A quantum experiment with joint exogeneity violation

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Joint work with Dr. Xingjian Zhang from University of Hong Kong

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Based on joint work with

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Acknowledgement

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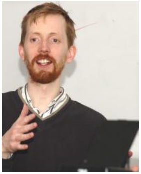

Thomas Richardson
U. of Washington

Causal inference 101

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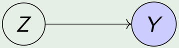
There are two types of exogeneity assumption in the literature:



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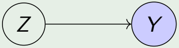

- **marginal exogeneity**: $Y(z) \perp\!\!\!\perp Z$ for $z \in \{0, 1\}$;
- **joint exogeneity**: $(Y(1), Y(0)) \perp\!\!\!\perp Z$.

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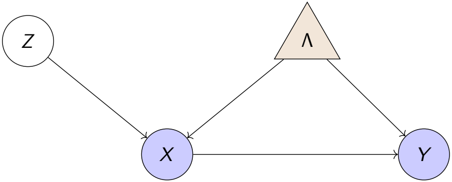
- We provide an example where assuming joint exogeneity of a fully randomized assignment results in a **contradiction** with other basic principles of causal models;
- We further discuss philosophical insights / open questions from this violation.

Experiment: a randomized experiment with noncompliance



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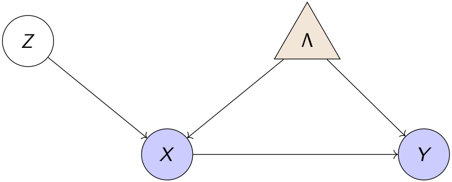

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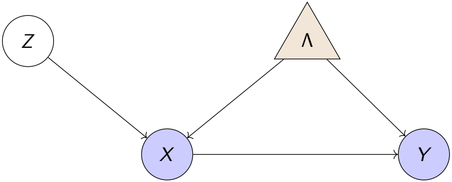

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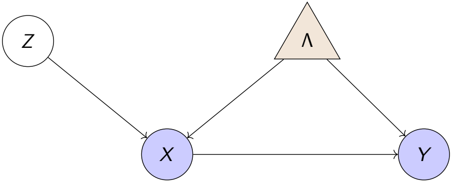

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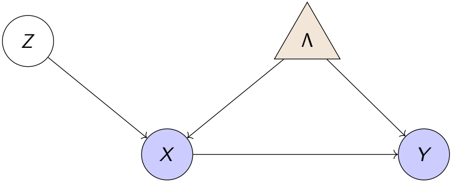

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$\Rightarrow$ **Ex:** adjusting the angle of polarizer based on the outputs.

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Theorem

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Then $\mathcal{I}_Q := -\langle Y\rangle_1 + 2\langle Y\rangle_2 + \langle X\rangle_1 - \langle XY\rangle_1 + 2\langle XY\rangle_3 \leq 3$, *where*

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This results in a **contradiction**:

- Chaves et al. (Nat. Phy. '18): there exists a quantum system constructed **according to** the IV graph s.t. $\mathcal{I}_Q > 3$.

$\Rightarrow$ It can be $\mathcal{I}_Q = 1 + 2\sqrt{2}$.

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  - Consistency
  - Intervention representability.

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Follows from exactly the same logic as def. of ATT / ATC:

- $\mathbb{E}[Y(1) \mid T = 1] - \mathbb{E}[Y(0) \mid T = 1]$;
- or more generally: $\mathbb{E}[Y(\boldsymbol{t}) \mid \boldsymbol{T} = \boldsymbol{t}']$.

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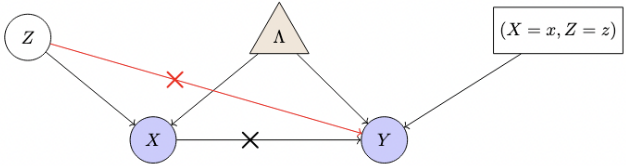

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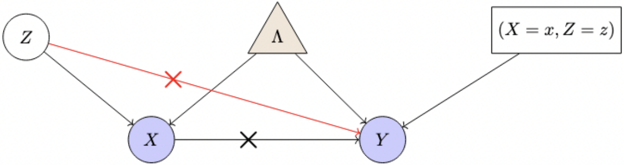

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- $M_x^z, N_y^x \in \mathbb{H}^{2\times 2}$: specification of how the photons sent to X&Y are measured;
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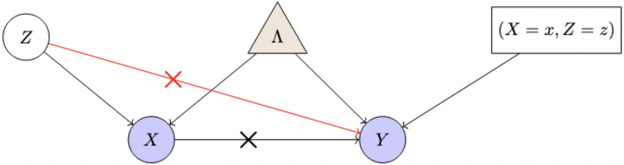

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$$\Downarrow$$

$$\mathbb{P}(Y(x, z_1) = y \mid X = x', Z = z') = \mathbb{P}(Y(x, z_2) = y \mid X = x', Z = z')$$

(stratified exclusion restriction).

