QBism Picture Book

November 2019

Some Things We're Sure Of
Some Things We're Not

Christopher A. Fuchs

UMass Boston

An Important Milestone, but QBism Was Still a Long Way Away …

PHYSICAL REVIEW A, VOLUME 65, 022305

Quantum probabilities as Bayesian probabilities

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(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

Birth of QBism, March 2010
arXiv:1003.5209

"Quantum Bayesianism, as it is called in the literature, usually refers to a point of view on quantum states originally developed by C. M. Caves, C. A. Fuchs, and R. Schack. The present work, however, goes far beyond those statements in the metaphysical conclusions it draws—so much so that the author cannot comfortably attribute the thoughts herein to the triumvirate as a whole. Thus, the term QBism to mark some distinction from the known common ground of Quantum Bayesianism. Needless to say, the author takes sole responsibility for any inanities herein."

QBism?

nature
THE INTERNATIONAL WEEKLY JOURNAL OF SCIENCE

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

NATURE.COM/NATURE
27 March 2014 £10
Vol. 507, No. 7493

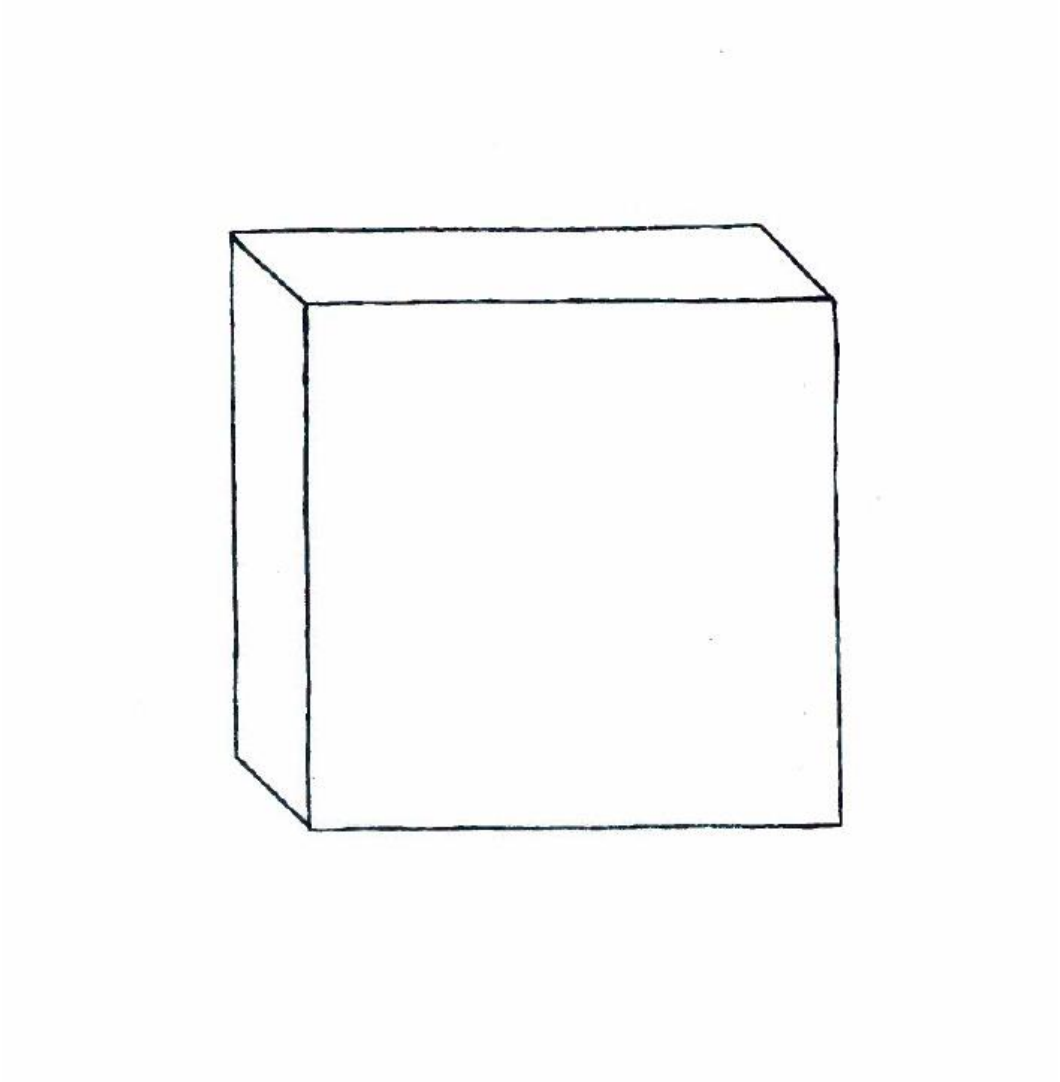
QBism puts the scientist back into science

A participatory view of science resolves quantum paradoxes and finds room in classical physics for 'the Now', says **N. David Mermin**.

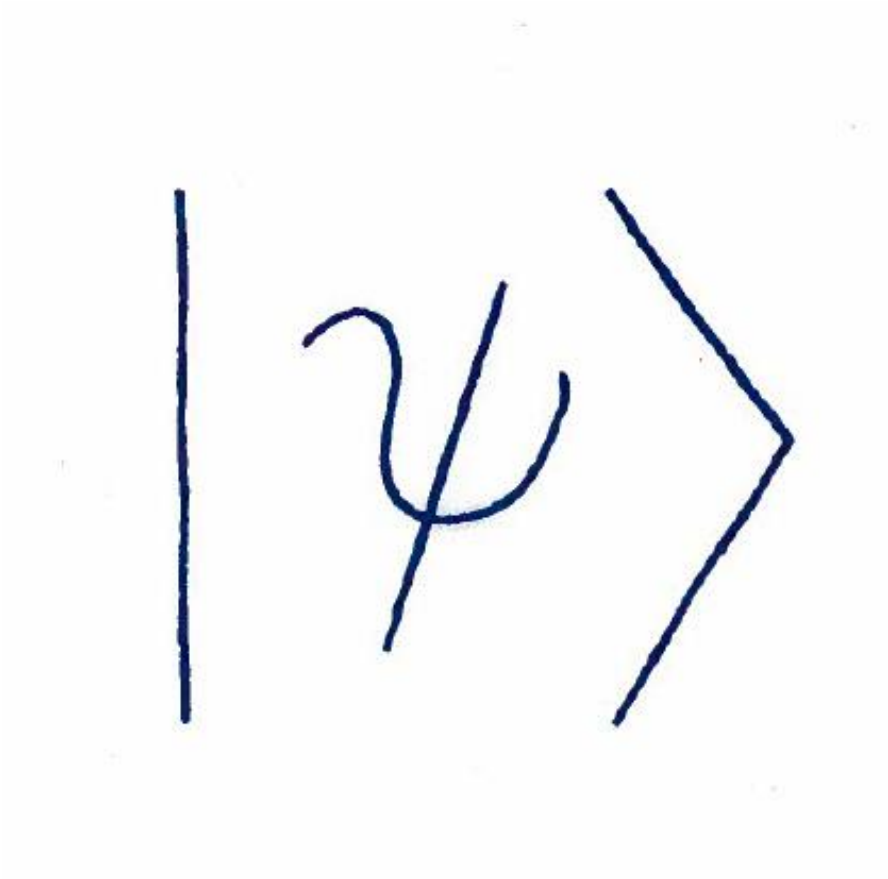
Some Things to Read on QBism

- CAF & B. C. Stacey, “QBism: Quantum Theory as a Hero's Handbook,” **arXiv:1612.07308**.
- CAF, N. D. Mermin, & R. Schack, “An Introduction to QBism with an Application to the Locality of Quantum Mechanics,” Am. J. Phys. **82**, 749 (2014).
- CAF, “Interview with a Quantum Bayesian,” **arXiv:1207.2141**.
- CAF, “On Participatory Realism,” **arXiv:1601.04360**.
- CAF, “Notwithstanding Bohr, the Reasons for QBism,” **arXiv:1705.03483**.
- CAF & R. Schack, “Quantum-Bayesian Coherence,'' Rev. Mod. Phys. **85**, 1693 (2013).
- N. D. Mermin, “Why QBism is Not the Copenhagen Interpretation and What John Bell Might Have Thought of It,” **arXiv:1409.2454**.
- H. C. von Baeyer, *QBism: The Future of Quantum Physics,* (Harvard U Press, Cambridge, 2016).

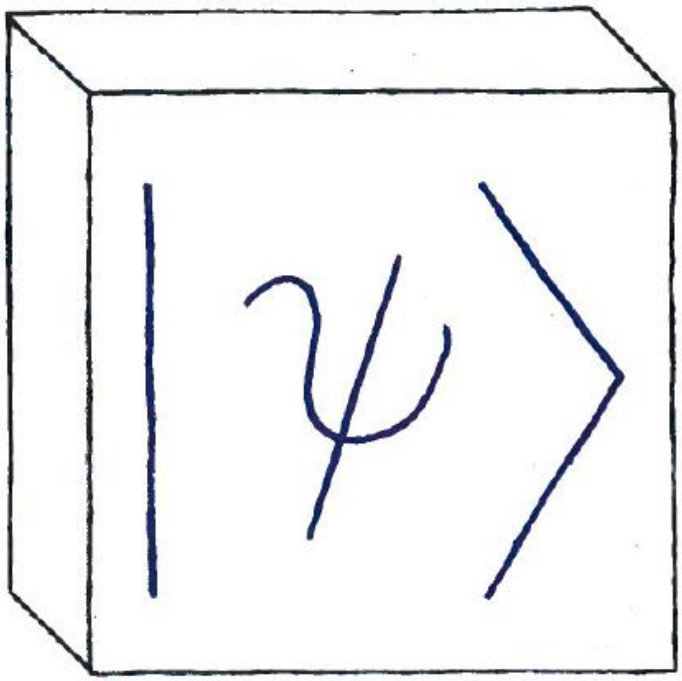
The World Is Made of Some Stuff



The Quantum State



What Is the Relation?



E. T. Jaynes, 1

Motivation for QBism

"Our present QM formalism is a peculiar mixture describing in part laws of Nature, in part incomplete human information about Nature – all scrambled up together by Bohr into an omelette that nobody has seen how to unscramble. Yet we think the unscrambling is a prerequisite for any further advance in basic physical theory. For, if we cannot separate the subjective and objective aspects of the formalism, we cannot know what we are talking about; it is just that simple."

A Corrective to Jaynes

Some (most!) elements of the formalism are *subjective*
—more subjective than Jaynes himself would ever go.

Whereas some relations in the formalism are *objective*
—as objective as one could want of a physical theory.

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You want to look for a statement about reality?
Then that's where you look!

$$P(H) = x$$

$$P(T) = 1 - x$$

My Expectations*!*

Ask the coin about my expectations for it, and it will laugh,
"Don't ask me, I don't have a clue – that's your business. Ask yourself."

