QBism and the character of the world

Rüdiger Schack
Royal Holloway, University of London

October 2014

Carl Caves, Chris Fuchs, RS, PRA 2002

PHYSICAL REVIEW A, VOLUME 65, 022305

Quantum probabilities as Bayesian probabilities

Carlton M. Caves,[1,*] Christopher A. Fuchs,[1] and Rüdiger Schack[2]
[1]*Bell Labs, Lucent Technologies, 600–700 Mountain Avenue, Murray Hill, New Jersey 07974*
[2]*Department of Mathematics, Royal Holloway, University of London, Egham, Surrey TW20 0EX, United Kingdom*
(Received 15 August 2001; published 4 January 2002)

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-

Chris Fuchs, arXiv 2010

QBism, the Perimeter of Quantum Bayesianism

Christopher A. Fuchs
Perimeter Institute for Theoretical Physics
Waterloo, Ontario N2L 2Y5, Canada
cfuchs@perimeterinstitute.ca

This article summarizes the Quantum Bayesian [1–7] point of view of quantum mechanics, with special emphasis on the view's outer edges—dubbed QBism.[1] QBism has its roots in personalist Bayesian probability theory, is crucially dependent upon the tools of quantum information theory, and most recently, has set out to investigate whether the physical world might be of a type sketched by some false-started philosophies of 100 years ago (pragmatism, pluralism, nonreductionism, and meliorism). Beyond conceptual issues, work at Perimeter Institute is focussed on the hard technical problem of finding a *good* representation of quantum mechanics purely in terms of probabilities, without amplitudes or Hilbert-space operators. The best candidate representation involves a mysterious entity called a symmetric informationally complete quantum measurement. Contemplation of it gives a way of thinking of the Born Rule as an *addition* to the *rules* of probability theory, applicable when an agent considers gambling on the consequences of his interactions with a newly recognized universal capacity: dimension (formerly Hilbert-space dimension). (The word "capacity" should conjure up an image of something like gravitational mass—a body's mass measures

to outward appearances is nearly identical to a common yearly annoyance. There are lessons here for quantum mechanics. In the history of physics, there has never been a healthier body than quantum theory; no theory has ever been more all-encompassing or more powerful. Its calculations are relevant at every scale of physical experience, from subnuclear particles, to table-top lasers, to the cores of neutron stars and even the first three minutes of the universe. Yet since its founding days, many physicists have feared that quantum theory's common annoyance—the continuing feeling that something at the bottom of it does not make sense—may one day turn out to be the symptom of something fatal.

There is something about quantum theory that is different in character from any physical theory posed before. To put a finger on it, the issue is this: The basic statement of the theory—the one we have all learned from our textbooks—seems to rely on terms our intuitions balk at as having any place in a fundamental description of reality. The notions of "observer" and "measurement" are

David Mermin, Nature, 27 March 2014

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

QBism puts the scientist back into science

An interpretation of quantum mechanics

QBism

- clearly defines terms such as “measurement”;
- focuses on how the theory is used in the lab;
- is free of any quantum weirdness.

An interpretation of quantum mechanics

QBism

- clearly defines terms such as “measurement”;
- focuses on how the theory is used in the lab;
- is free of any quantum weirdness.

In QBism,

- experience is real, not an epiphenomenon;
- our actions on the world matter.

In QBism, quantum states are subjective

QBism . . .

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

In QBism, quantum states are subjective

QBism . . .

. . . 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 judgements of the agent who assigns them.

In QBism, quantum states are subjective

QBism . . .

. . . 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 judgements of the agent who assigns them.
- HENCE: A quantum state is a personal judgement of the agent who assigns it.

Heads or Tails

Tossing a "fair" coin, following *The Logic of Science* by E. T. Jaynes:

Heads or Tails

Tossing a "fair" coin, following *The Logic of Science* by E. T. Jaynes:

Observation 1

prob $= 1/2$ is not a property of the coin.

Heads or Tails

Tossing a "fair" coin, following *The Logic of Science* by E. T. Jaynes:

Observation 1

prob $= 1/2$ is not a property of the coin.

Observation 2

prob $= 1/2$ is not a joint property of coin and tossing mechanism.

Heads or Tails

Tossing a "fair" coin, following *The Logic of Science* by E. T. Jaynes:

Observation 1

prob $= 1/2$ is not a property of the coin.

Observation 2

prob $= 1/2$ is not a joint property of coin and tossing mechanism.

Observation 3

Any probability assignment starts from a *prior probability*.

Personalist Bayesian probability

- de Finetti, Ramsey, Savage, Jeffrey, . . .

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 belief that the event will happen.

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 belief that the event will happen.
- The agent uses his probability assignments to make decisions in the face of uncertainty.

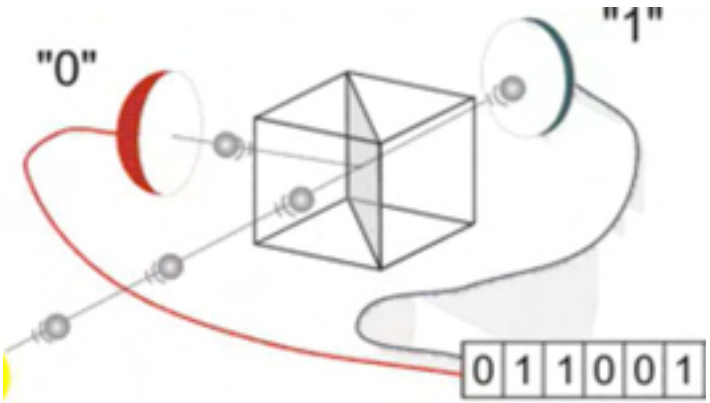
Personalist Bayesian probability

- 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 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.

Personalist Bayesian probability

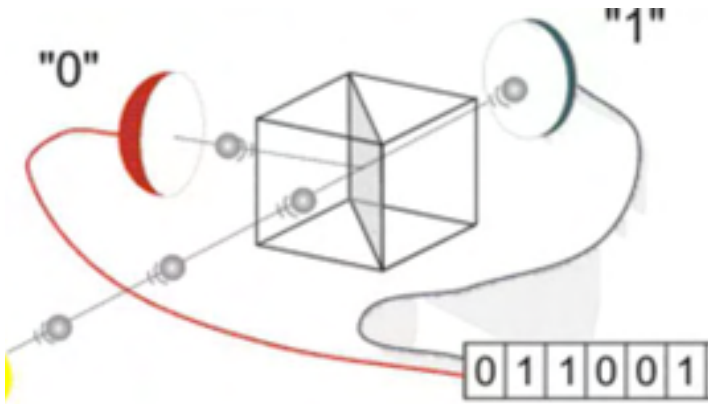
- de Finetti, Ramsey, Savage, Jeffrey, ...
- A probability is a number assigned by an agent (a user of probability theory) to an event to quantify the strength of his belief that the event will happen.
- The agent uses his probability assignments to make decisions in the face of uncertainty.
- Probabilities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

What about a quantum random number generator?



