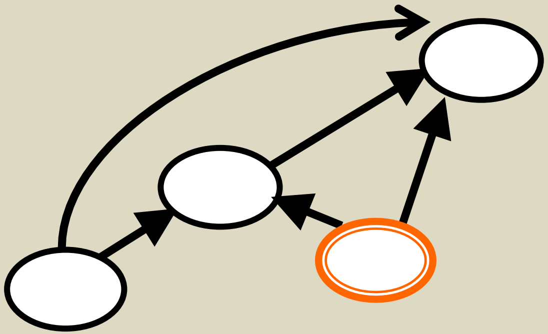
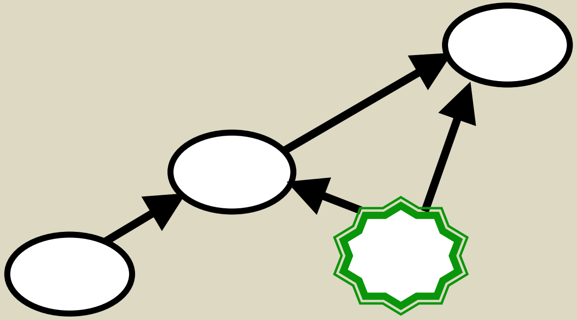
Witnessing need for different structure

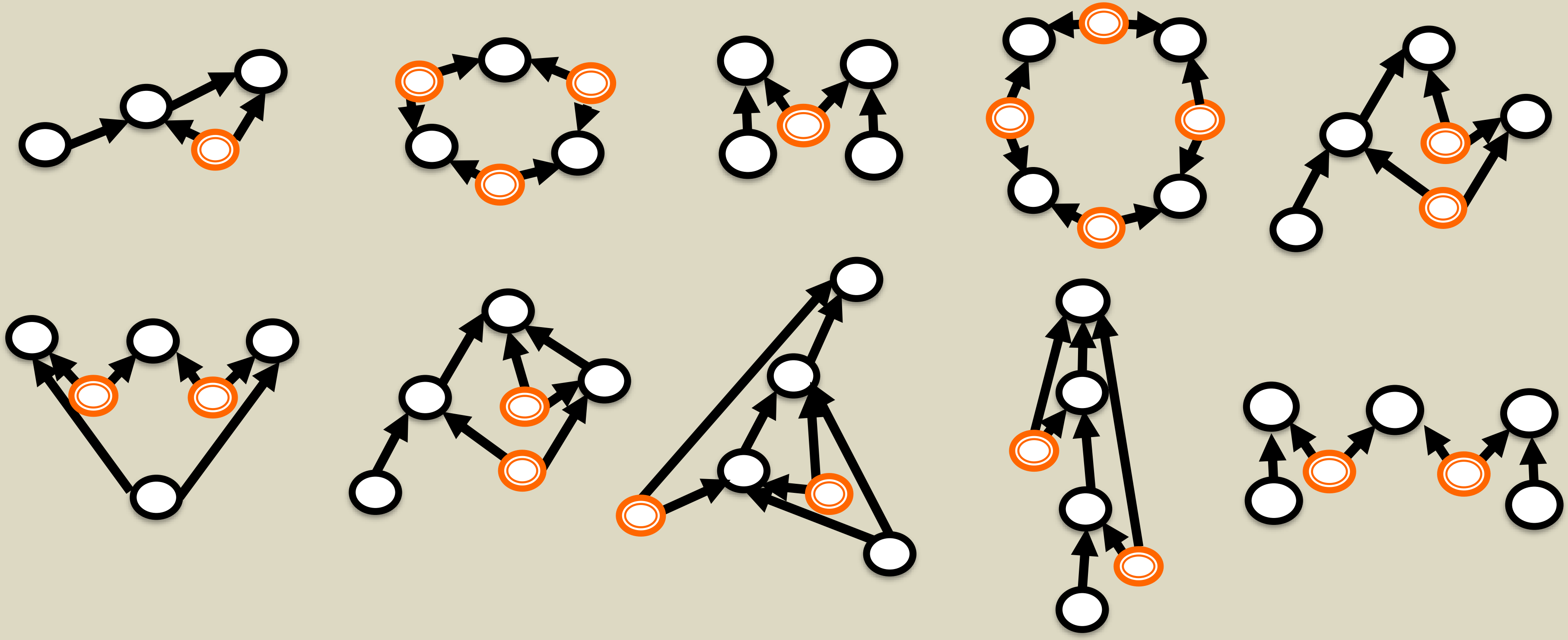


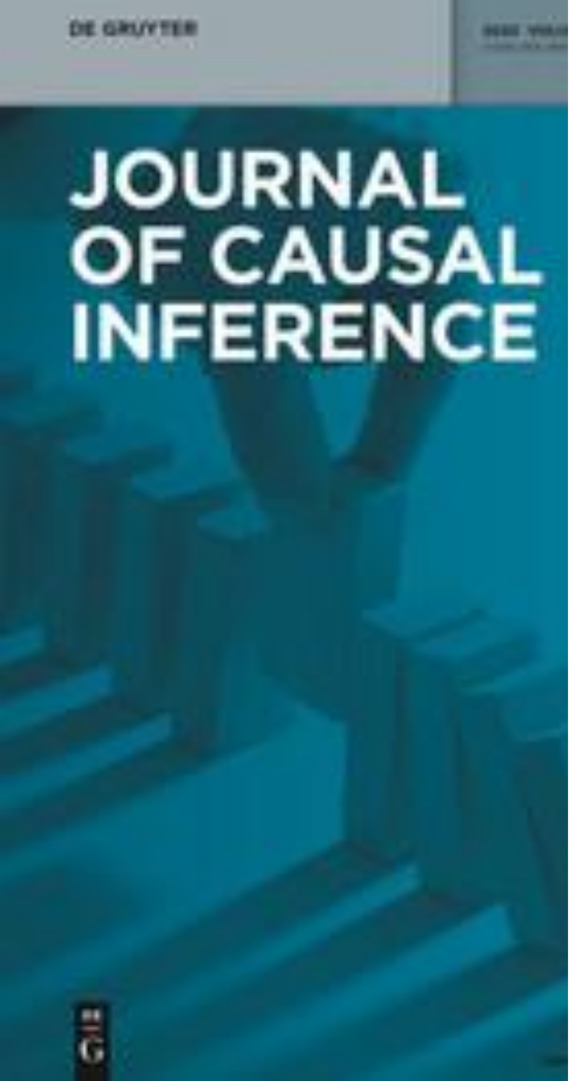
Witnessing quantumness



van Himbeeck, Bohr Brask, Pironio, Ramanathan, Sainz & Wolfe, *Quantum* 3, 186 (2019)
Chaves, Carvacho, Agresti, Di Giulio, Aolita, Giacomini & Sciarrino, *Nat. Phys.* 47, 291296 (2018)

Some causal structures that admit of inequality constraints





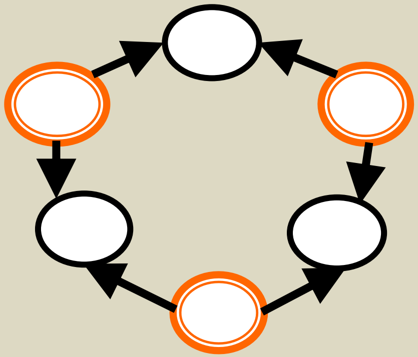
DE GRUYTER J. Causal Infer. 2019; 20170020