Different People, Different Beliefs*!*

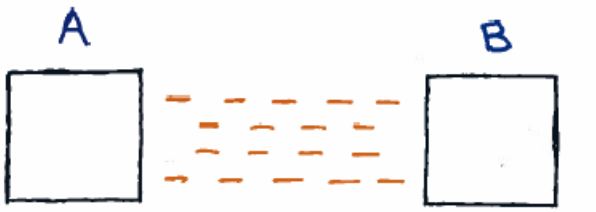
$$F(p_0, p_1) = \sum_b \sqrt{p_0(b)}\sqrt{p_1(b)}$$

Immediate Explanatory Power

Cannot make

$|\psi\rangle \rightarrow |\psi\rangle|\psi\rangle$

No-Cloning Theorem



$|\Psi^-\rangle = \frac{1}{\sqrt{2}}(|\uparrow\rangle|\downarrow\rangle - |\downarrow\rangle|\uparrow\rangle)$

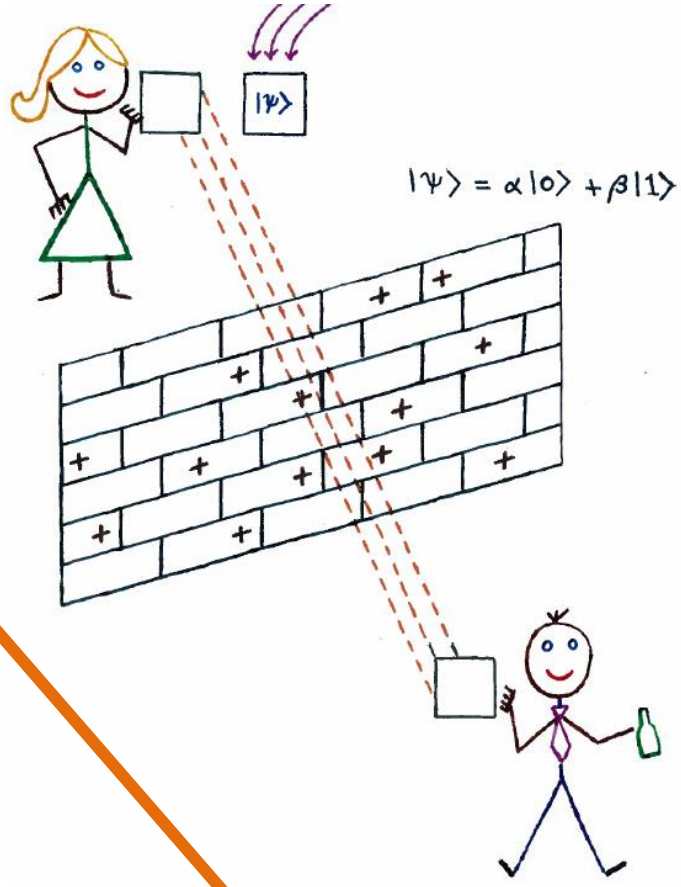
Einstein's Locality Concerns

Alice measure $|\uparrow\rangle, |\downarrow\rangle$ basis

Bob's system $|\uparrow\rangle$ or $|\downarrow\rangle$ afterward

Alice measure $|\rightarrow\rangle, |\leftarrow\rangle$ basis

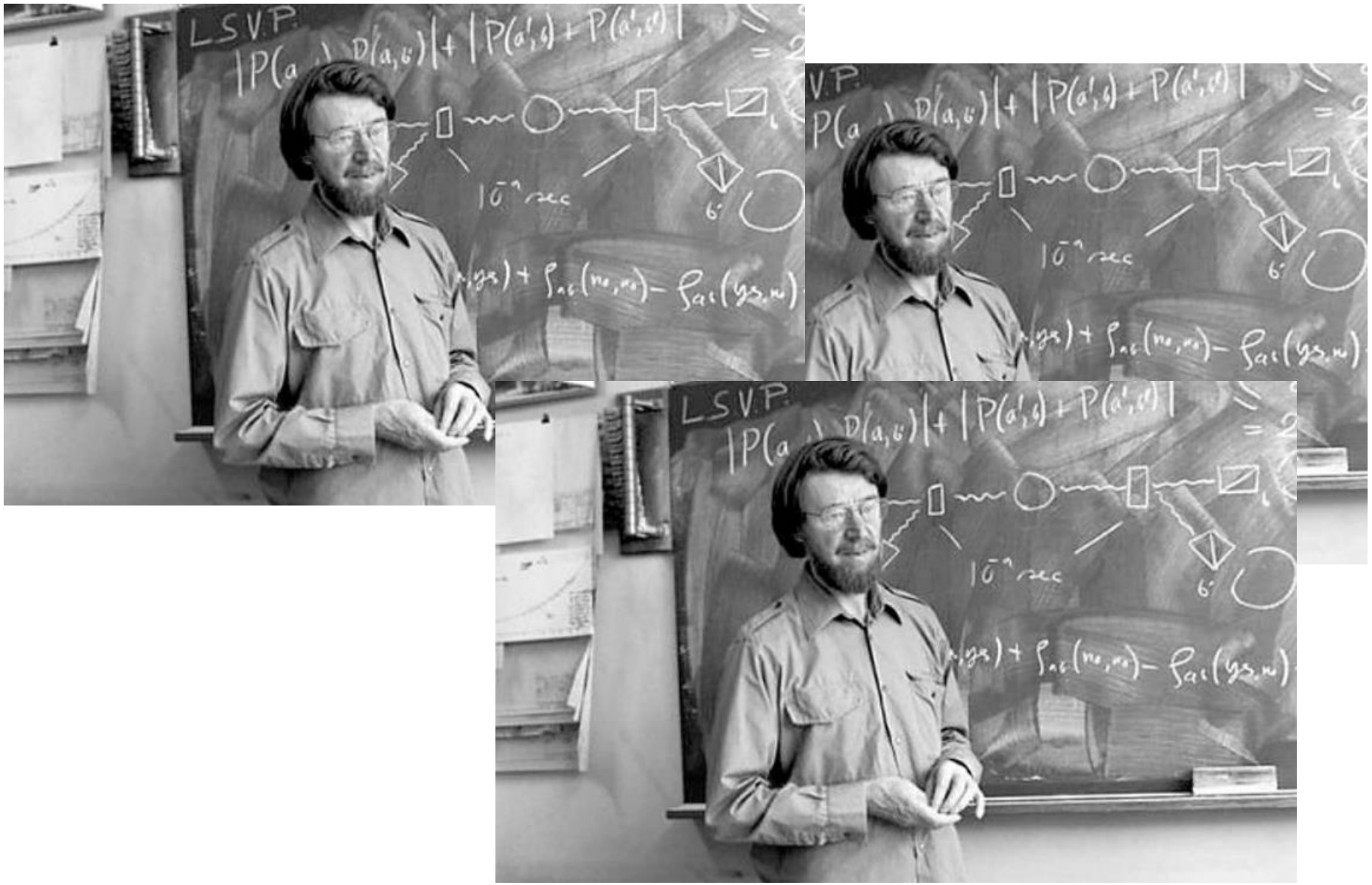
Bob's system $|\leftarrow\rangle$ or $|\rightarrow\rangle$ afterward



Quantum Teleportation

All these phenomena are simply understood
if one assumes
quantum states are states of belief.

What was the great lesson of John Bell?



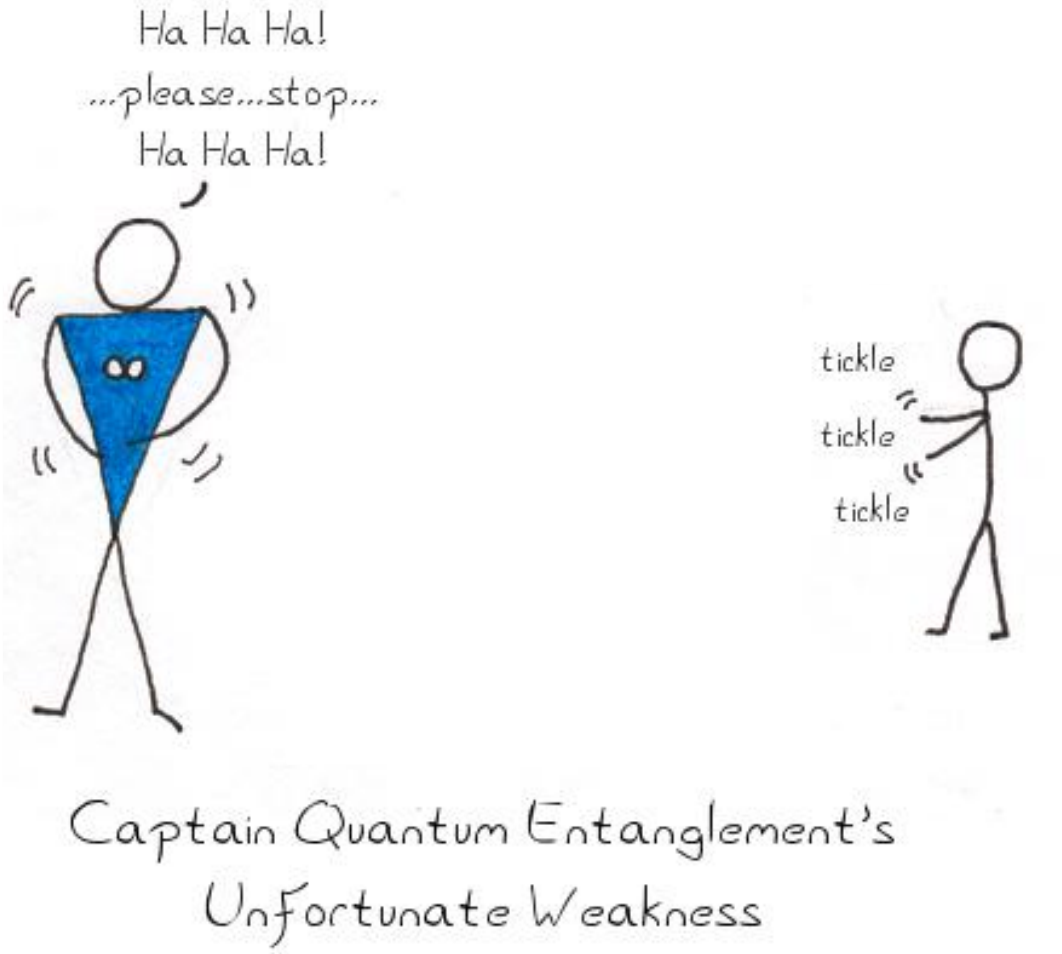
The Culture of Many Philosophy of Physics Meetings

"What Bell proved, and what theoretical physics has not yet properly absorbed, is that the physical world itself is nonlocal."

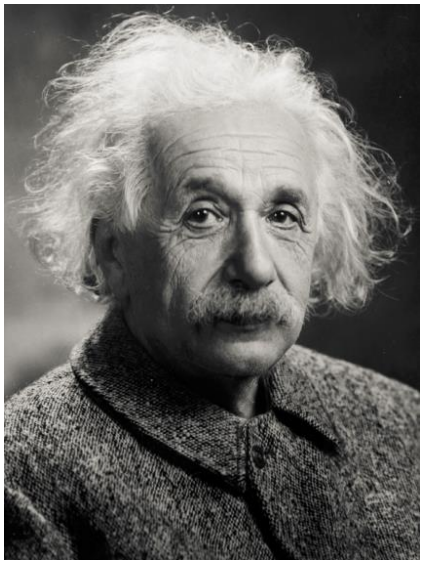
– Tim Maudlin
"What Bell Did," 2014

A.k.a. Spooky action at a distance.

But, makes most physicists suspicious. Where does it stop?