©www.idquantique.com

What about a quantum random number generator?



The probabilities for 0 and 1 are not a property of the device. They depend on the the prior quantum state for the device, i.e., on an agent's prior beliefs.

©www.idquantique.com

Epistemic quantum states

Einstein 1935 (not EPR)

Assuming λ (elements of physical reality) and locality (no spooky action at a distance) implies ψ is epistemic.

Epistemic quantum states

Einstein 1935 (not EPR)

Assuming λ (elements of physical reality) and locality (no spooky action at a distance) implies ψ is epistemic.

PBR, Colbeck and Renner, Hardy, ...

Assuming λ plus further assumptions implies ψ is not epistemic.

Epistemic quantum states

Einstein 1935 (not EPR)

Assuming λ (elements of physical reality) and locality (no spooky action at a distance) implies ψ is epistemic.

PBR, Colbeck and Renner, Hardy, ...

Assuming λ plus further assumptions implies ψ is not epistemic.

Bell

Assuming λ and locality contradicts quantum mechanics.

Epistemic quantum states

Einstein 1935 (not EPR)

Assuming λ (elements of physical reality) and locality (no spooky action at a distance) implies ψ is epistemic.

PBR, Colbeck and Renner, Hardy, ...

Assuming λ plus further assumptions implies ψ is not epistemic.

Bell

Assuming λ and locality contradicts quantum mechanics.

Spekkens

Assuming ψ is epistemic explains a long list of otherwise puzzling quantum phenomena, from no cloning to teleportation and steering.

QBism abandons the assumption of a 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.

Probability of what?

QBism: Quantum mechanics is a tool

that anyone can use to evaluate, on the basis of one's past experience, one's probabilistic expectations for one's subsequent experience.

QBism

- clearly defines terms such as “measurement”;
- focuses on how the theory is used in the lab;
- is free of any quantum weirdness.

In QBism,

- experience is real, not an epiphenomenon;
- our actions on the world matter.

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 — a new experience for that agent.

An outcome does not preexist the measurement

Asher Peres:

Unperformed experiments have no results.

An outcome does not preexist the measurement

Asher Peres:

Unperformed experiments have no results.

Agent undertaking an experiment:

This experiment has no outcome until I experience one.

An outcome does not preexist the measurement

Asher Peres:

Unperformed experiments have no results.

Agent undertaking an experiment:

This experiment has no outcome until I experience one.

The experience *is* the outcome.

Experiences do not exist prior to being experienced.

QBism so far

- 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

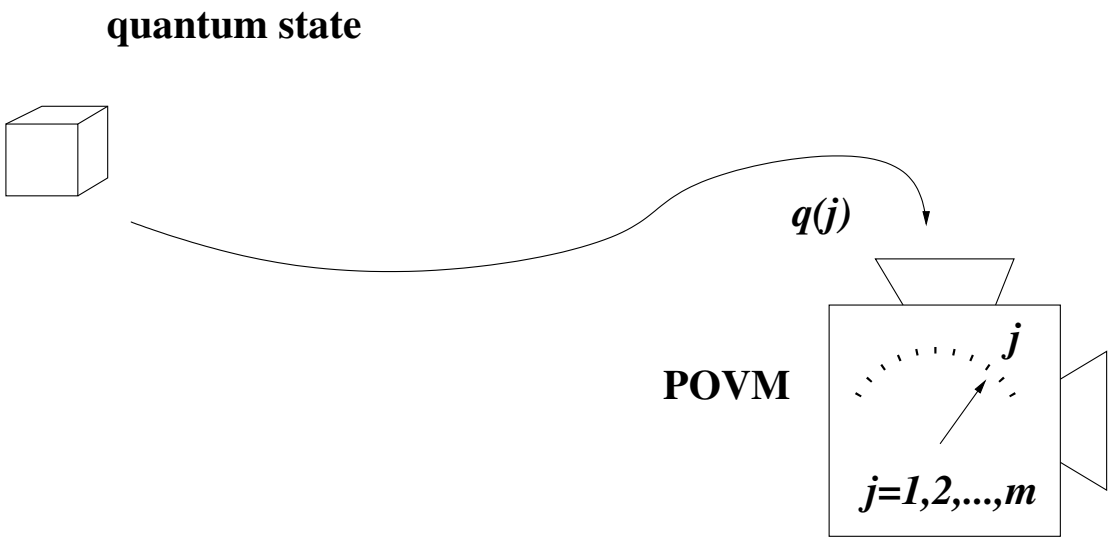
Informationally complete rank-1 POVMs

For any dimension d, there exists a (not necessarily symmetric) POVM $\{F_i\}$ with d^2 outcomes such that any density operator ρ is fully determined by the probabilities $p(i) = \mathrm{tr}(F_i\rho)$ and any POVM $\{E_j\}$ is fully determined by the matrix of conditional probabilities $r(j|i) = \mathrm{tr}(E_jF_i)/\mathrm{tr}(F_i)$.