Elie Wolfe*, Robert W. Spekkens, and Tobias Fritz

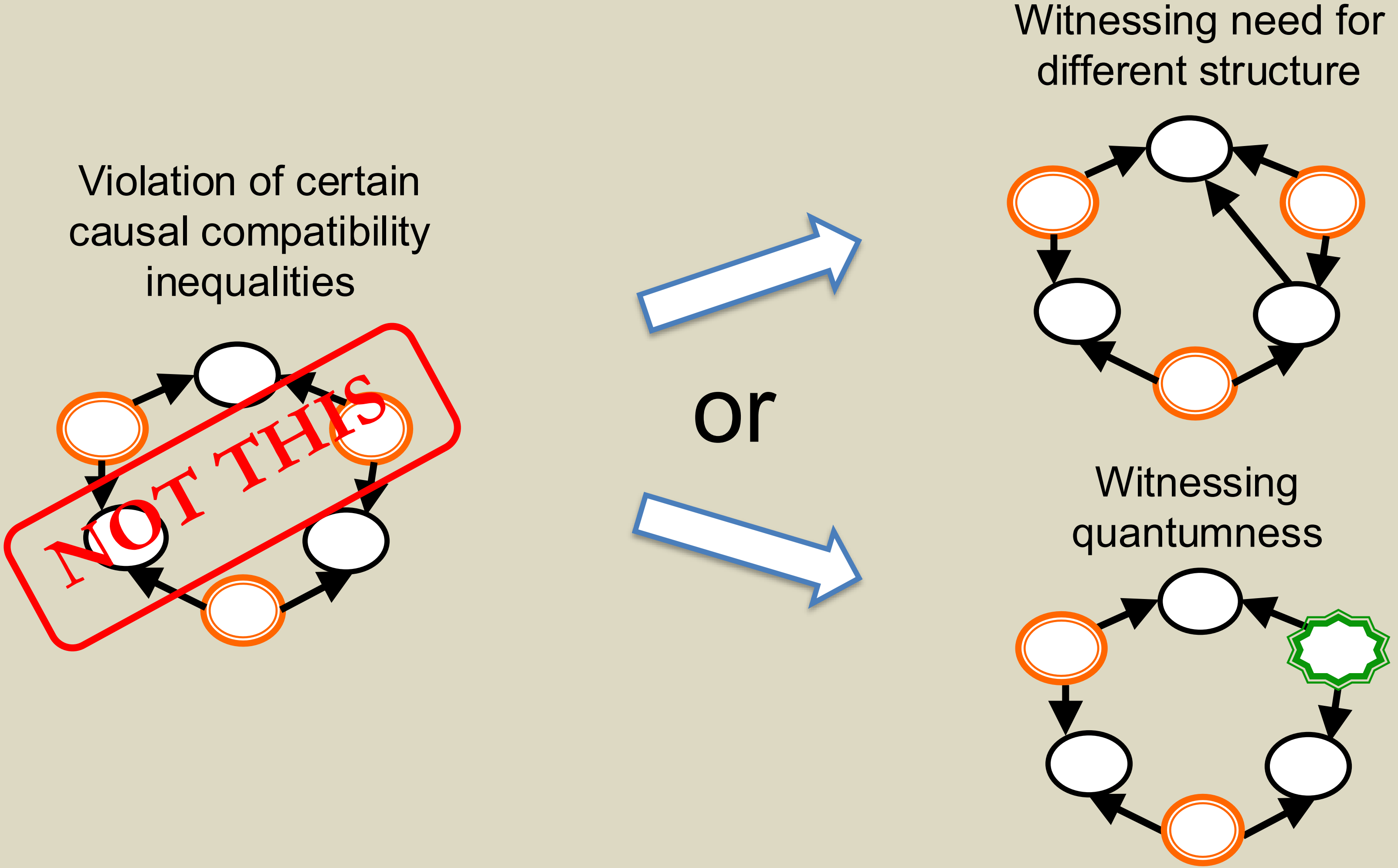
The Inflation Technique for Causal Inference with Latent Variables

https://doi.org/10.1515/jci-2017-0020
Received August 16, 2017; revised August 31, 2018; accepted June 10, 2019

Abstract: The problem of causal inference is to determine if a given probability distribution on observed variables is compatible with some causal structure. The difficult case is when the causal structure includes latent variables. We here introduce the *inflation technique* for tackling this problem. An inflation of a causal structure is a new causal structure that can contain multiple copies of each of the original variables, but where the ancestry of each copy mirrors that of the original. To every distribution of the observed variables that is compatible with the original causal structure, we assign a family of marginal distributions on certain subsets of the copies that are compatible with the inflated causal structure. It follows that compatibility constraints for the inflation can be translated into compatibility constraints for the original causal structure. Even if the constraints at the level of inflation are weak, such as observable statistical independences implied by disjoint causal ancestry, the translated constraints can be strong. We apply this method to derive new inequalities whose violation by a distribution witnesses that distribution's incompatibility with the causal structure (of which Bell inequalities and Pearl's instrumental inequality are prominent examples). We describe an algorithm for deriving all such inequalities for the original causal structure that follow from ancestral independences in the inflation. For three observed binary variables with pairwise common causes, it yields inequalities that are stronger in at least some aspects than those obtainable by existing methods. We also describe an algorithm that derives a weaker set of inequalities but is more efficient. Finally, we discuss which inflations are such that the inequalities one obtains from them remain valid even for quantum (and post-quantum)



Violation of certain causal compatibility inequalities

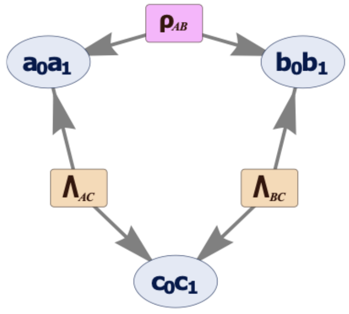


Violation of certain causal compatibility inequalities
NOT THIS
or
Witnessing need for different structure
Witnessing quantumness

