Title: Agency, causal structure and locality in Qbism

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Abstract: In QBism, a quantum state represents an agent's personal degrees of belief regarding the consequences of her actions on any part of her external world. The quantum formalism provides consistency criteria that enable the agent to make better decisions. QBism thus gives a central role to the agent, or user of the theory, and explicitly rejects the ontological model framework introduced by Harrigan and Spekkens. This talk addresses the status of agents and the notion of locality in QBism. Our definition of locality is independent of the assumption of an ontological model. Instead it depends on an appropriate formalization of the idea of a causal structure.

Carl Caves, Chris Fuchs, RS, PRA 2002

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Quantum probabilities as Bayesian probabilities

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In the Bayesian approach to probability theory, probability quantifies a degree of belief for a single trial, without any *a priori* connection to limiting frequencies. In this paper, we show that, despite being prescribed by a fundamental law, probabilities for individual quantum systems can be understood within the Bayesian approach. We argue that the distinction between classical and quantum probabilities lies not in their definition, but in the nature of the information they encode. In the classical world, *maximal* information about a physical system is *complete* in the sense of providing definite answers for all possible questions that can be asked of the system. In the quantum world, *maximal information is not complete and cannot be completed.* Using this distinction, we show that any Bayesian probability assignment in quantum mechanics must have the form of the quantum probability rule, that maximal information about a quantum system leads to a unique quantum-

David Mermin, Nature, 27 March 2014

Pablo Picasso, *Le Vieux Marc* (oil on canvas), 1912.

QBism puts the scientist back into science

In QBism, quantum states are personal judgments

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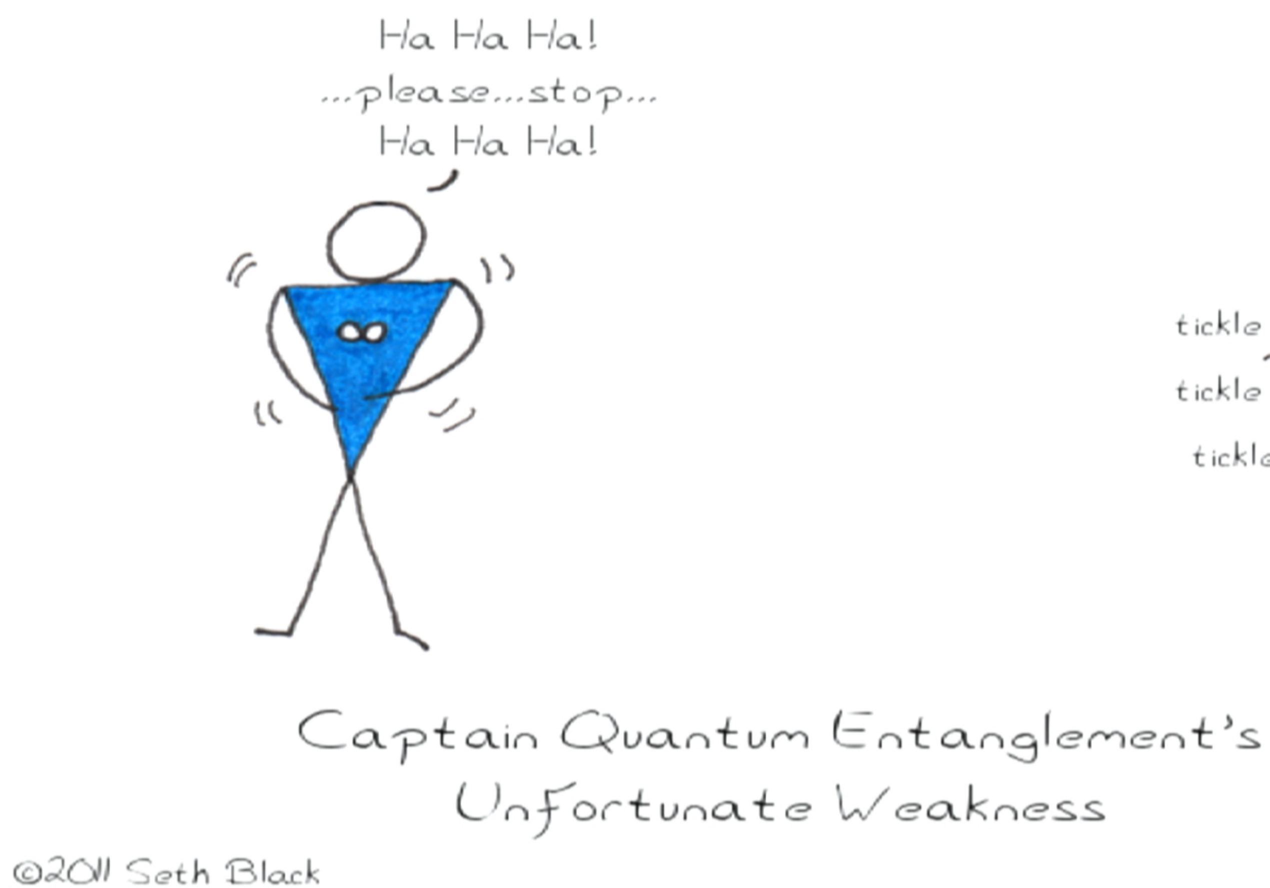
. . . takes *all* probabilities to be personalist Bayesian degrees of belief. This includes probabilities 0 and 1 and probabilities derived from pure quantum states.