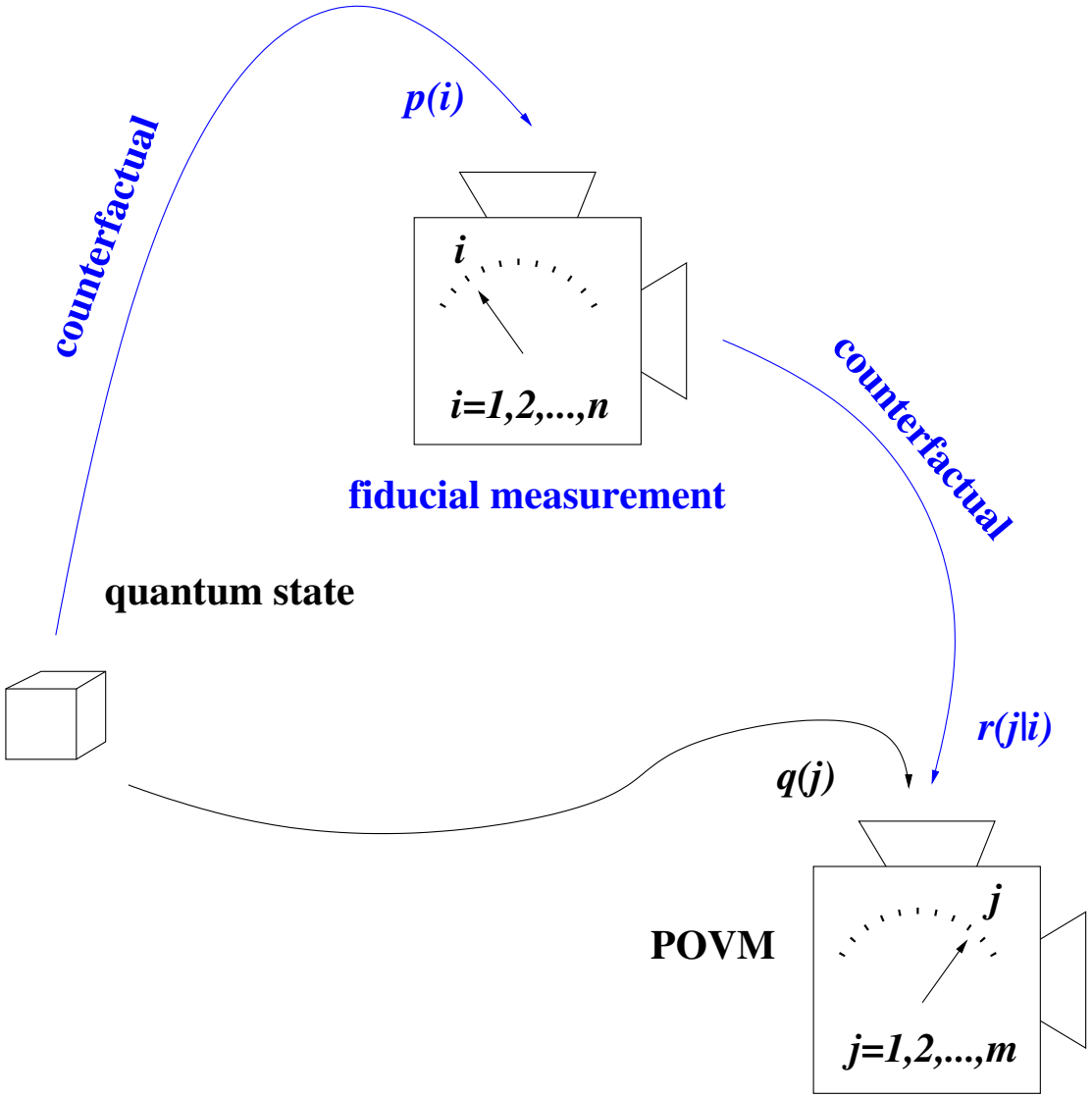
The Born rule as an object-subject relation

Born rule

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



The Born rule as an object-subject relation



Born rule

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

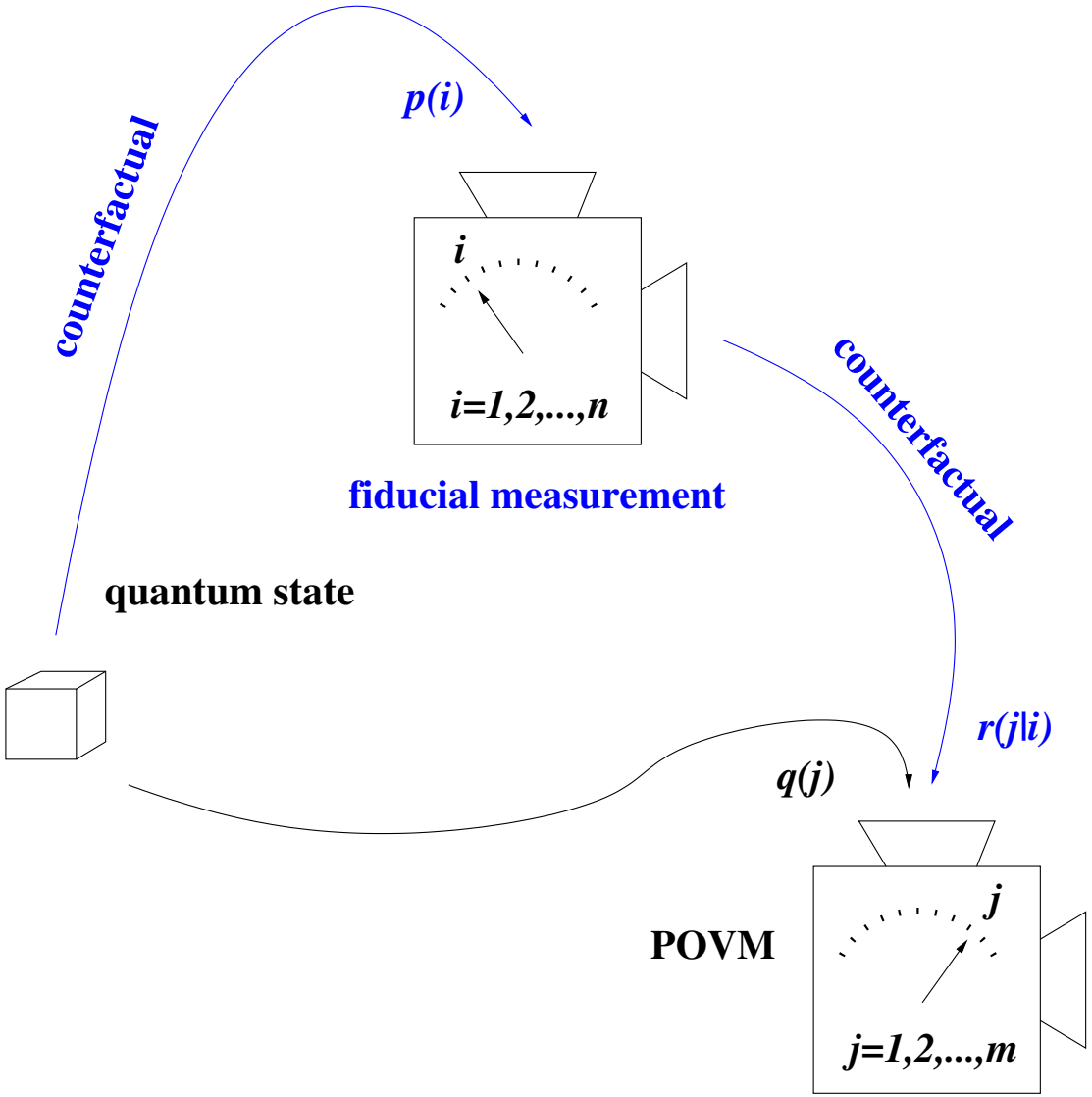
quantum state

$$\rho \longleftrightarrow p(i)$$

POVM

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

The Born rule as an object-subject relation



Born rule

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

quantum state

$$\rho \longleftrightarrow p(i)$$

POVM

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

Born rule, rewritten

$$q(j) = f(p(i), r(j|i))$$

The Born rule as an object-subject relation

- The Born rule connects an agent's outcome probabilities with his probabilities for a counterfactual fiducial measurement.