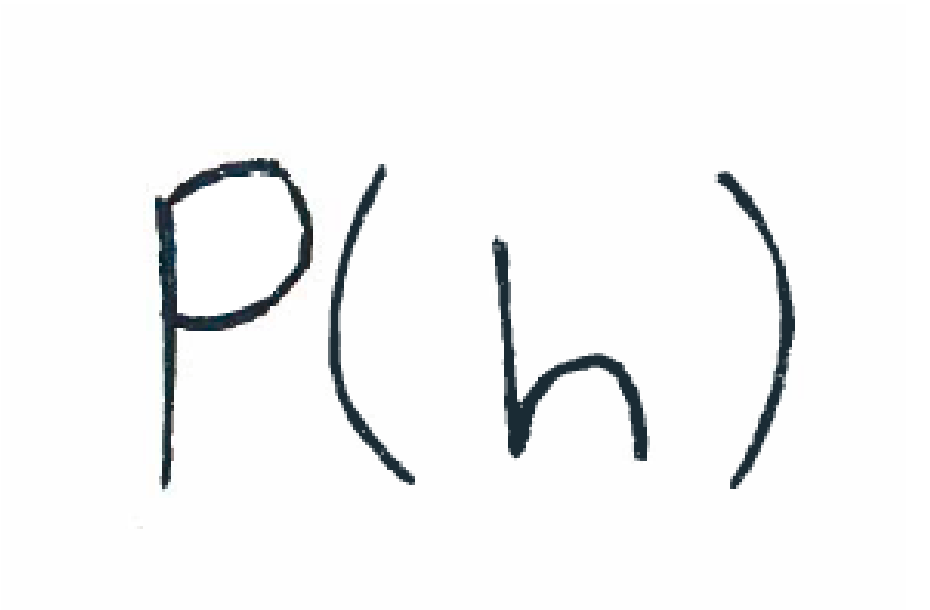


Einstein's Worry



If one asks what is characteristic of the realm of physical ideas, then above all the following attracts our attention: The concepts of physics refer to a real external world … Moreover, it is characteristic of these physical things that they are conceived of as being arranged in a space-time continuum. Further, it appears to be essential for this arrangement that, at a specific time, these things claim an existence independent of one another. Without such an assumption of the mutually independent existence of spatially distant things physical thought in the sense familiar to us would not be possible. Nor does one see how physical laws could be formulated and tested without such a clean separation.

What are Quantum Probabilities? Indeed, what are probabilities?

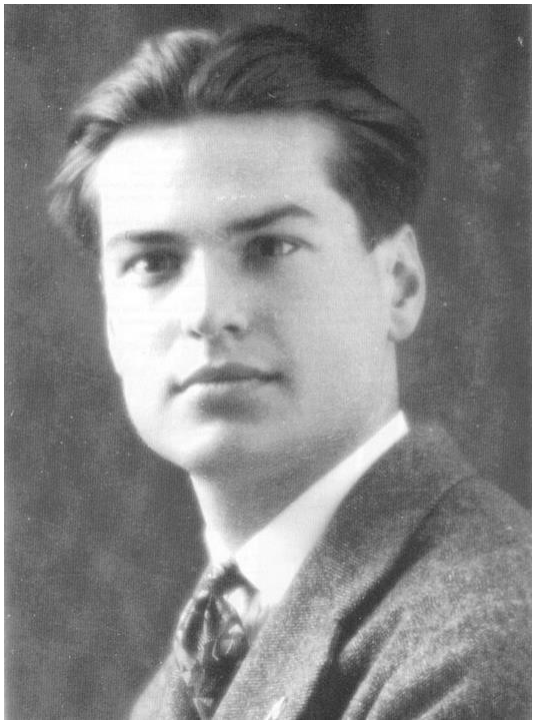


Unless we want tickle, tickle, tickle, they must be banished from the external world.

My thesis, paradoxically, and a little provocatively, but nonetheless genuinely, is simply this:

PROBABILITY DOES NOT EXIST.

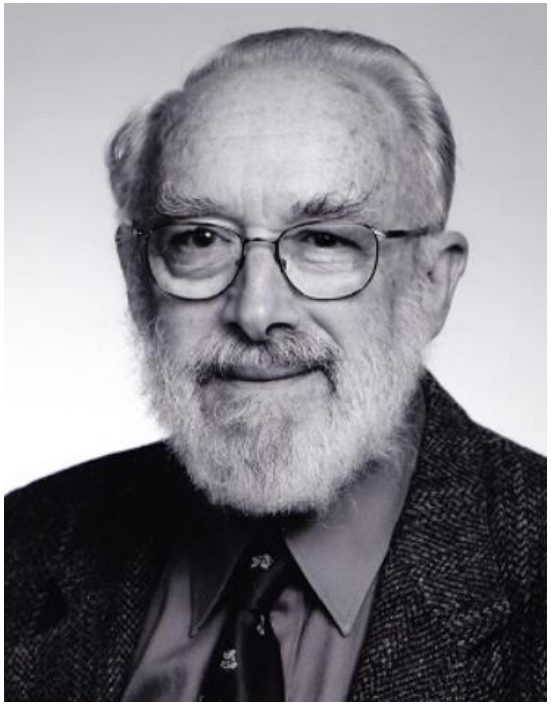
The abandonment of superstitious beliefs about the existence of Phlogiston, the Cosmic Ether, Absolute Space and Time, ..., or Fairies and Witches, was an essential step along the road to scientific thinking. Probability, too, if regarded as something endowed with some kind of objective existence, is no less a misleading conception, an illusory attempt to exteriorize or materialize our actual probabilistic beliefs.



Bruno de Finetti
1906 – 1985

The Coherentist Paradigm

"The topic studied is the situation of an individual who is faced with uncertainty about some events of concern to him. All of us find ourselves in this position … De Finetti's task is first to recognize openly the uncertainty surrounding us and then see how we can best understand it. The main result is that uncertainty can only be described satisfactorily in terms of probability."

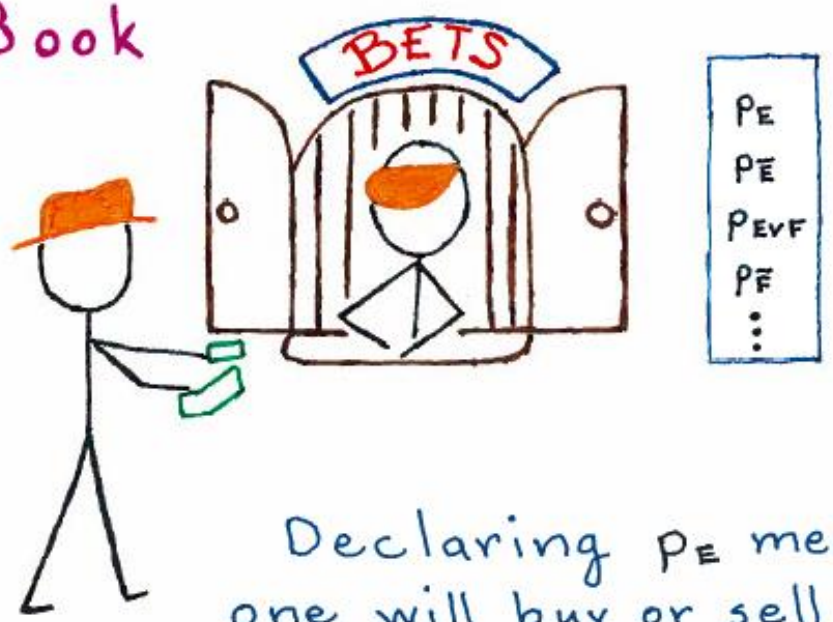


Dennis V. Lindley
1923—2013

"The [coherentist] paradigm is egocentric. It is a tale of a [single] person contemplating the world and not wanting to be stupid. He realizes that to do this his statements of uncertainties must [satisfy the laws of probability]."

Defining Probability

Dutch Book



Declaring p_E means one will buy or sell a lottery ticket

Worth \$1 if E

for $\$p_E$.

Dutch Book

Normative Rule:

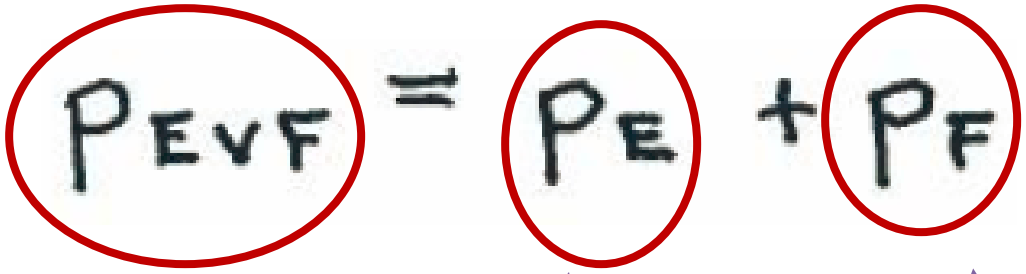
Never declare p_E, $p_{\bar{E}}$, $p_{E \vee F}$, etc. that will lead to sure loss.

That one simple rule (or suggestion really) leads to all the laws of probability theory.

$$p_{E \vee F} = p_E + p_F \qquad p_{E \wedge F} = p_F p_{E|F}$$

Etc.

The Normative Reading



Maybe from another.

Maybe from one source of thinking.

And maybe from still another.

Dutch Book

Example 1:

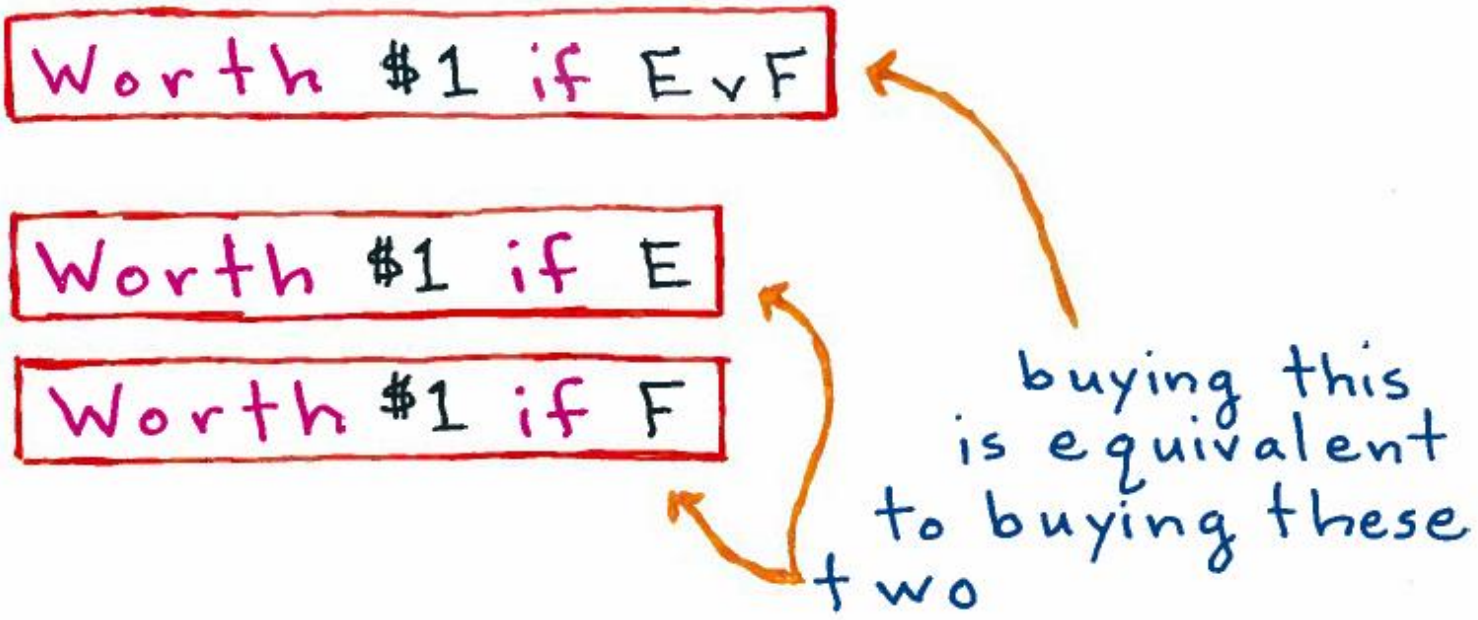
If $p_E < 0$, bookie will sell ticket for negative money. Sure loss!