- A quantum state determines probabilities through the Born rule.
- Probabilities are personal judgments of the agent who assigns them.
- HENCE: A quantum state is a personal judgment of the agent who assigns it.

QBism embraces locality



QBism embraces locality

(1) QBism rejects the EPR criterion of reality

and thus blocks Bell's 1964 argument.

(2) QBism rejects Reichenbach's common cause principle

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QBism's notions of reality, locality and causality

do not depend on the EPR criterion, Reichenbach's principle or an ontological model.

Personalist Bayesian probability

- de Finetti, Ramsey, Savage, Jeffrey, . . .
- A probability is a number assigned by an agent (a user of probability theory) to an event to quantify the strength of his or her belief that the event will happen.
- The agent uses his probability assignments to make decisions in the face of uncertainty.
- Probabilities can be assigned to single events as well as repeated trials.
- Different agents with different beliefs will in general assign different probabilities.

Dutch book (adapted from Wikipedia)

horse	odds offered				
1 2 3	even 1:2 1:3				

Dutch book (adapted from Wikipedia)

horse	odds offered		amount bet	payout if horse wins	net loss
1	even		$120	$240	$20
2	1:2		$80		
3	1:3		$60		
	total		$260		

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Unlike roulette, where one is certain to lose in the long run, here the bettor will lose \$20 with certainty in a single race!

Dutch book coherence

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How should I gamble?

The Dutch-book derivation results in a theory with a normative character.

Probability-1 judgments are judgments

Alice is certain that horse 1 will win: $P(\text{horse 1 wins}) = 1$.
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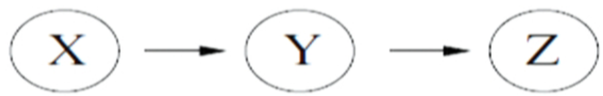
QBism rejects the EPR criterion of reality:

"If, without in any way disturbing a system, we can predict with certainty (i.e., with probability equal to unity) the value of a physical quantity, then there exists an element of physical reality corresponding to this physical quantity."

(2) Reichenbach's common cause principle

Reichenbach's common cause principle is implicit in the causal network formalism developed by Pearl. E.g.,