Dutch book (adapted from Wikipedia)

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

Dutch book (adapted from Wikipedia)

horse	**odds offered**		**amount bet**		
1	even		\$120		
2	1:2		\$80		
3	1:3		\$60		
	total		\$260		

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		

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	\$240	\$20
3	1:3		\$60		
	total		\$260		

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	\$240	\$20
3	1:3		\$60	\$240	\$20
	total		\$260		

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	\$240	\$20
3	1:3		\$60	\$240	\$20
	total		\$260		

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 (adapted from Wikipedia)

horse	**odds offered**	**implied prob.**	**amount bet**	**payout if horse wins**	**net loss**
1	even	1/2	\$120	\$240	\$20
2	1:2	1/3	\$80	\$240	\$20
3	1:3	1/4	\$60	\$240	\$20
	total		\$260		

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 (adapted from Wikipedia)

horse	**odds offered**	**implied prob.**	**amount bet**	**payout if horse wins**	**net loss**
1	even	1/2	\$120	\$240	\$20
2	1:2	1/3	\$80	\$240	\$20
3	1:3	1/4	\$60	\$240	\$20
	total	13/12	\$260		

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

Definition

An agent's probability assignments are called *Dutch book coherent* if they rule out the possibility of a Dutch book.

Dutch book coherence

Definition

An agent's probability assignments are called *Dutch book coherent* if they rule out the possibility of a Dutch book.

Theorem

An agent's probability assignments are Dutch book coherent if and only if they obey the standard probability rules.

Probability theory provides explanations

Probability theory provides explanations

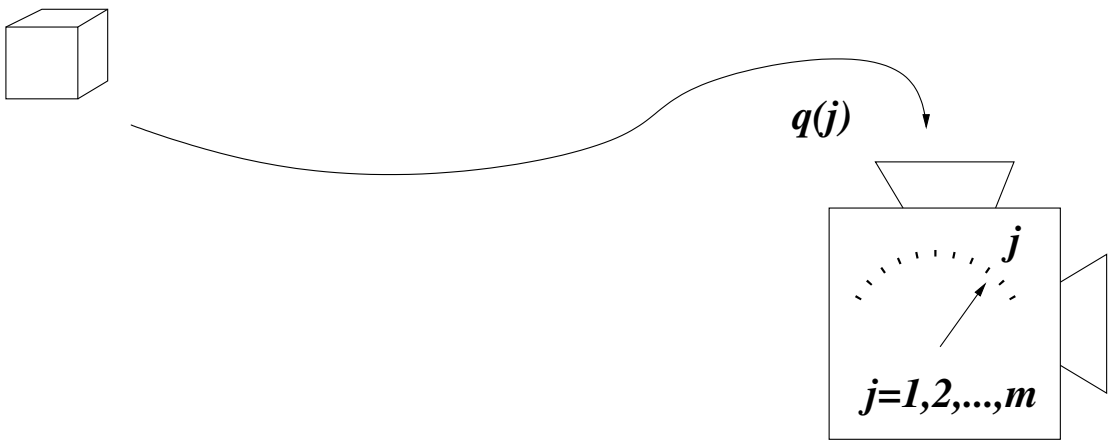
Quantum mechanics is like probability theory:

It gives no mechanism for any particular outcome, but a formalism connecting probabilities.

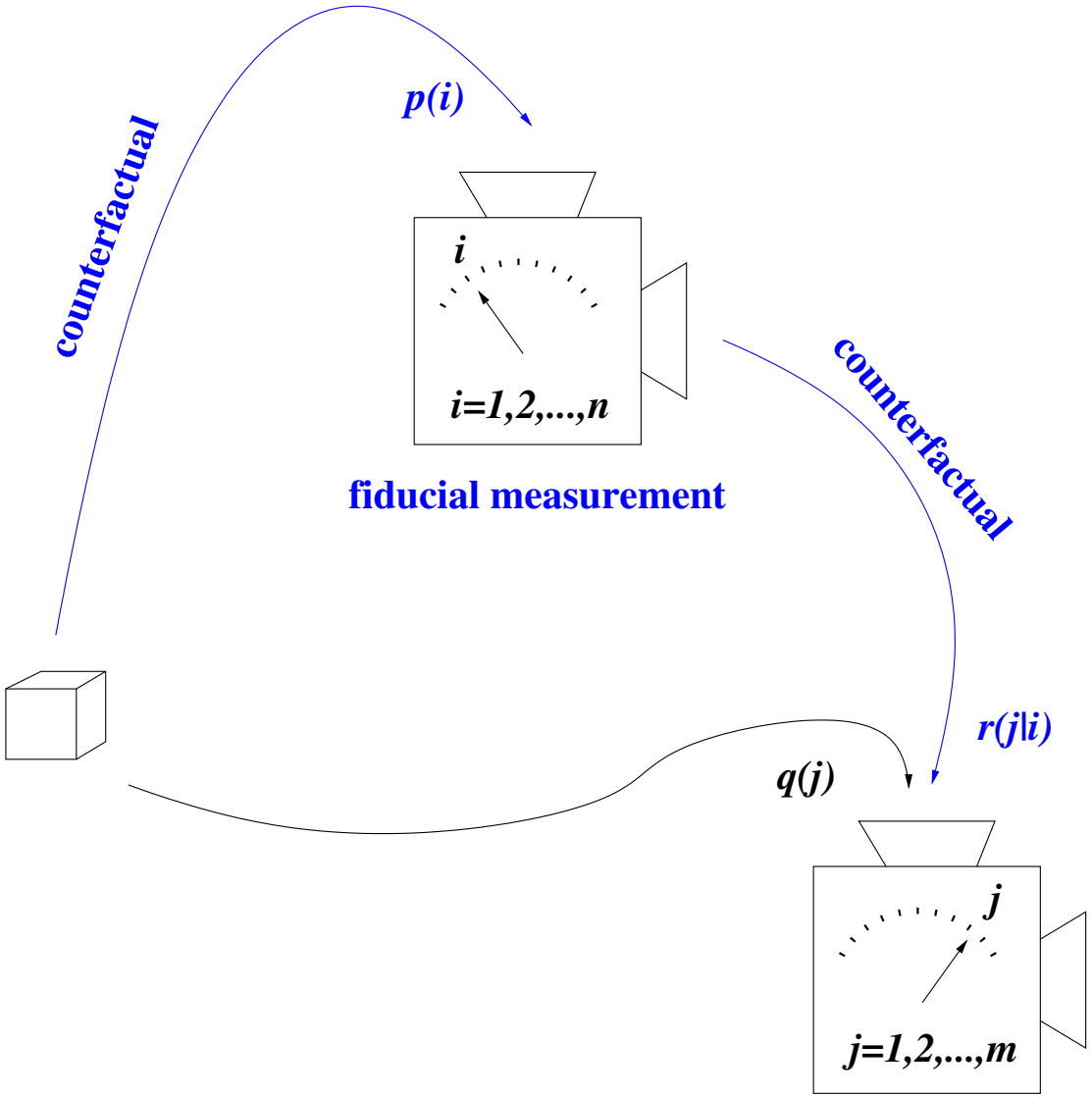
Classical mechanics as an object-subject relation