Example 2:

If $p_E > 1$, bookie will buy ticket for more than it is worth in best case. Sure loss.

Example 3:

Suppose E and F mutually exclusive.



So must have $P_{E \vee F} = P_E + P_F$.

Bayes Rule

Thomas Bayes
1701—1761

Consider conditional lotteries:

If $E \wedge F$ give full price, but if $\overline{F}$ return money.

Thus:

Worth #1 if $E \wedge F$; Worth # $p_{E|F}$ if $\overline{F}$.	price # $p_{E|F}$

But:

Worth #1 if $E \wedge F$	price # $p_{E \wedge F}$
Worth # $p_{E|F}$ if $\overline{F}$	price # $p_{E|F} p_{\overline{F}}$

recall example 4

So must have:

$$p_{E|F} = p_{E \wedge F} + p_{E|F} p_{\overline{F}} \Rightarrow \boxed{p_{E \wedge F} = p_F p_{E|F}}$$

Why Normative?
Why Not Necessitarian?

$p(A)$, $p(B)$, $p(C)$, ...

$p(A \mid B)$, $p(A \mid B \vee C)$,

$p(A \wedge B \mid C \vee D)$, $p(A, B)$

$p(A \wedge (B \vee C) \mid Z \wedge Y \wedge (X \vee W))$

$p(Z \wedge (A \vee (L \wedge K)) \mid \neg M \wedge (\neg F \vee Y))$

⋮

Discussion from arXiv:1003.5209

The key idea of personalist Bayesian probability theory is that it is a calculus of consistency (or "coherence'" as the practitioners call it) for one's decision-making degrees of belief. Probability theory can only say if various degrees of belief are consistent or inconsistent with each other. The actual beliefs come from another source, and there is nowhere to pin their responsibility but on the agent who holds them.

A probability *assignment* is a tool an agent uses to make gambles and decisions – it is a tool he uses for navigating life and responding to his environment. Probability *theory* as a whole, on the other hand, is not about a single isolated belief, but about a whole mesh of them. When a belief in the mesh is found to be incoherent with the others, the theory flags the inconsistency. However, it gives no guidance for how to mend any incoherences it finds. To alleviate the discord, one can only dip back into the source of the assignments – specifically, the agent who attempted to sum up all his history, experience, and expectations with those assignments in the first place. This is the reason for the terminology that a probability is a "degree of belief" rather than a "degree of truth" or "degree of facticity."

Where personalist Bayesianism breaks away the most from other developments of probability theory is that it says there are no *external* criteria for declaring an isolated probability assignment right or wrong. The only basis for a judgment of adequacy comes from the *inside*, from the greater mesh of beliefs the agent may have the time or energy to access when appraising coherence.

The Normative Struggle

(certainly a mark of a *quantum mechanical* agent)

Question: Can an ant use probability theory in this sense?

Answer: No.

Discussion from a Recent Email

The issue came up as to what counts as a "user" of quantum theory. Must the user be conscious? I said I did not like that way of phrasing things, for it takes the issue too far afield. I myself would prefer to say it is whatever it takes to be a user of probability theory. Dogs don't collapse wave functions because dogs don't use wave functions.* There was immediate protest: "But ants already use probabilities, it has been shown. For the paths they take, one can model the trajectories with an appropriate choice of probabilities and utilities." I said, "No, that's not what I mean. And that is no proof whatsoever that ants ***use*** probability theory in the sense I mean it." To use probability theory, I mean one must use it internally, and in the ***normative*** sense my talk emphasized. Probability assignments spring from an attempt to organize one's previous experience for the purpose of future actions. Ants are surely not using it ***normatively***. "So you do require consciousness?" And so it went. I think that discussion helped me in that it focused me on what I think is the key point: Modeling agents from the outside (at least in the discussions I've seen so far) never takes into account the normative struggle that is required for any but the most trivial probability assignments.

*With apologies to little Q Bism Fuchs (first name, middle name, last).

Certainty

What means probability 1?

It means one will buy or sell a lottery ticket

Worth #1 if E

for in fact #1, full stop.

That is all it means.

Probability 1 does not imply truth or existence.

"The Bayesian framework replaces … affirmation and denial … by a continuum of judgmental probabilities in the interval 0 to 1, endpoints included – or what comes to the same thing – a continuum of judgmental odds in the interval 0 to ∞, endpoints included. Zero and 1 are probabilities no less than 1/2 and 99/100 are. Probability 1 corresponds to infinite odds, 1:0. That's a reason for thinking in terms of odds: to remember how momentous it may be to assign probability 1 to a hypothesis. It means you'd stake your all on it."

Richard Jeffrey
1926—2002

(But that doesn't mean it is true!)

Bear in mind, this is only about probabilities so far.

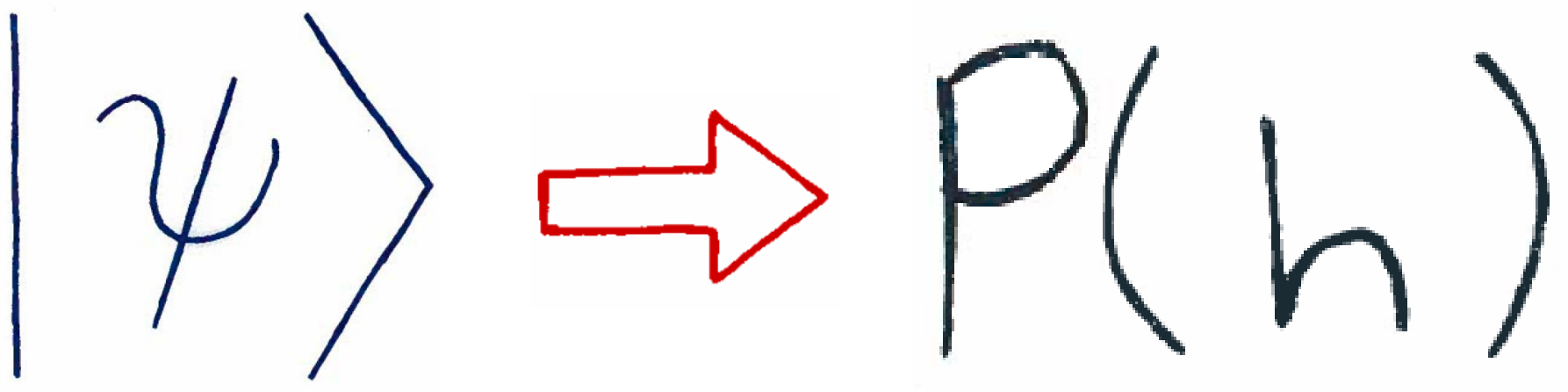
There is no commitment to an ontology yet.

Most of the time one sees Bayesian probabilities characterized as measures of ignorance or imperfect knowledge. But that description carries with it a metaphysical commitment that is not necessary for the personalist Bayesian.

Imperfect knowledge? It sounds like something that could be perfected, making all probabilities zero or one—one uses probabilities only because one does not know the true, pre-existing state of affairs.

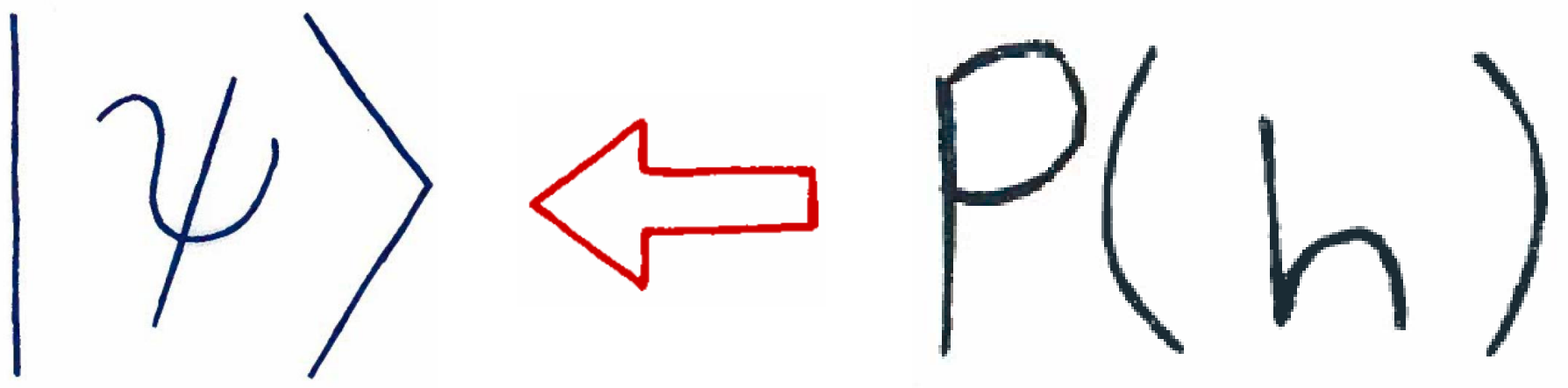
All that matters is that there is *uncertainty* for whatever reason. There might be uncertainty because there is ignorance of a true state of affairs, but there might be uncertainty because the world itself does not yet know what it will give—i.e., there is an objective indeterminism.

What We Do with Quantum States

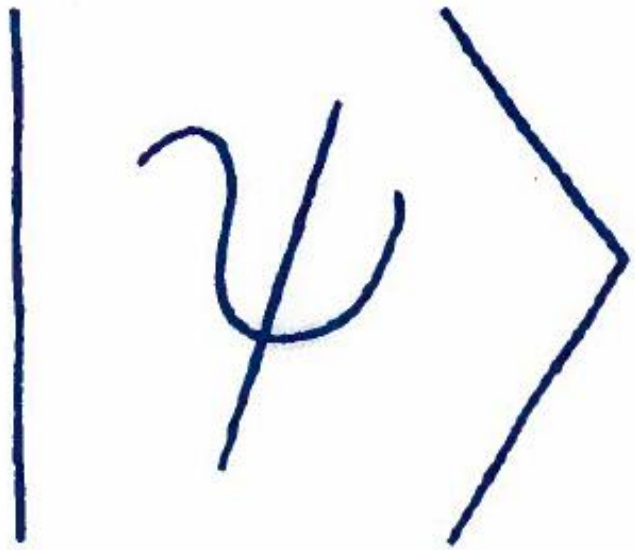


We calculate probabilities.