means

(i) $P(X, Y, Z) = P(X) \times P(Y|X) \times P(Z|Y)$

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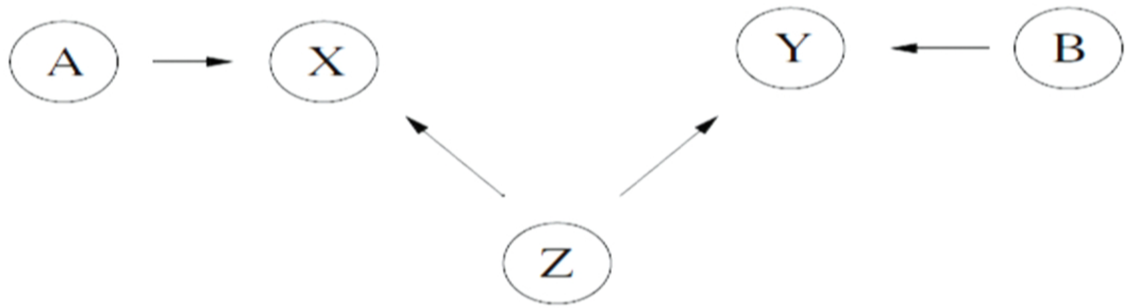
(i) $P(X, Y, Z) = P(X) \times P(Y|X) \times P(Z|Y)$

and

(ii) $P(X, Z \mid do(Y = y)) = P(X) \times P(Z|Y = y)$

Bipartite scenario



implies

$P(X|Z, A, B) = P(X|Z, A)$, or "parameter independence",

$P(X|Z, A, B, Y) = P(X|Z, A, B)$, or "outcome independence"

plus similar for Y, and hence implies Bell inequalities.

Fine tuning

Theorem (Wood and Spekkens): Any account of quantum correlations within the Pearl framework requires fine tuning.

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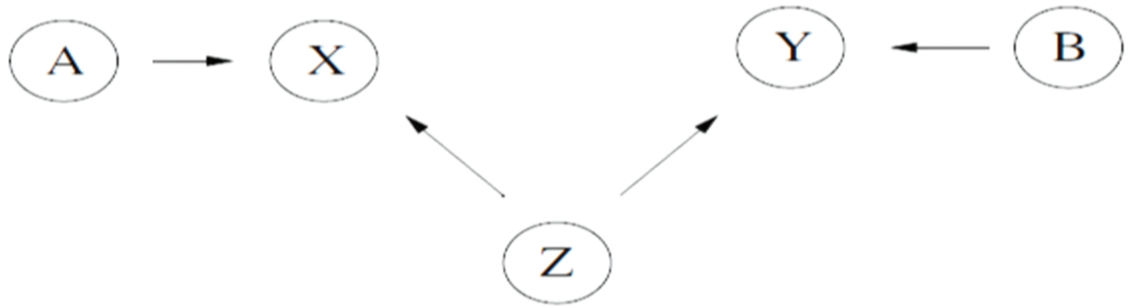
Example: Bohmian mechanics:

$P(X \mid Z, A, B) \neq P(X \mid Z, A)$, i.e., allows signaling given Z.

Not the right concept of causality



In Pearl's framework,

- the "natural" causal order for a Bell experiment leads to a conflict with quantum mechanics;

(3) Ontological models (“λ”)

In an ontological model (Harrigan and Spekkens),

for any measurement on a physical system, the outcome probabilities are determined by the system's real properties, λ.

No go theorems (PBR, Colbeck and Renner, Hardy, . . .)

Assuming λ plus further assumptions implies ψ is determined by λ.

QBism rejects λ

Schrödinger to Sommerfeld (1931):

One can only help oneself through something like the following emergency decree:
Quantum mechanics forbids statements about what really exists — statements about the object. It deals only with the object-subject relation. Even though this holds, after all, for any description of nature, it evidently holds in quantum mechanics in a much more radical sense.

Measurement in QBism

A quantum measurement finds nothing but makes something:

A measurement is an action on the world by an agent that results in the *creation* of an outcome.

An agent's first-person perspective

- A quantum state is my personal judgement.
- Quantum mechanics is a tool to organize my experience.
- A measurement is an action on the world I take to elicit a new experience.