probabilities

$q(j) = ?$



Classical mechanics as an object-subject relation



probabilities

$q(j) = ?$

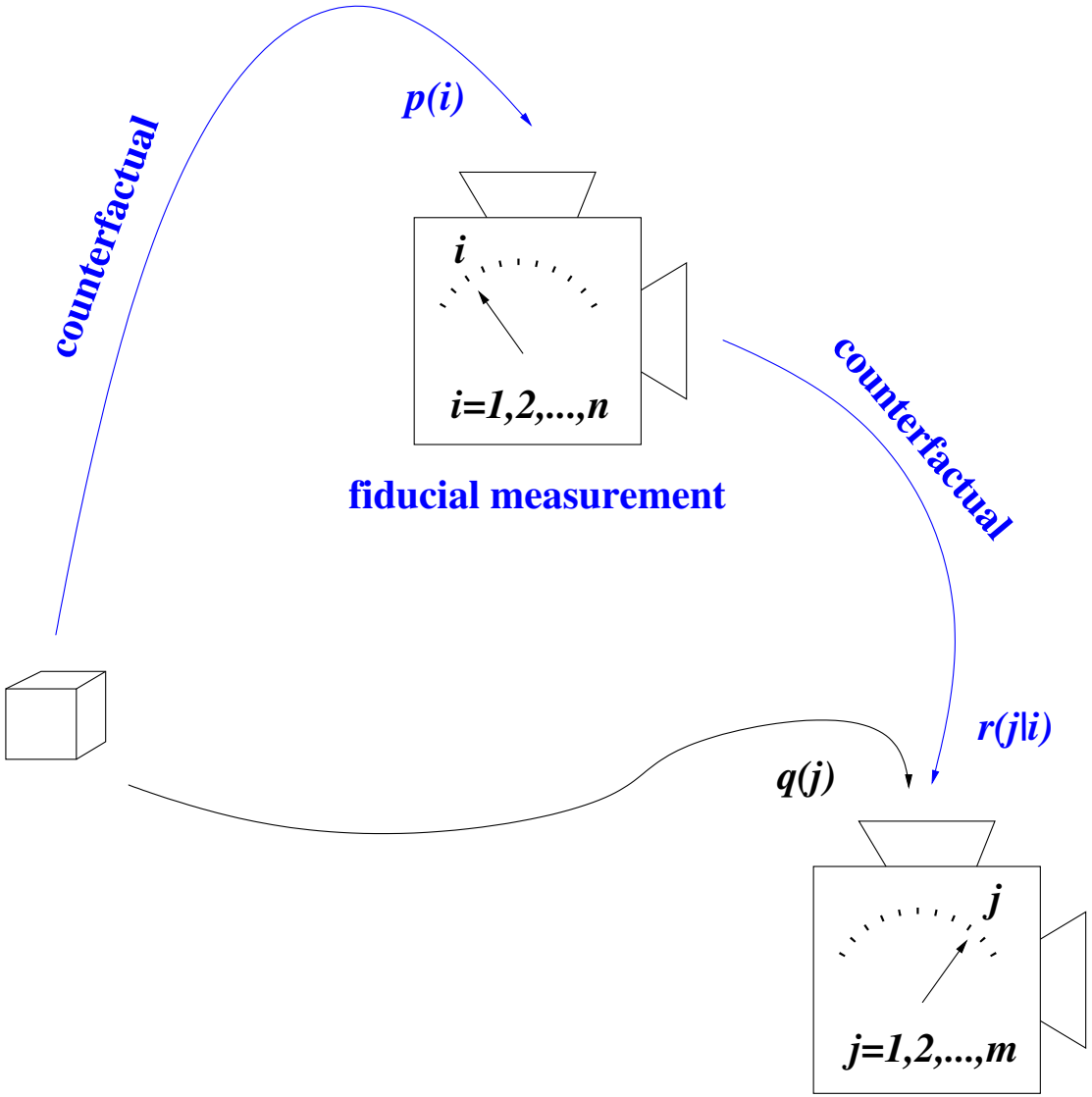
classical state

$p(i)$

conditional probabilities

$r(j|i)$

Classical mechanics as an object-subject relation



probabilities

$q(j) = ?$

classical state

$p(i)$

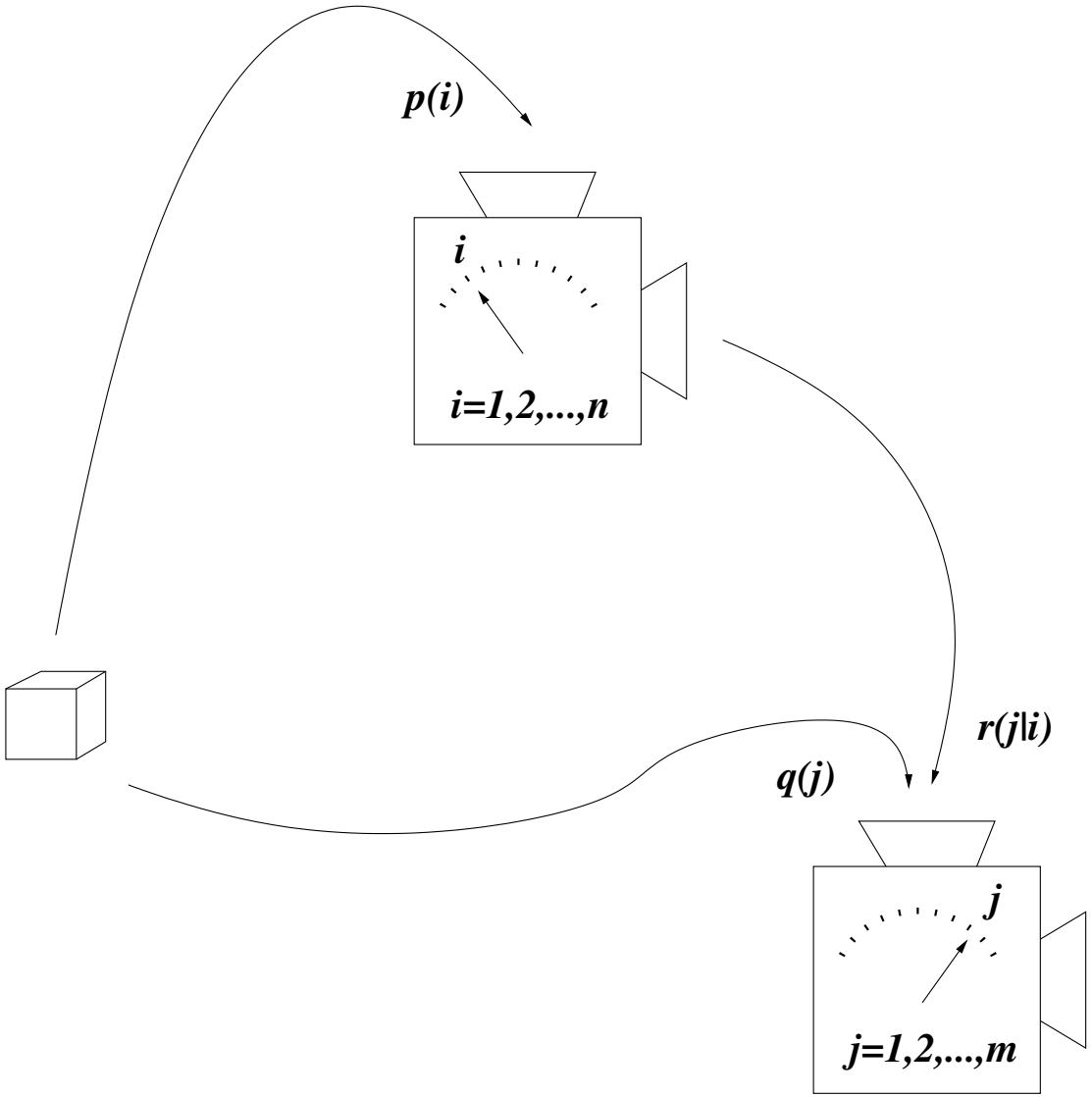
conditional probabilities

$r(j|i)$

classical probabilistic law

$q(j) = \sum_i r(j|i)p(i)$

Treating outcomes i as elements of reality