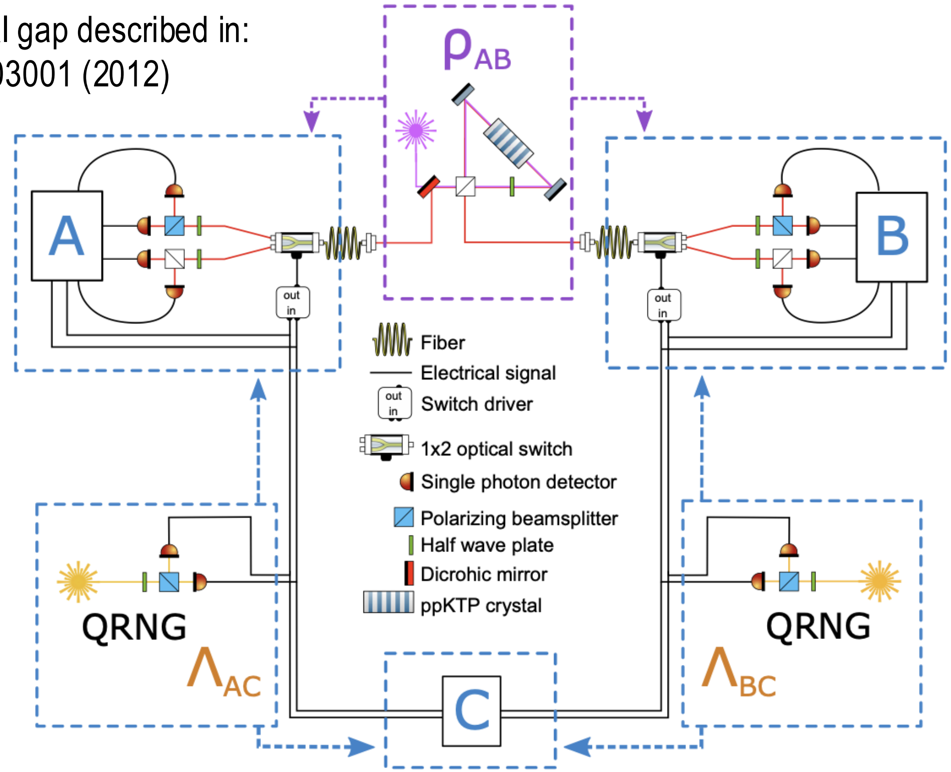
Collaboration with experimental group of Fabio Sciarrino

Polino et al., Nature Communications 14, 909 (2023)

Targeting the quantum-classical gap described in:
Fritz, New J. Phys. 14, 103001 (2012)