Nature cover, 27 March 2014

Assumptions

To apply quantum mechanics, I need to assume

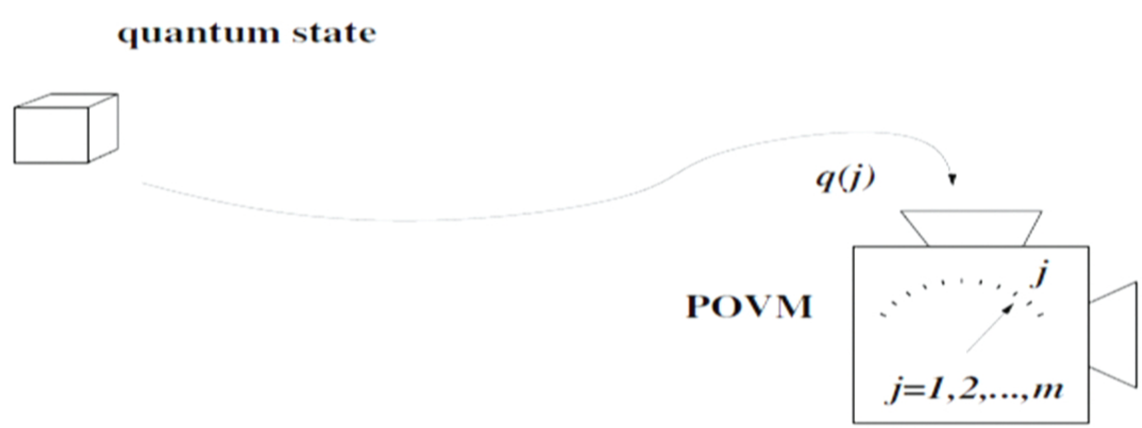
(i) a distinction between myself and my external world;
(ii) my ability to experience;
(iii) my own agency, i.e., my ability to act freely on the world.

These seem very natural assumptions. Without them, it is hard to see what it could mean to do science.

The Born rule and the double slit experiment

Born rule

$$q(j) = \mathrm{tr}(\rho E_j)$$



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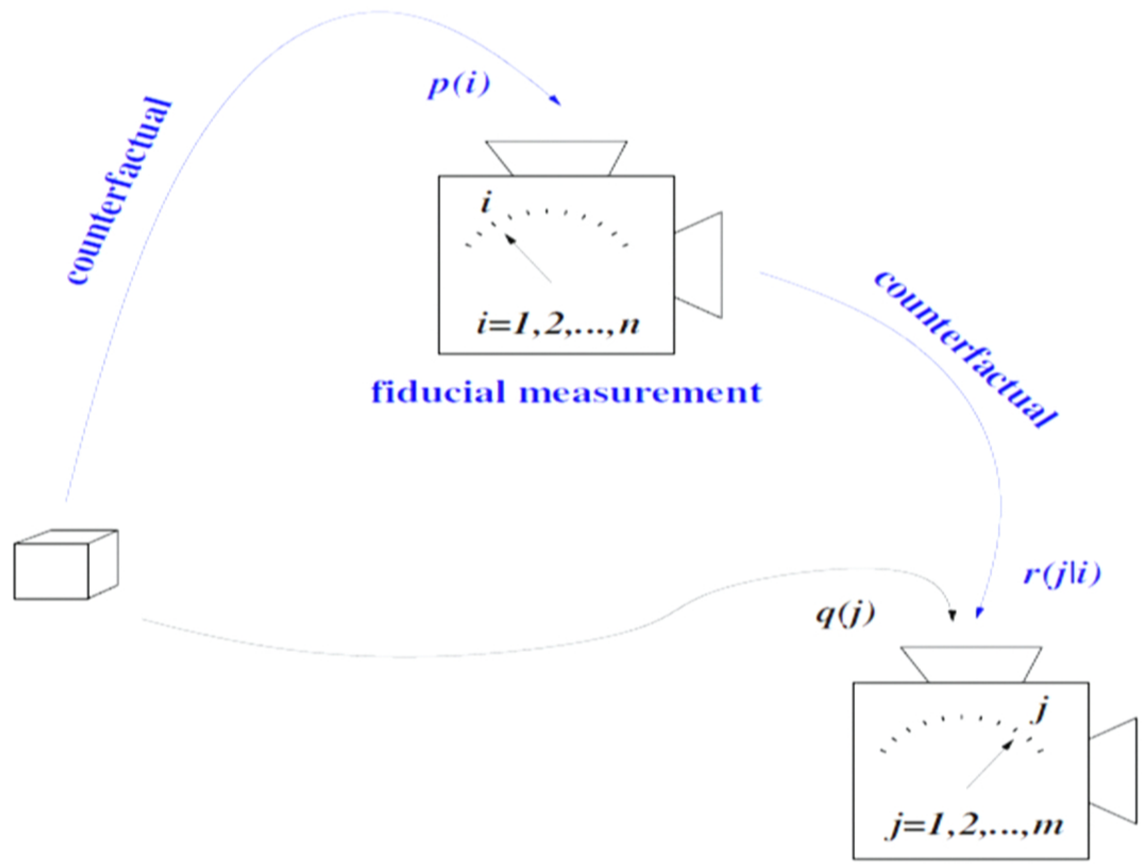