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Problem transferred to: giving an upper bound of $\mathcal{I}_Q$ under stratified exclusion restriction & joint exogeneity;

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Proved that $\mathcal{I}_Q \leq 3$.

Assumption summary

Assumption 1

There exists random variables $Y(0,1), \ldots, Y(1,3)$ with

(i) Consistency;

(ii) Intervention representability.

Assumption 2

Joint exogeneity

$$Z \perp\!\!\!\perp (Y(0,1), \ldots, Y(1,3)).$$

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Joint exogeneity

$$Z \perp\!\!\!\perp (Y(0,1),\ldots,Y(1,3)).$$

Consistency seems to be a fundamental assumption, so more likely:

joint exogeneity & intervention representability

cannot co-exist.

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- So it's **more likely** that J.E. is violated.

Discussions & Open questions

Conditional interventional distribution

The contradiction motivates me to take a further investigation into $\Rightarrow$

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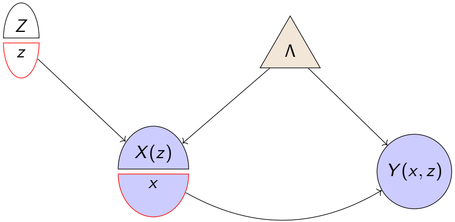
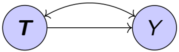


$\Rightarrow$ we can only define $\mathbb{P}(Y(x,z) = y \mid X = x', Z = z)$

Open question



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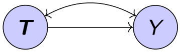

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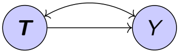

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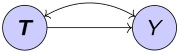

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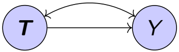

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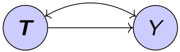

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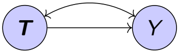

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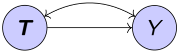

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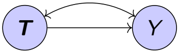

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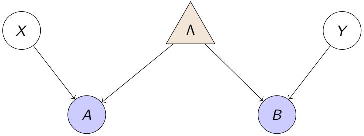
- **If not,** does that mean P.O.s **cannot** model all ATT/ATC like queries?

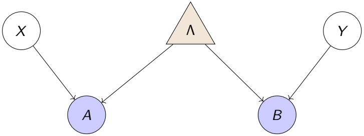
Connections to Bell experiments



Showed the following three physical principles cannot coexist:

- Realism, freedom & locality;

Connections to Bell experiments



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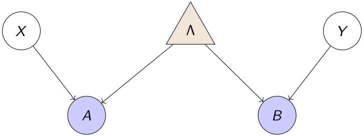

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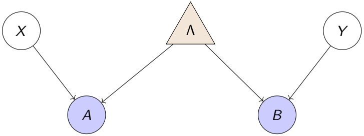

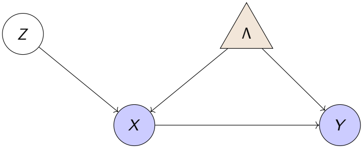

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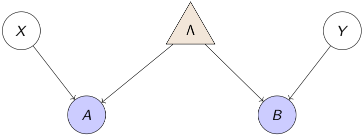

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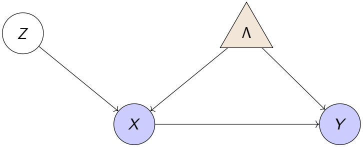

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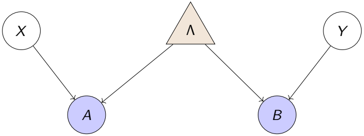

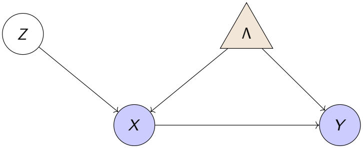

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- **Q:** since we don't assume "locality", why contradiction still exists?

Discussion with quantum physcists / quantum logician

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⇝ Different from Robins et al. (15), Gill (14): locality is not required if we just want to define P.O.s.

Thank you for your attention!

Previous version (may be substantially revised based on feedbacks from open questions):

Wang, Y., & Zhang, X. (2025). *"A quantum experiment with joint exogeneity violation."* arXiv:2507.22747