Experimental DAG

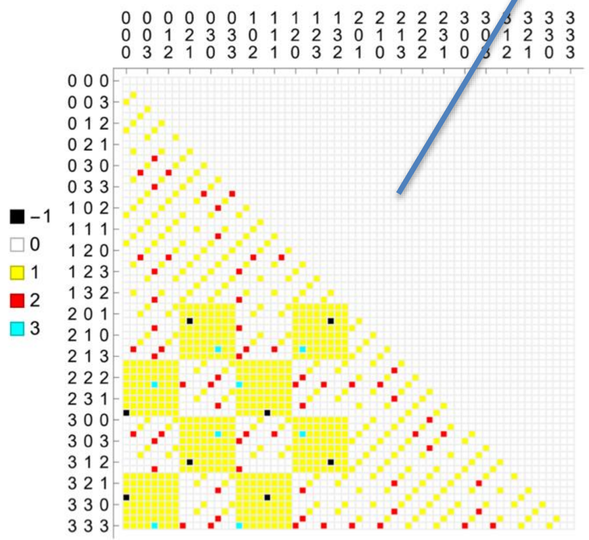


Data-seeded inflation technique

$$V := \sum_{a,b,c,a',b',c'} y_{abca'b'c'} P_{ABC}(abc) P_{ABC}(a'b'c') \geq 0$$

Data-seeded inflation technique

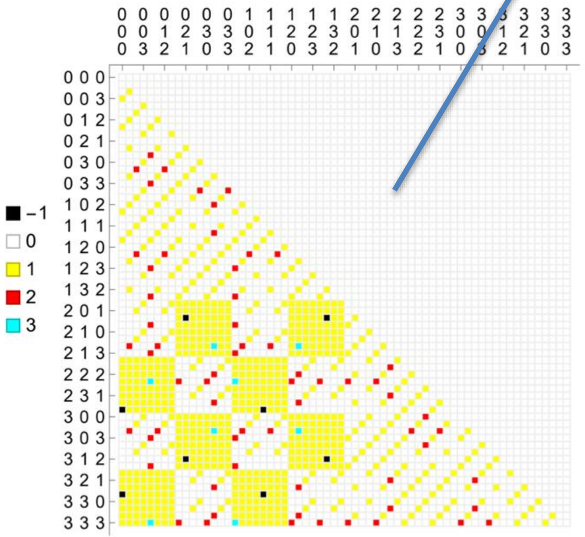
$$V := \sum_{a,b,c,a',b',c'} y_{abca'b'c'} P_{ABC}(abc) P_{ABC}(a'b'c') \geq 0$$



(b) **The coefficients of a quadratic inequality**

Data-seeded inflation technique

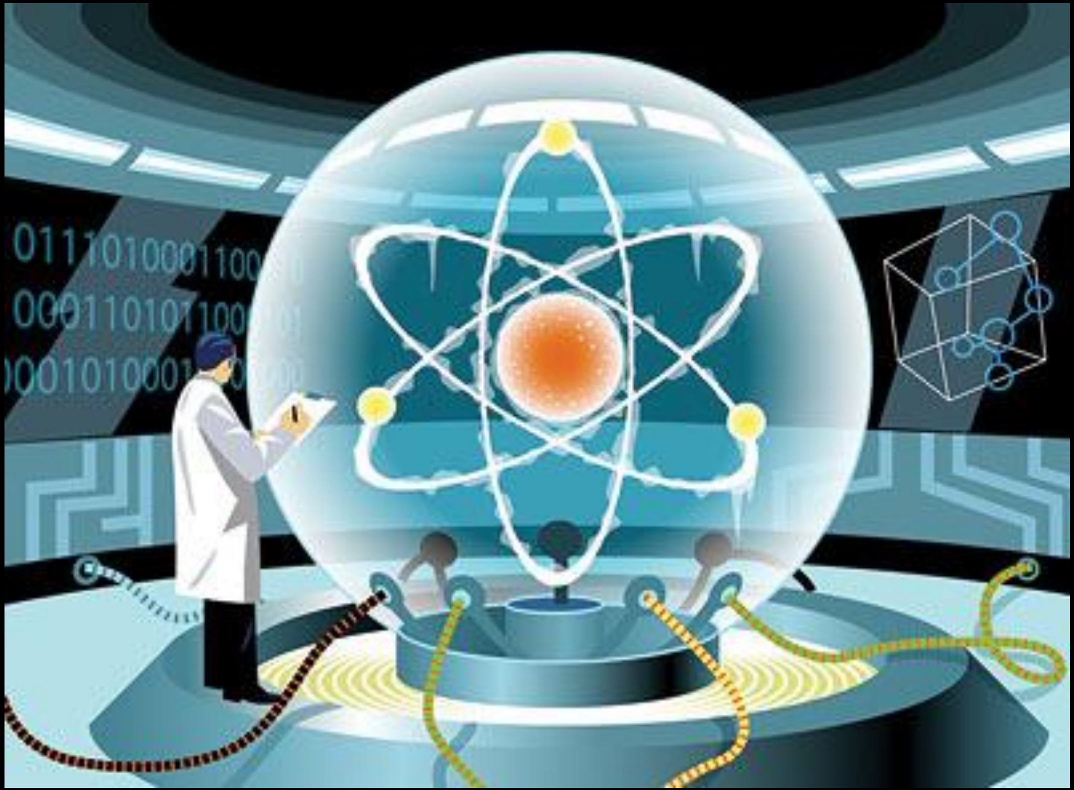
$$V := \sum_{a,b,c,a',b',c'} y_{abca'b'c'} P_{ABC}(abc) P_{ABC}(a'b'c') \geq 0$$