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quantum state

$\rho \longleftrightarrow p(i)$

POVM

$\{E_j\} \longleftrightarrow r(j|i)$

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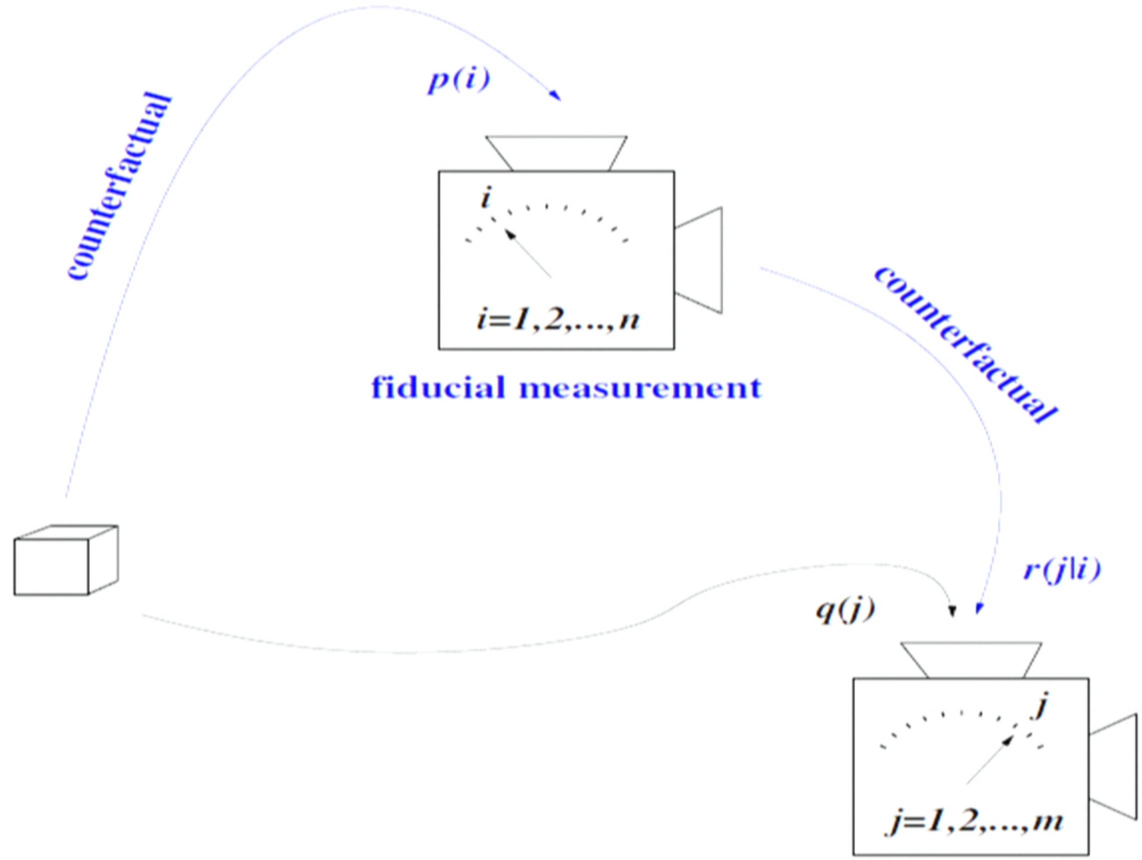

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The Born rule and the double slit experiment

- The Born rule provides a connection between my probabilities for the outcomes of different and in general incompatible measurements.
- The Born rule has normative character. “How should I gamble?”
- Unlike probability theory, which can be derived from Dutch book coherence arguments (“no sure loss!”), the Born rule is empirical. It is a statement about the character of the world.