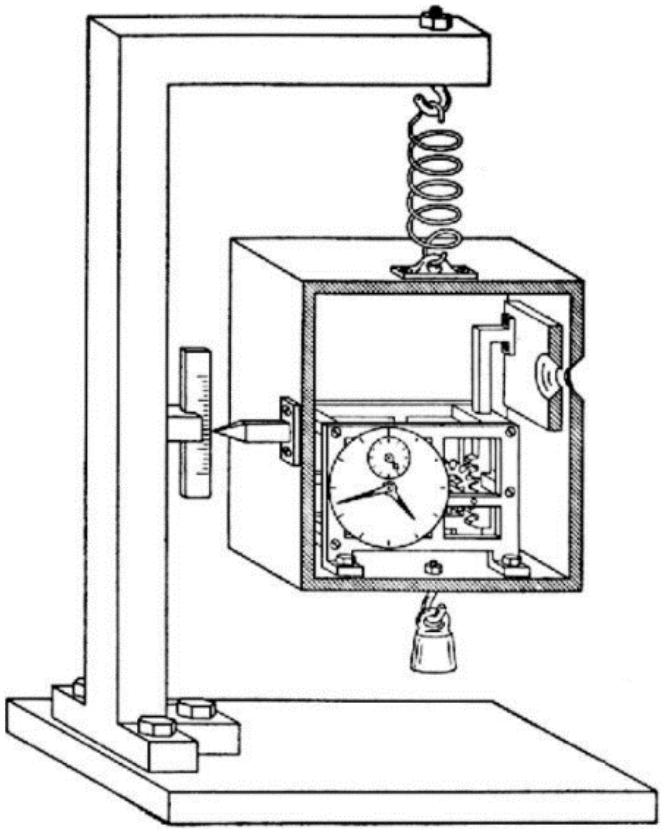
And if you know enough quantum information theory …



… by considering a robust enough set of measurements.

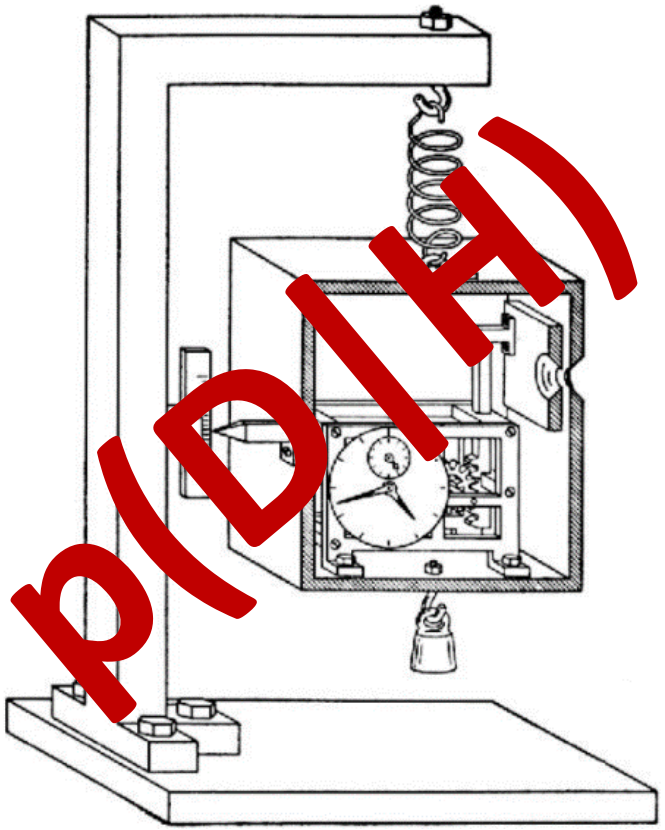


Must have to do with a tale of a single person not wanting to be stupid.



But what about quantum measuring devices?
Solid, objective?

CAF, arXiv:quant-ph/0205039



More elaborate quantum information analysis shows them to be of the character of conditional probability assignments.

Tenet 1: All probabilities, including all quantum probabilities, are so personal or subjective they never tell nature what to do. This includes probability-1 assignments. Thus, quantum states, measurement operators, and unitary time evolution operators have no "ontic hold" on the world. They all represent personal judgments.

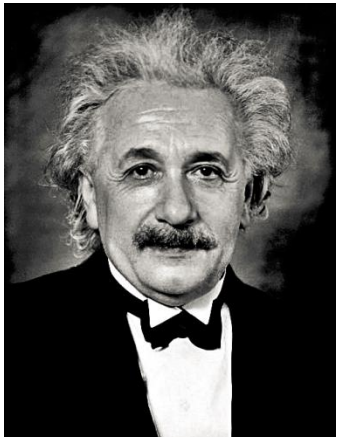
"Measurement"

Does it reveal a pre-existing, but unknown, value?

or

Does it in some sense go toward creating the very value?

Einstein, Podolsky, and Rosen (EPR) Criterion of REALITY



(1935)

"If, without in any way disturbing a system [one can gather the information required to] 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."

"If I could make one change to the EPR paper in retrospect it would be to alter the characterization of this criterion. The authors call it 'reasonable' and 'in agreement with classical as well as quantum-mechanical ideas of reality', but its status is actually much stronger than that: the criterion is, in the parlance of philosophers, *analytic*. That is, this criterion follows just from the very meanings of the words used in it."

Tim Maudlin

Not in QBism.

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Tim Maudlin

And that gets rid of tickle, tickle, tickle …

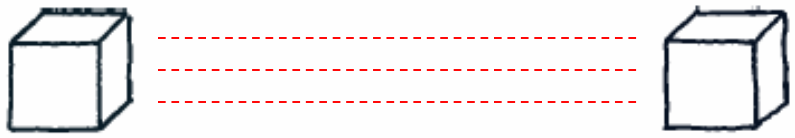
CAF, Mermin, Schack, Am. J. Phys. **82**, 749 (2014)
D. Glick & F. J. Boge, arXiv.org:1909.11893

Modern-Day Version of EPR

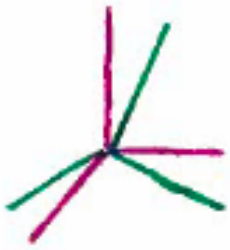
CAF, Stacey, arXiv:1401.7254

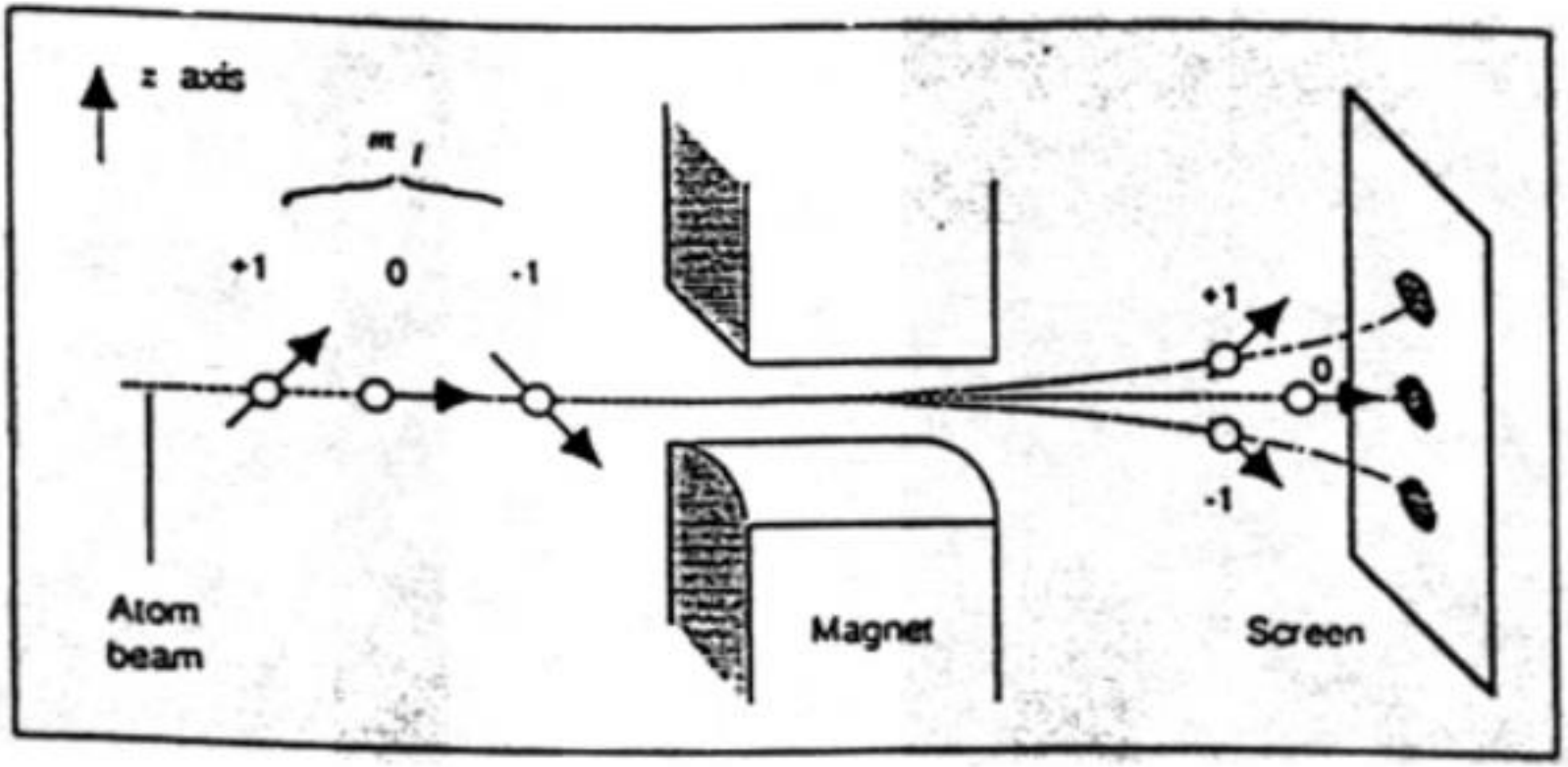
Consider two spatially separated qutrits in a maximally entangled state:

$$|EPR\rangle = \sum_{i=1}^{3} |i\rangle|i\rangle$$



Now measure the left one any way you like. Say with A or B:




z axis
m_l
+1
0
-1
+1
0
-1
Atom beam
Magnet
Screen

Discussion from arXiv:1003.5209

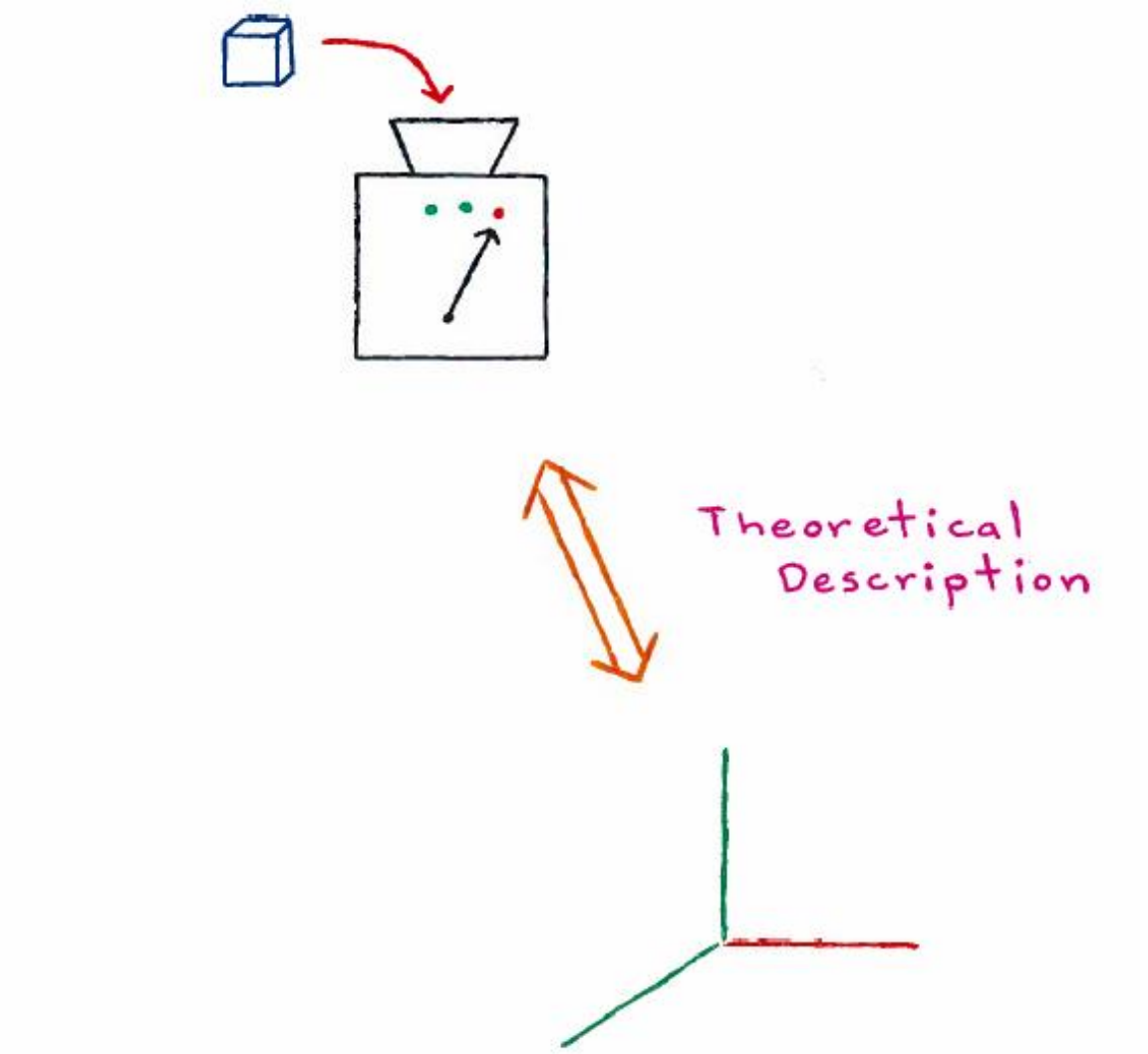
We know that there exist pairs of measurements, one for each of the separate systems, such that if the outcome of one is known (whatever the outcome), one will thereafter make a probability-one statement concerning the outcome of the other. For instance, if a nondegenerate Hermitian operator is measured on the left-hand system, then one will thereafter ascribe a probability-one assignment for the appropriate outcome of the transposed operator on the right-hand system. What this means for a Bayesian agent is that after performing the first measurement he will bet his life on the outcome of the second.

But how could that be if he has already recognized two systems with no instantaneous causal influence between each other? Mustn't it be that the outcome on the right-hand side is “already there” simply awaiting confirmation or registration? Indeed it must be this kind of thinking that led EPR to their famous sufficient criterion for an “element of [preexistent] reality.”

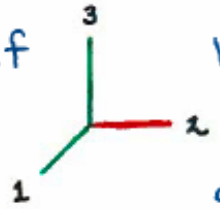
Without doubt, no personalist Bayesian would ever utter such a notion: Just because he believes something with all his heart and soul and would gamble his life on it, it would not make it necessarily so by the powers of nature---even a probability-one assignment is a state of belief for the personalist Bayesian. But he might still entertain something not unrelated to the EPR criterion of reality. Namely, that believing a particular outcome will be found with certainty on a causally disconnected system entails that one *also* believes the outcome to be “already there” simply awaiting confirmation.

But it is not so, and QBism has already built this into his story of measurement. Let us show this presently by combining all the above with a beautifully simple Kochen-Specker style construction discovered by [Peres].

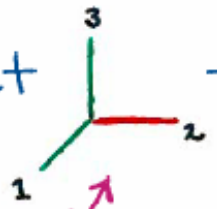
General Description of Measurement



So measurement is simple revelation after all?

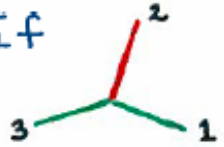
If 

here,

can predict 

there.

element of reality

If 

here,

can predict 

there.

element of reality

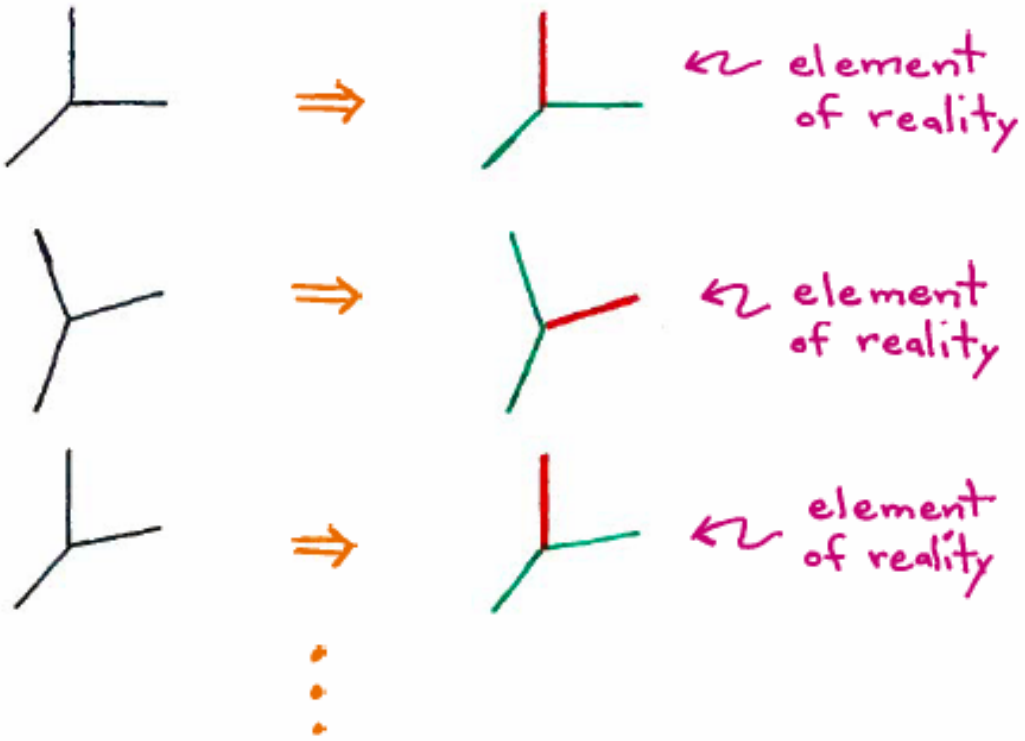
Not So Fast!

Key Argument

Then we should be able to color every set of orthogonal rays in $\mathbb{R}^3$ red-green-green.

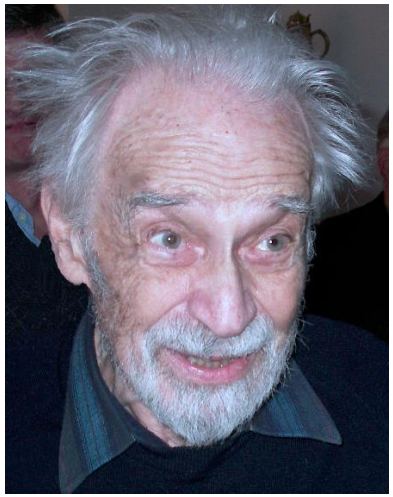
EPR Implodes

But must consider many more bases than two.



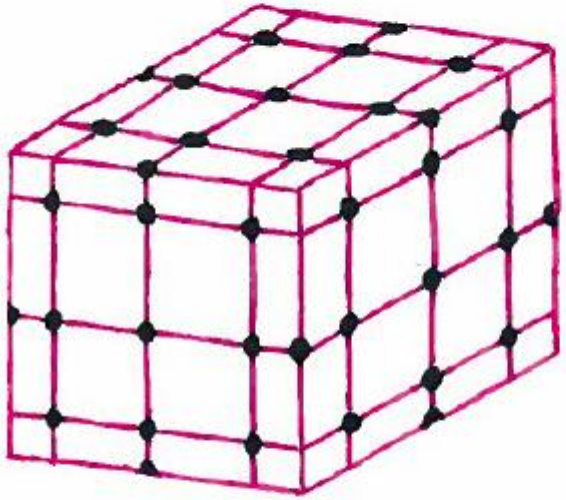
Until contradiction.

Simon Kochen



Ernst Specker
1920 – 2011

Cannot be colored:

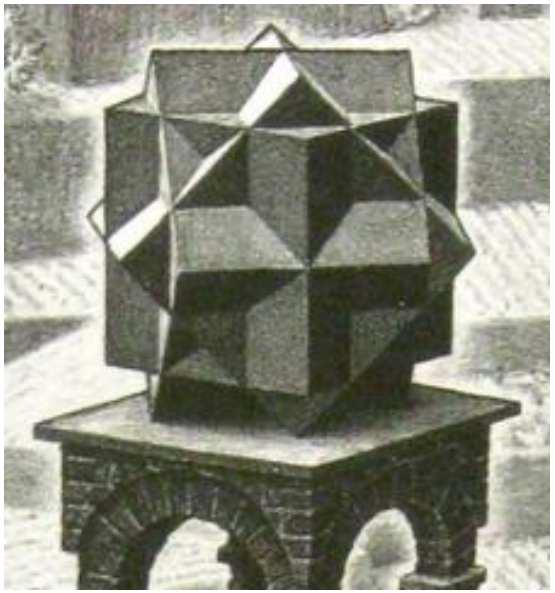


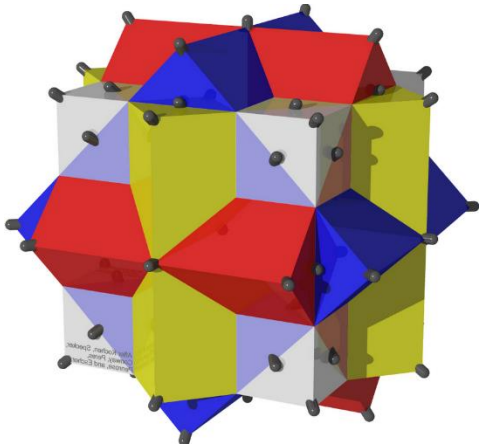
33 rays, Peres

(when completed into full triads, consists of 40 triads made from 57 rays)