probabilities

$q(j) = ?$

classical state

$p(i)$

conditional probabilities

$r(j|i)$

law of total probability

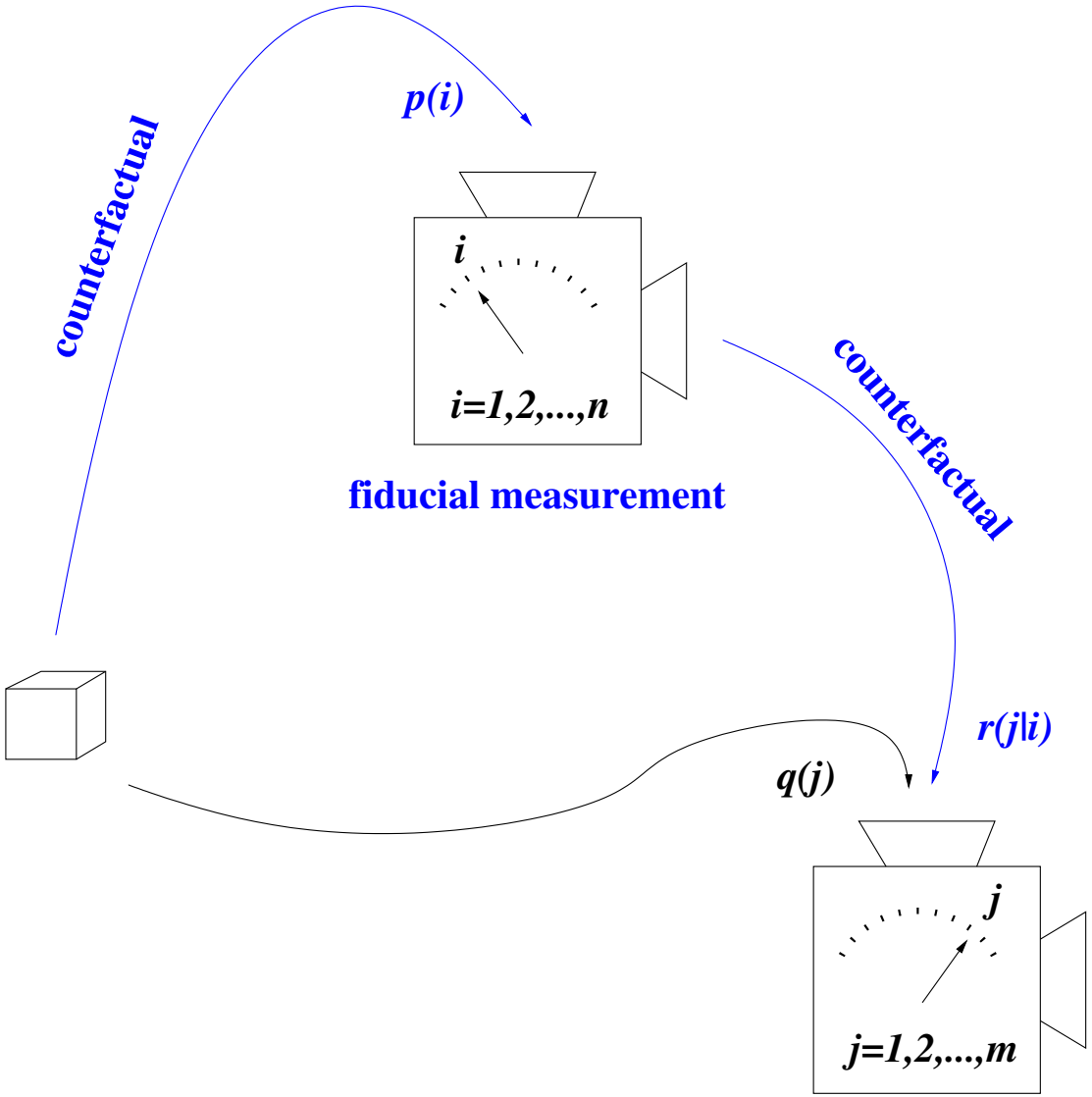
$q(j) = \sum_i r(j|i)p(i)$

A 2000-year old Greek maneuver

Schrödinger in *Nature and the Greeks*:

[. . .] the scientist subconsciously, almost inadvertently, simplifies his problem of understanding Nature by disregarding or cutting out of the picture to be constructed himself, his own personality, the subject of cognizance. [. . .]