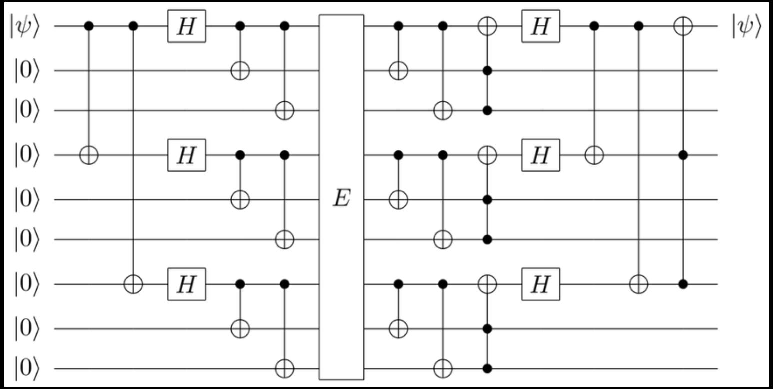

(b) **The coefficients of a quadratic inequality**

This causal compatibility inequality is violated by the data

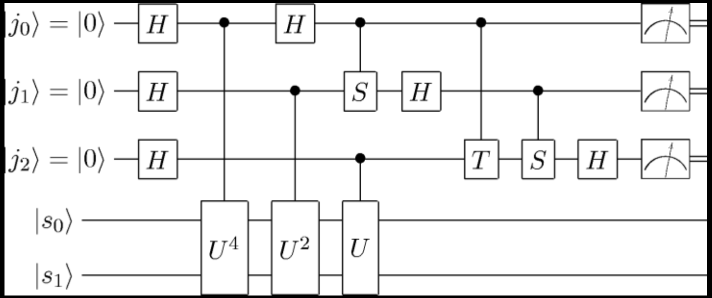
$$V_{\mathrm{exp}} = -0.02436 \pm 0.00016$$

Applications for Quantum Technology





$|\psi\rangle$
$|0\rangle$
H
E
$|\psi\rangle$



$|j_0\rangle = |0\rangle$
$|j_1\rangle = |0\rangle$
$|j_2\rangle = |0\rangle$
$|s_0\rangle$
$|s_1\rangle$
H
S
T
U^4
U^2
U