Physical systems possess intrinsic autonomy

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for how any particular experience arises; even the simplest quantum system has an "interiority" that neither my experience nor my theory can penetrate.

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Any part of the world has intrinsic freedom.

When I act on a part of the world, quantum mechanics puts no constraints on what particular experience will result.

I am not special

A Copernican principle:

By one category of thought we are agents, but by another category of thought we are physical systems. And when we take actions upon each other, the category distinctions are symmetrical.

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By one category of thought we are agents, but by another category of thought we are physical systems. And when we take actions upon each other, the category distinctions are symmetrical.

When you and I take actions on each other,

something real is shared between you and me. But quantum mechanics rules out a third-person account of this "something".

Pearl's causal networks revisited

Compare

(i)
$$P(X, Y) = P(X)P(Y|X)$$

(ii)
$$P(X \mid do(Y = y)) = P(X)$$

with

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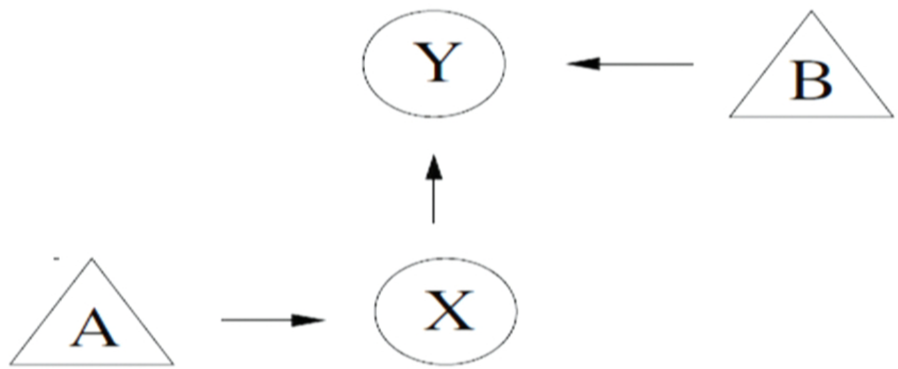
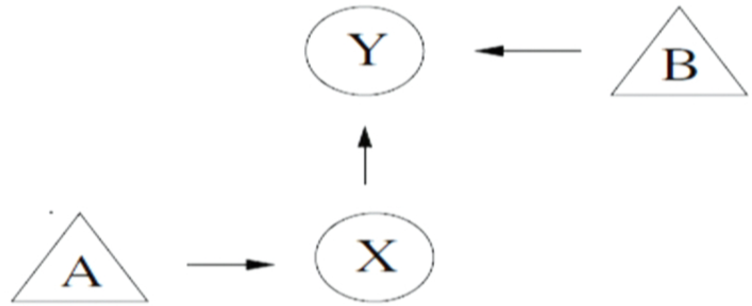
QBist causal networks . . .

. . . are directed acyclic graph with two kinds of nodes: action nodes (A, B, . . .) and outcomes nodes (X, Y, . . .):



I (the agent) freely choose actions A, B, . . . and experience outcomes X, Y, ...

QBist causal networks



X is not in the causal future of B.

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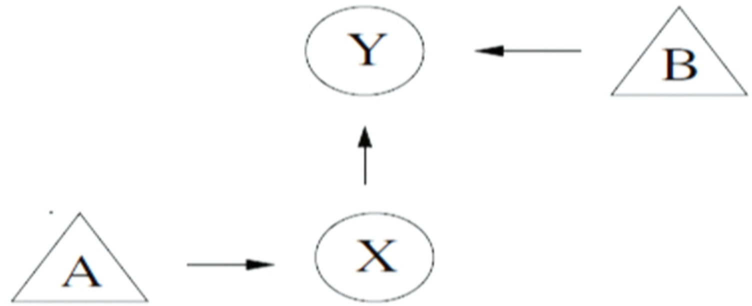
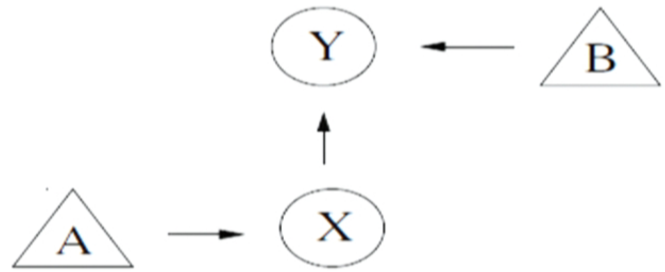