Asher Peres
1934 – 2005

Hidden in M. C. Escher





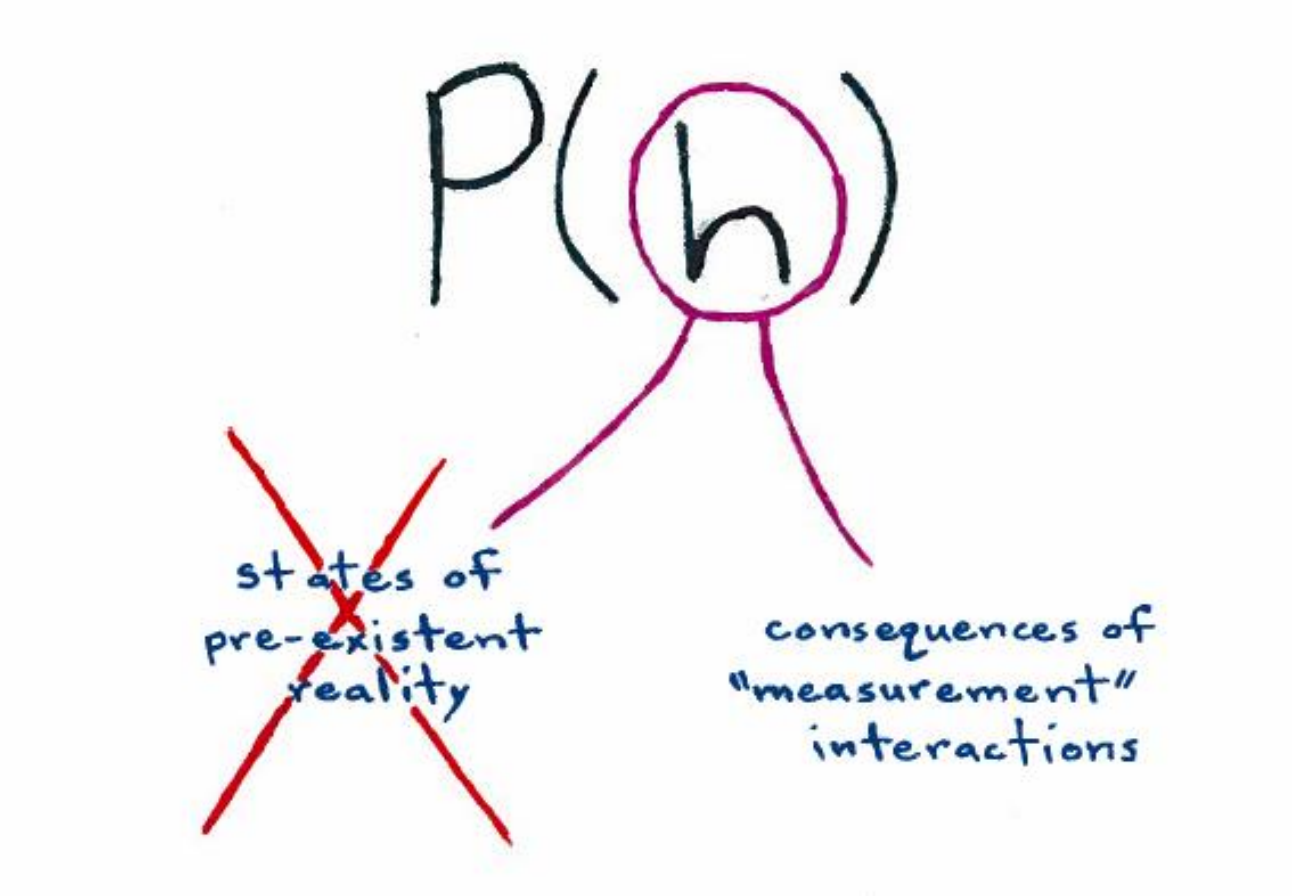
"Measurement"

Does it reveal a pre-existing, but unknown, value?

or

Does it in some sense go toward creating the very value?

What Quantum Probabilities Are About



The Great Lesson of John Bell for QBism

It is not that nature is nonlocal.

It is that nature is creative.

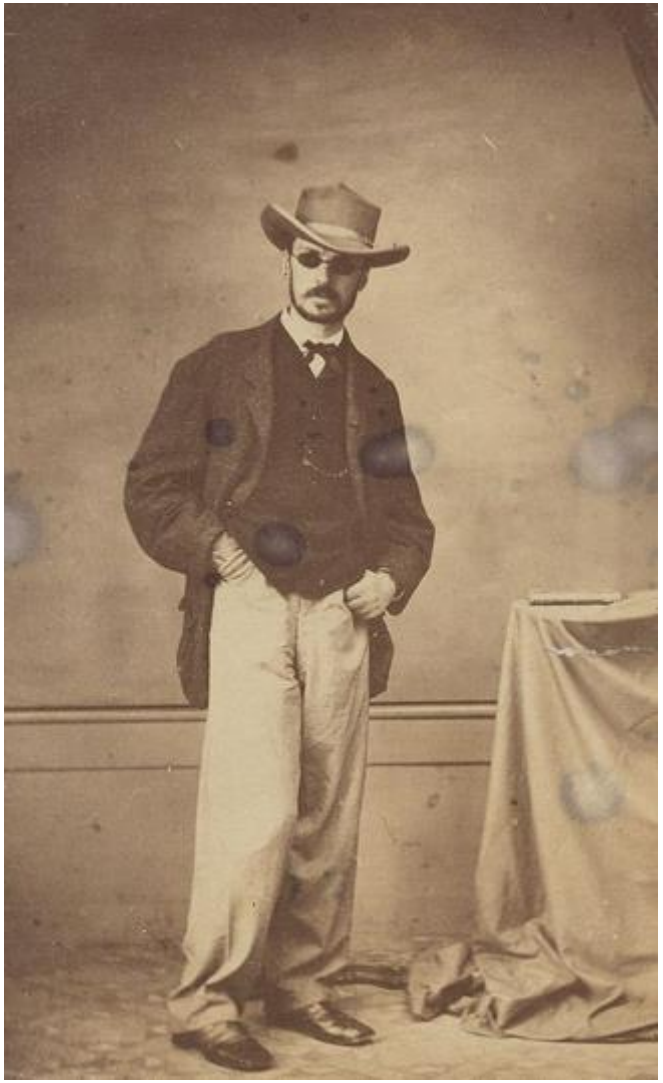
As it was put in a recent QBist manifesto*: "With every quantum measurement set by an experimenter's free will, the world is shaped just a little as it takes part in a moment of creation. So too it is with every action of every agent everywhere, not just experimentalists in laboratories. Quantum measurement represents those moments of creation that are sought out or noticed."

*CAF, arXiv:1405.2390

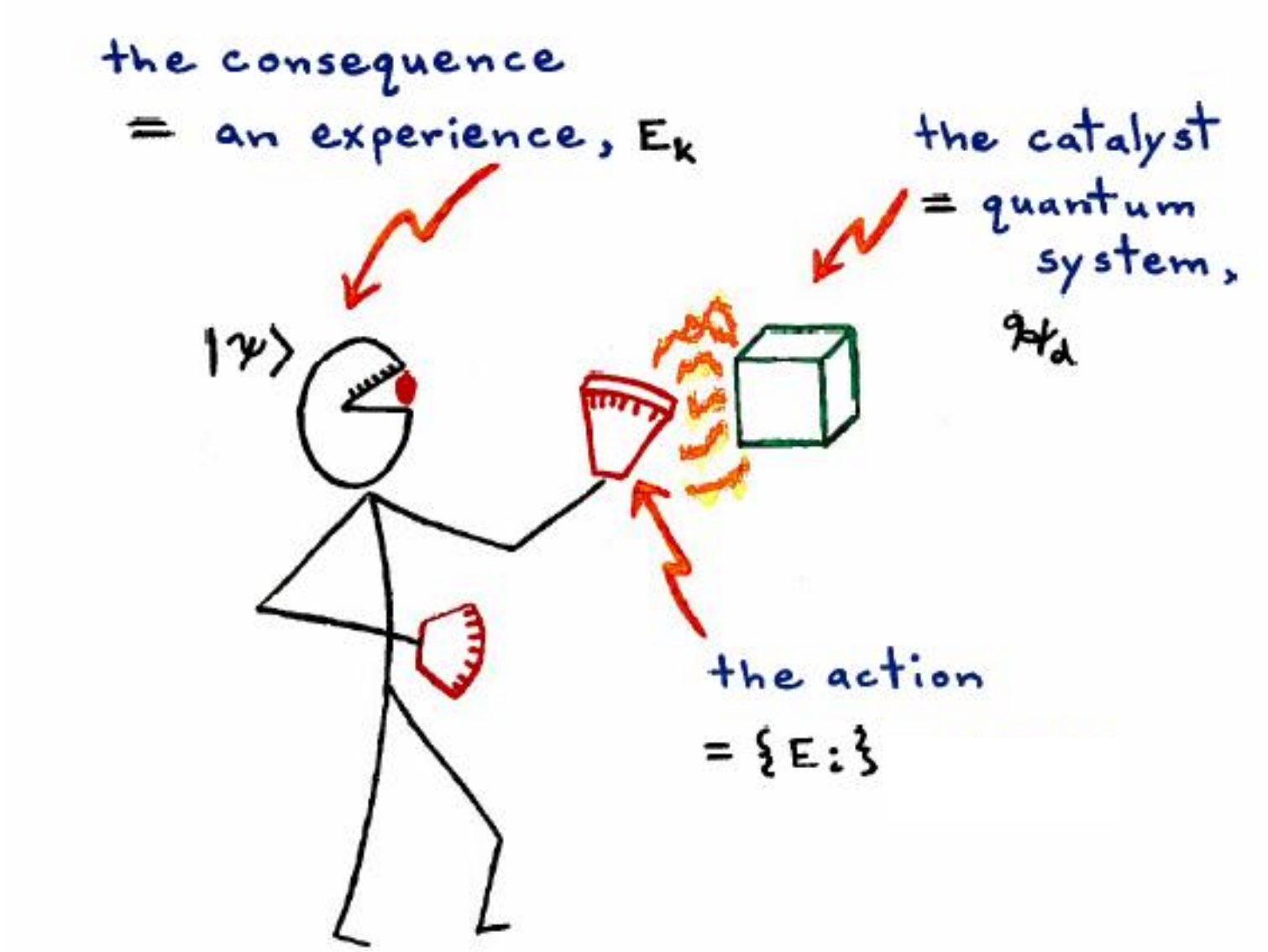
One Possible Ontology: Autonomy All the Way Down?

Chance is a purely negative and relative term, giving us no information about that of which it is predicated, except that it happens to be disconnected with something else—not controlled, secured, or necessitated by other things in advance of its own actual presence. What I say is that it tells us nothing about what a thing may be in itself to call it "chance." All you mean by calling it "chance" is that this is not guaranteed, that it may also fall out otherwise. For the system of other things has no positive hold on the chance-thing. Its origin is in a certain fashion negative: it escapes, and says, "Hands off!" . . . coming, when it comes, as a free gift, or not at all.

This negativeness, however, and this opacity of the chance-thing when thus considered *ab extra*, or from the point of view of previous things or distant things, do not preclude its having any amount of positiveness and luminosity from within, and at its own place and moment. All that its chance-character asserts about it is that there is something in it really of its own, something that is not the unconditional property of the whole. If the whole wants this property, the whole must wait till it can get it. That the universe may actually be a sort of joint-stock society of this sort, in which the sharers have both limited liabilities and limited powers, is of course a simple and conceivable notion.