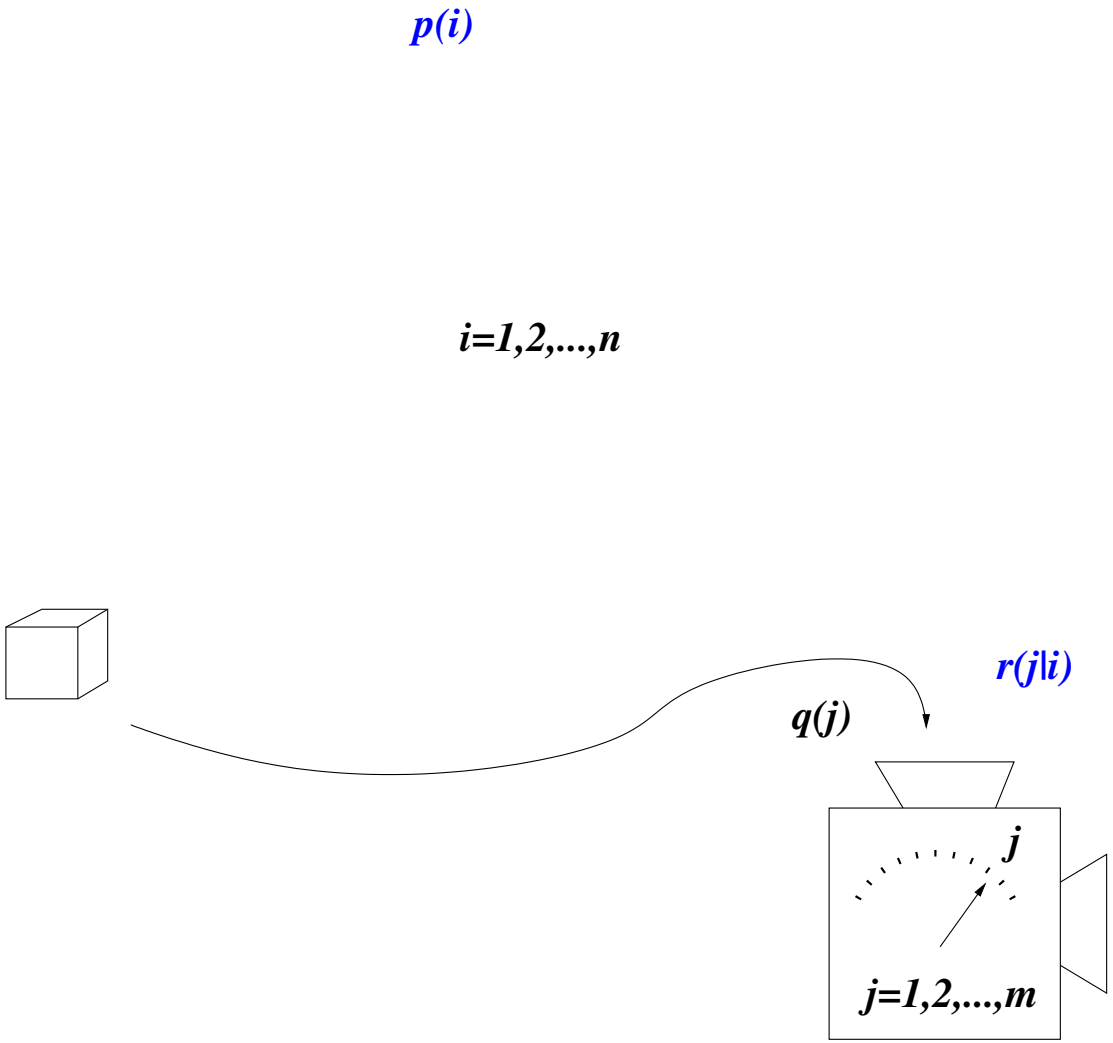
Quantum theory is not classical



In quantum theory, there is no fiducial measurement such that, in general

$$q(j) = \sum_i r(j|i)\ p(i)$$

λ-realism



In ontological models the i (from now on λ) are taken as elements of reality, implying that the law of total probability holds:

$$q(j) = \sum r(j|\lambda)\ p(\lambda)$$

What's wrong with λ-realism

It creates pseudo problems,

e.g., the problem of free will, the problem of qualia, the mind-body problem.

What's wrong with λ-realism

It creates pseudo problems,

e.g., the problem of free will, the problem of qualia, the mind-body problem.

It describes a dead world:

If the world is fully desribed by a mathematical model, or a computer program, what is the difference between the world and the mathematical description?

What's wrong with λ-realism

It creates pseudo problems,

e.g., the problem of free will, the problem of qualia, the mind-body problem.

It describes a dead world:

If the world is fully desribed by a mathematical model, or a computer program, what is the difference between the world and the mathematical description?

Hence it cannot be distinguished from solipsism:

If the world is equivalent to a computer program, then how can I tell that it is not my brain that is running it?

There is no experimental evidence for λ-realism

QBism

- clearly defines terms such as "measurement";
- focuses on how the theory is used in the lab;
- is free of any quantum weirdness.

In QBism,

- experience is real, not an epiphenomenon;
- our actions on the world matter.

λ-realism is responsible for quantum weirdness

QBism

- clearly defines terms such as "measurement";
- focuses on how the theory is used in the lab;
- is free of any quantum weirdness.

In QBism,

- experience is real, not an epiphenomenon;
- our actions on the world matter.

λ-realism is responsible for quantum weirdness

Examples of pseudo-problems created by λ-realism:

- The problem of the collapse of the wavefunction.
- The measurement problem.
- The problem of quantum nonlocality.

Wigner's friend

Wigner's friend makes a measurement

in a closed lab and experiences an outcome. Wigner, outside the lab, doesn't experience an outcome and writes down an entangled state.

Wigner's friend

Wigner's friend makes a measurement

in a closed lab and experiences an outcome. Wigner, outside the lab, doesn't experience an outcome and writes down an entangled state.

The friend's measurement outcome is personal to the friend.

Wigner's friend

Wigner's friend makes a measurement

in a closed lab and experiences an outcome. Wigner, outside the lab, doesn't experience an outcome and writes down an entangled state.

The friend's measurement outcome is personal to the friend.

A paradox is created

by assuming the measurement outcome is an objective feature of the world. Then either the friend is hallucinating, or Wigner is inconsistent.

If Wigner were Alice, Bob would be her friend

Quantum correlations for a bipartite system:

they refer to Alice's experiences resulting from her (necessarily local) actions on A and B, respectively.

If Wigner were Alice, Bob would be her friend

Quantum correlations for a bipartite system:

they refer to Alice's experiences resulting from her (necessarily local) actions on A and B, respectively.

Bob's measurement outcomes are personal to Bob.

If Wigner were Alice, Bob would be her friend

Quantum correlations for a bipartite system:

they refer to Alice's experiences resulting from her (necessarily local) actions on A and B, respectively.