X is not in the causal future of B.

The causal structure is a *constraint* on my probability assignments and thus part of my probabilistic beliefs:

I cannot influence X by my choice of action $b \in B$, i.e., $P(X \mid A = a, B = b)$ is independent of b.

Locality

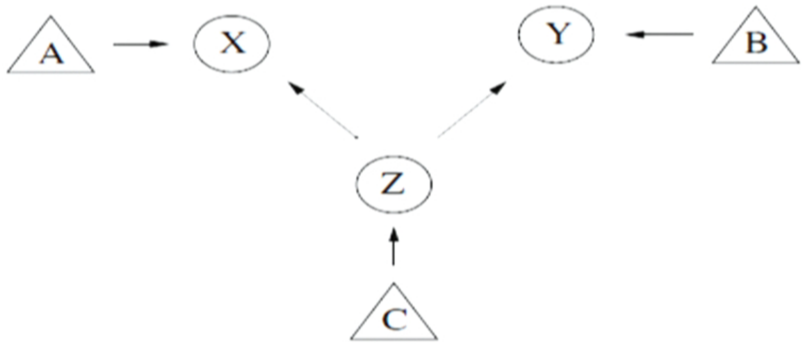


Definition: A probability assignment is *local with respect to a given causal structure*

if $P(\Gamma_B \,|\, A = a, B = b, \ldots)$ is independent of b for any action node B and any set Γ_B of outcome nodes not in the causal future of B.

Quantum mechanics results in local probability assignments.

Relation to work by Colbeck and Renner

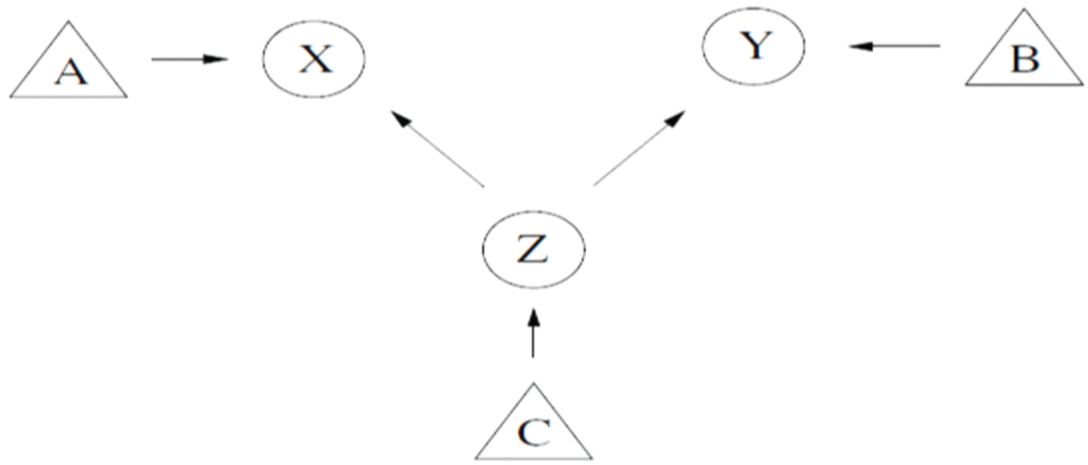


QBist causal networks are essentially equivalent to the causal networks introduced by Colbeck and Renner.

Minor difference: we do not require transitivity.

Our definition of "locality with respect to the causal structure" is essentially equivalent to their "A and B are free with respect to the causal structure".