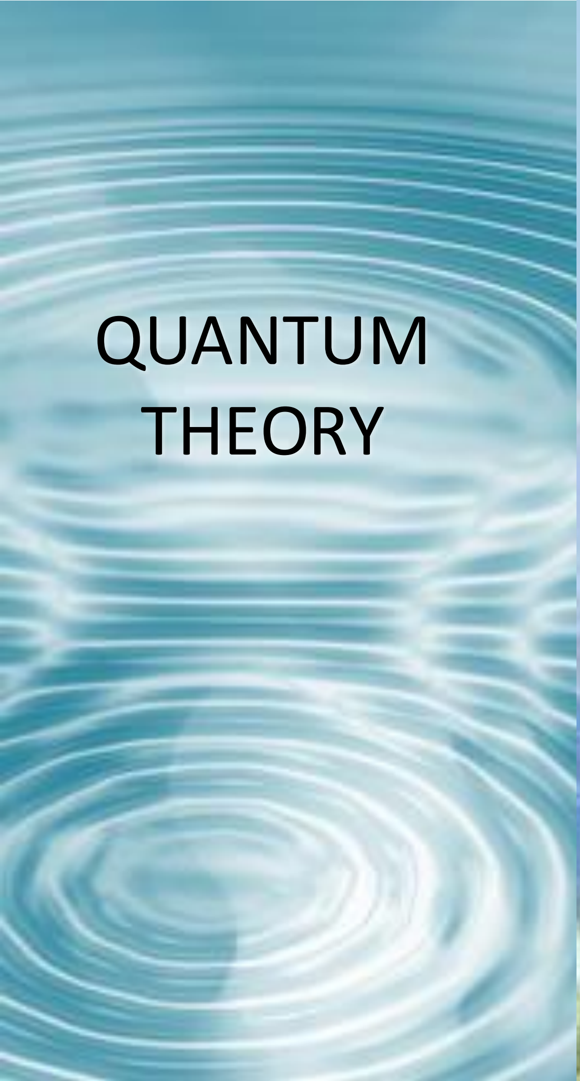
Applications to Quantum Physics

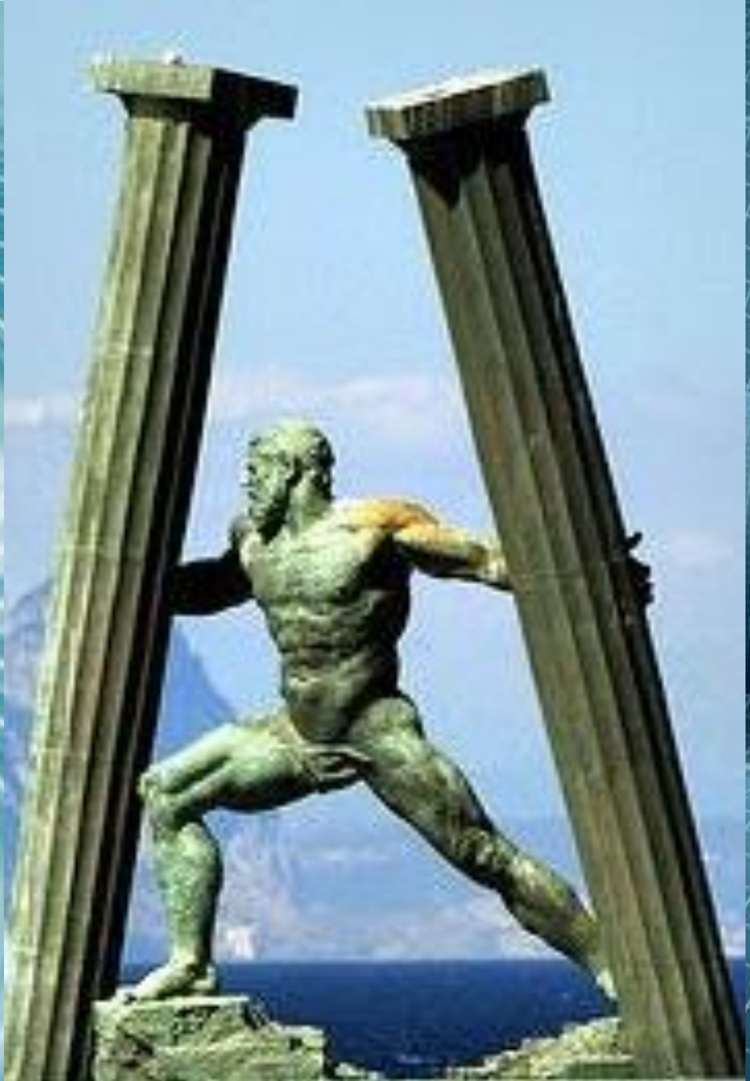
The formalism and conceptual scheme of causal inference resolved various puzzles of statistics (e.g., Simpson’s paradox)

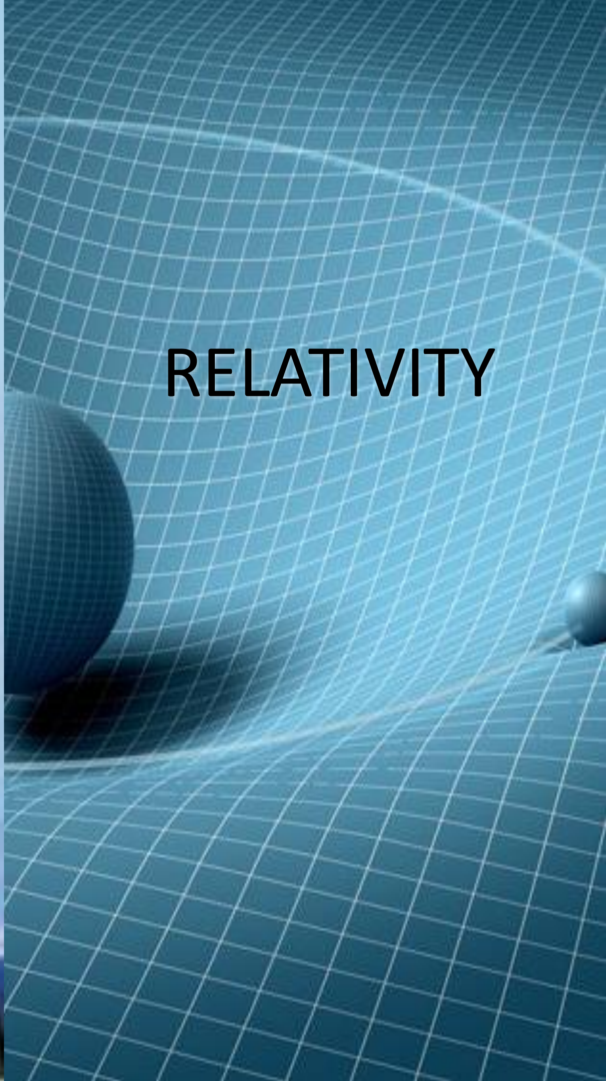
The lesson:
We must unscramble the omelette of inference and causation both conceptually and in the formalism