Bob's measurement outcomes are personal to Bob.

A paradox is created

("spooky action at a distance") by assuming that Bob's outcome is an objective feature of the world.

QBism's realism

QBism

- clearly defines terms such as "measurement";
- focuses on how the theory is used in the lab;
- is free of any quantum weirdness.

In QBism,

- experience is real, not an epiphenomenon;
- our actions on the world matter.

QBist evidence for a world beyond my experience

Quantum mechanics refuses to give a mechanism

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

QBist evidence for a world beyond my experience

Quantum mechanics refuses to give a mechanism

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

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.

QBist evidence for a world beyond my experience

Quantum mechanics refuses to give a mechanism

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

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.

When I act on the world, it changes,

as witnessed by my changed expectations for my future experiences.

A world under construction

QBism

- clearly defines terms such as “measurement”;
- focuses on how the theory is used in the lab;
- is free of any quantum weirdness.

In QBism,

- experience is real, not an epiphenomenon;
- our actions on the world matter.

Experience

- I take as real the "multiple aspects" of my experience, thus adopting "the classical pragmatists' rich theory of experience".

Experience

- I take as real the "multiple aspects" of my experience, thus adopting "the classical pragmatists' rich theory of experience".
- My experience is personal to myself.

Experience

- I take as real the "multiple aspects" of my experience, thus adopting "the classical pragmatists' rich theory of experience".
- My experience is personal to myself.
- In every quantum measurement something new is created.

Experience

- I take as real the "multiple aspects" of my experience, thus adopting "the classical pragmatists' rich theory of experience".
- My experience is personal to myself.
- In every quantum measurement something new is created.
- Every experience is an addition to the world.

Experience

- I take as real the "multiple aspects" of my experience, thus adopting "the classical pragmatists' rich theory of experience".
- My experience is personal to myself.
- In every quantum measurement something new is created.
- Every experience is an addition to the world.
- Quantum mechanics allows me to organize my experience with spectacular success.

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.

I am not special

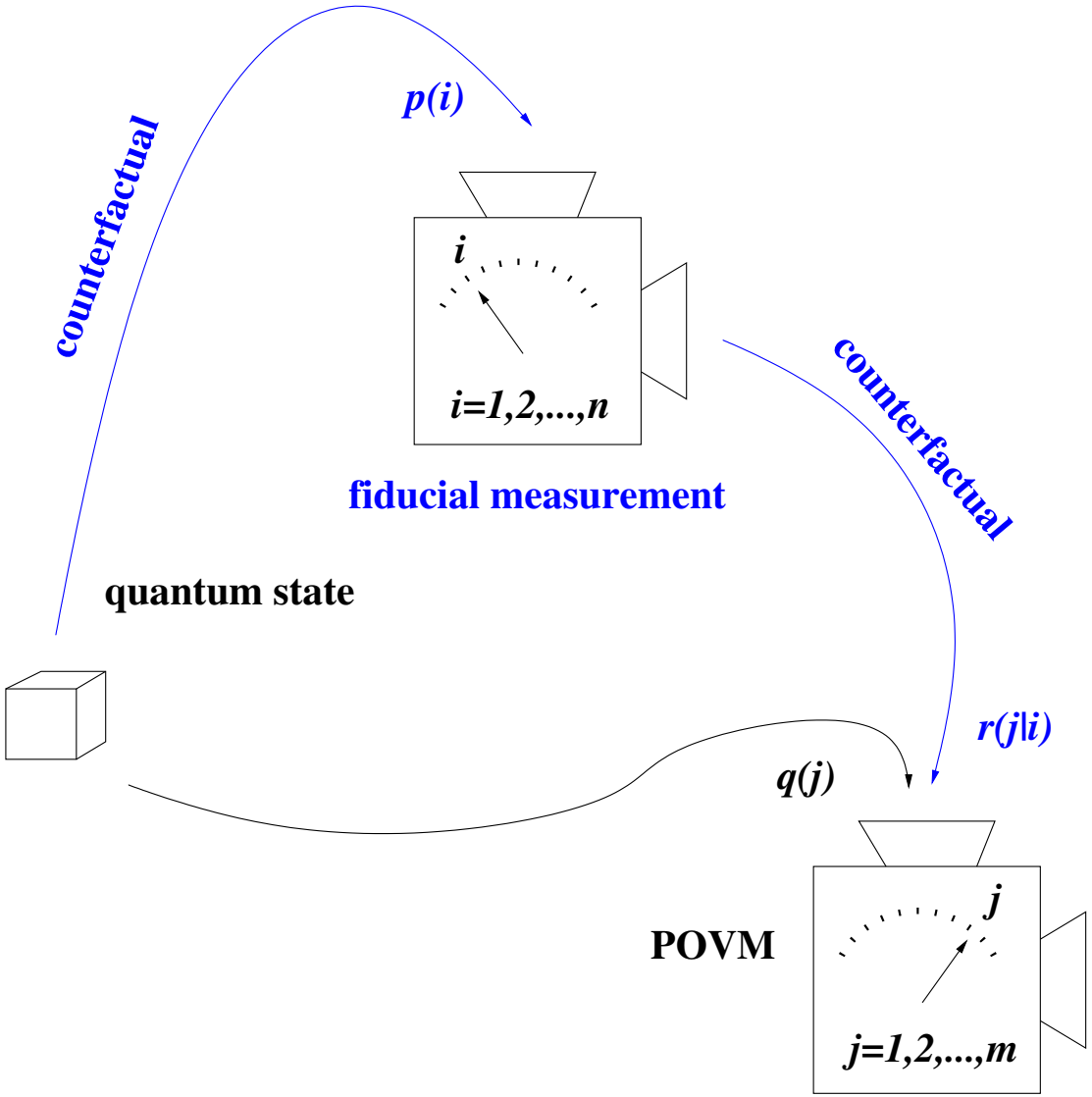
A Copernican principle:

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.

This leads to the idea of a "pluriverse"

in which each agent's private experience is as real as mine.

The glue that holds the pluriverse together



Assuming that SICs exist in all d, there exists a fiducial measurement such that, in general,

$$q(j) = \sum_i r(j|i)\,((d+1)p(i) - \tfrac{1}{d})$$

The "urgleichung"

A quantum postulate:

For every quantum system, there exists a fiducial measurement such that, for all measurements, $q(j) = \sum_i r(j|i)\ (\alpha p(i) - \beta)$

See C. A. Fuchs and RS, Found. Phys. (2011) and Rev. Mod. Phys. (2013).

Summary

QBism

- clearly defines terms such as “measurement”;
- focuses on how the theory is used in the lab;
- is free of any quantum weirdness.

In QBism,

- experience is real, not an epiphenomenon;
- our actions on the world matter.