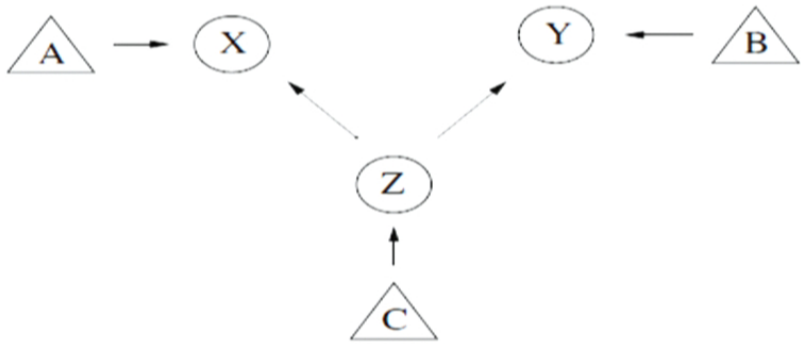
Back to the bipartite scenario



Locality implies $P(X \mid Z, A, B) = P(X \mid Z, A)$ plus similar for Y, but not outcome independence.

Guarantees no signaling without fine tuning.

Relation to work by Colbeck and Renner



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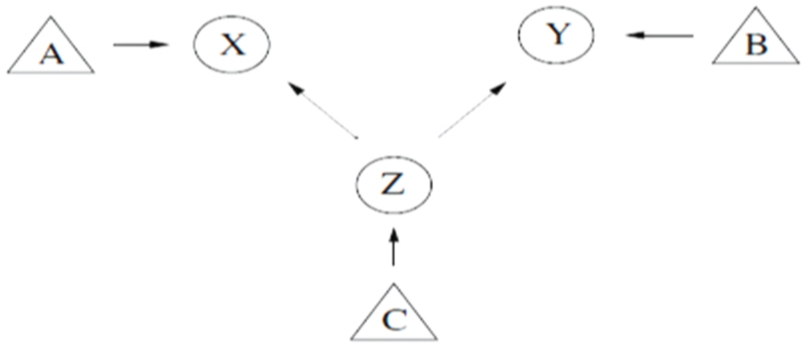
Colbeck and Renner, Nat. Commun. (2011)



Theorem: Quantum mechanics and
$P(X \mid \lambda, A, B) = P(X \mid \lambda, A)$ plus similar for Y implies
$P(X, Y \mid \lambda, A, B) = P(X, Y \mid A, B)$.

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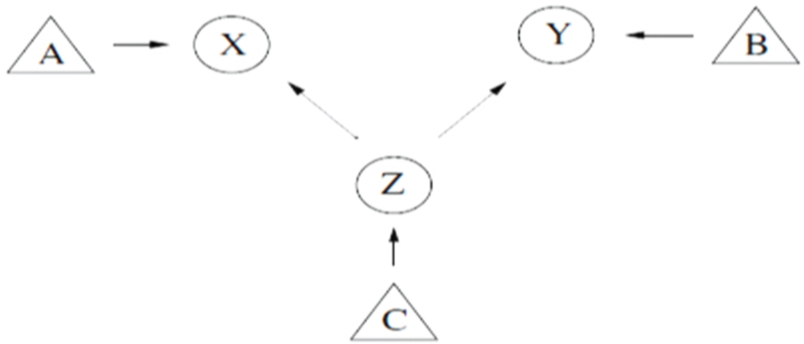

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Bell versus a QBist reading of Colbeck and Renner

Bell:

Start from an ontological model (or derive it from perfect correlations using the EPR criterion of reality and a counterfactual argument), then define “local causality” within the ontological model and derive a contradiction with quantum mechanics. If you now reject the ontological model, it may seem that you are left with nothing.

Bell versus a QBist reading of Colbeck and Renner

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QBist reading of Colbeck and Renner:

Define causality and locality as part of an agent's belief structure and show that any hidden variable theory that respects this belief structure is trivial. Now if you reject the hidden variables, you lose nothing.

Thank you

Pablo Picasso, *Le Vieux Marc* (oil on canvas), 1912.

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Strategy: Abandon (i), keep (ii).