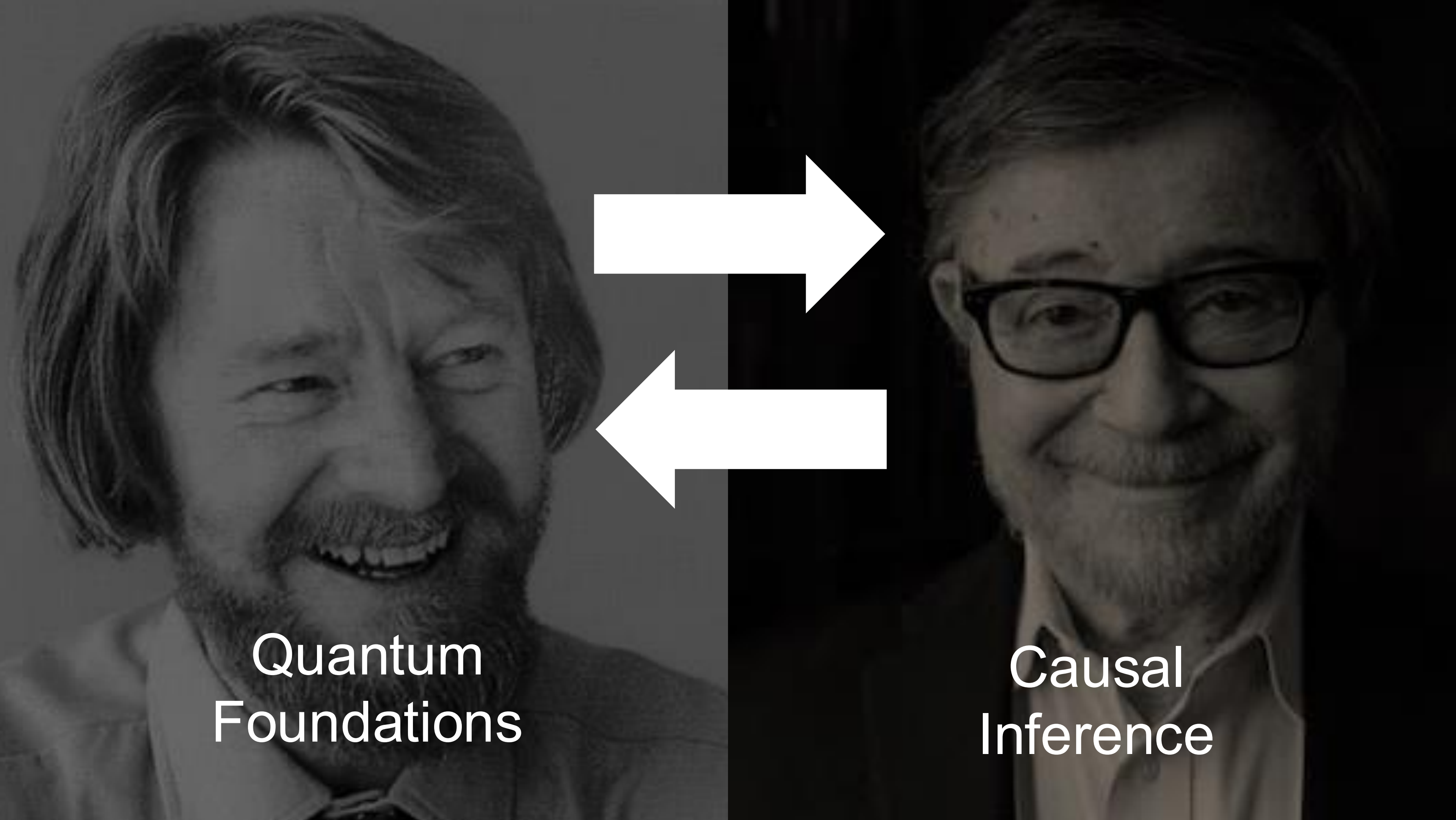
But what hope do we have of succeeding in the quantum context if we do not understand how to do so in the classical context?

$$\frac{\text{Quantum Causation and Inference}}{\text{Classical Causation and Inference}} \approx \frac{\text{Relativistic Notions of Space and Time}}{\text{PreRelativistic Notions of Space and Time}}$$


QUANTUM
THEORY




RELATIVITY


Quantum
Foundations
Causal
Inference