William James, 1842 – 1910

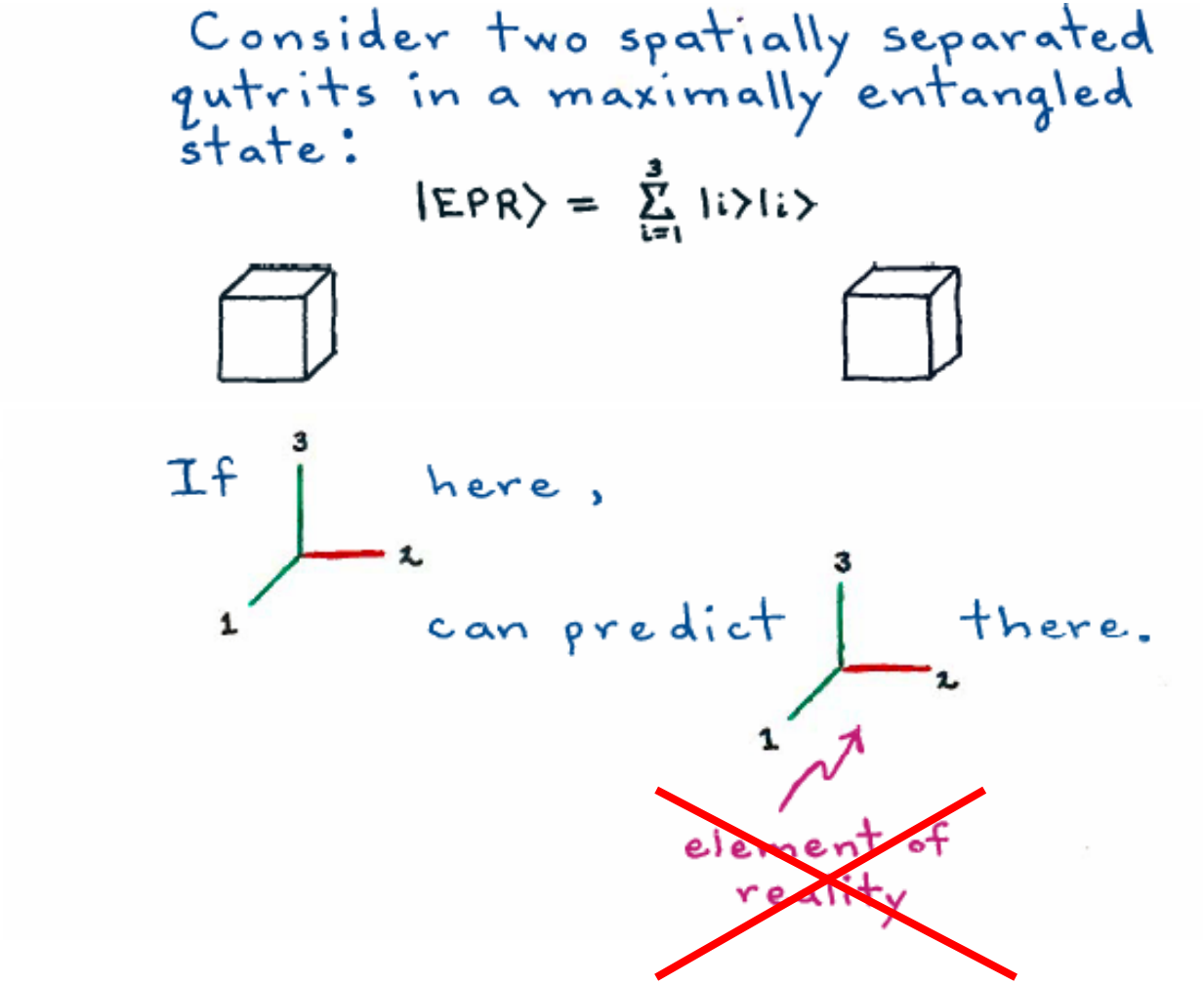


Quantum measurement represents those moments of creation that are enacted or noticed.

With this much in hand,
a good exercise is to see how QBism
actually does treat Bell's scenario.

(It's all about how a single agent will gamble.)

EPR Redux … QBist Style



QBism's Story: Take an action, walk, take an action.
Consequence is always a new creation.

Example 1: The Pure Einstein

Alice measures one half of an EPR pair, updating to $|\psi\rangle$ for the other side.

All it means is if she were to walk to the other side and measure $\{|\psi\rangle\langle\psi|, I - |\psi\rangle\langle\psi|\}$ she would gamble her life on getting outcome $|\psi\rangle\langle\psi|$.

QUANTUM MYSTERIES FOR ANYONE

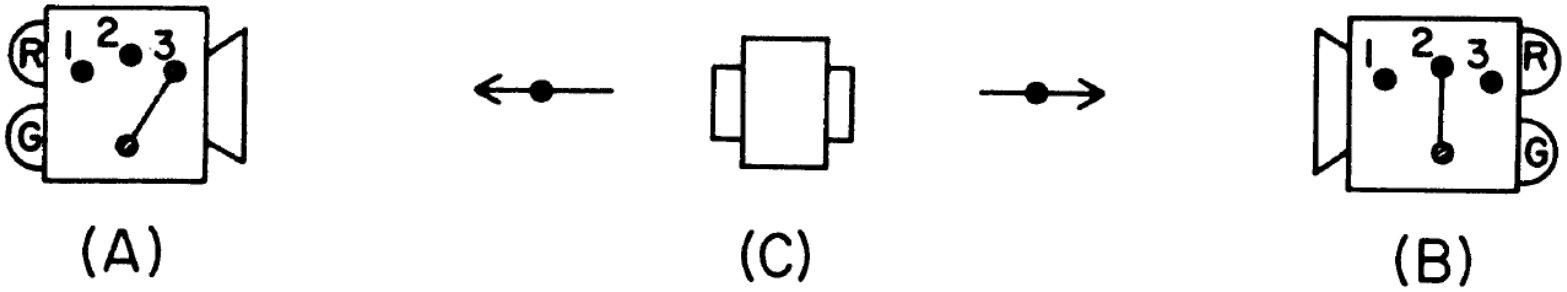


Fig. 2. The complete device. A and B are the two detectors. C is the box from which the two particles emerge.

N. David Mermin

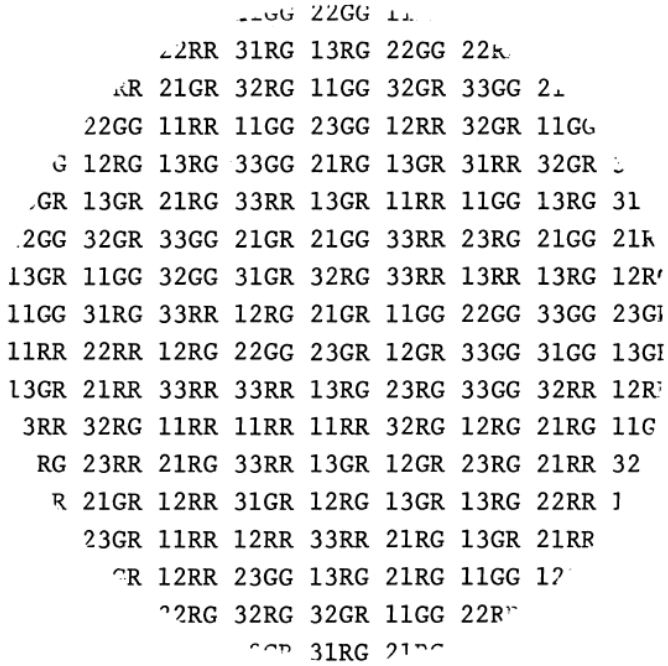


Fig. 4. Fragment of a page of a volume from the set of notebooks recording a long series of runs.

QUANTUM MYSTERIES FOR ANYONE

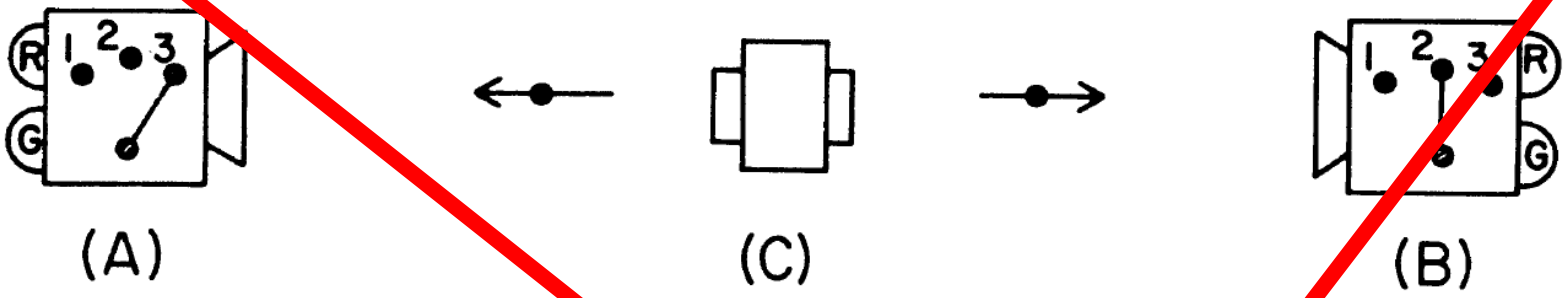


Fig. 2. The complete device. A and B are the two detectors. C is the box from which the two particles emerge.

Sorry David! The whole scenario requires a *God's-eye-view* for its very statement.

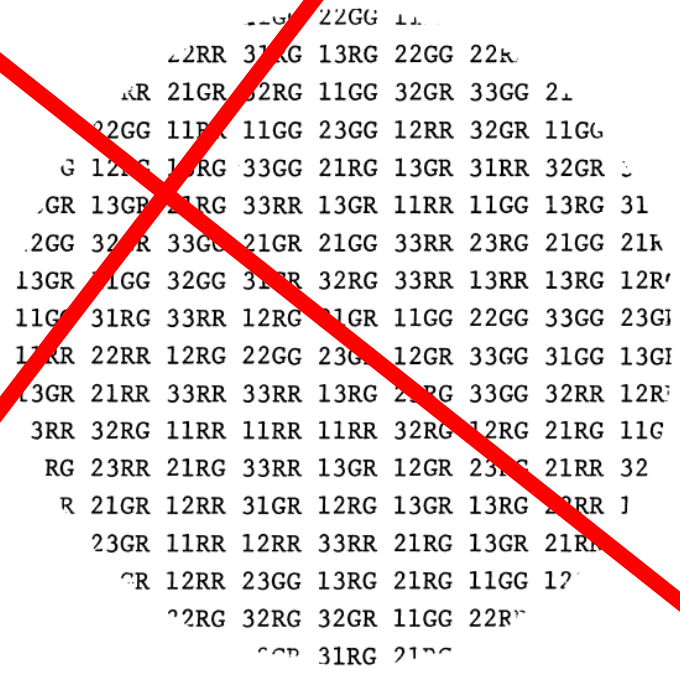


Fig. 4. Fragment of a page of a volume from the set of notebooks recording a long series of runs.

Example 2: Scenario of Bell Inequality Tests

Alice and Bob set out to demonstrate Bell inequality violations.

Alice believes quantum mechanics.

Alice's beliefs evolve:

initial $|EPR\rangle\langle EPR| \otimes \rho_{Bob} \equiv \rho_0$

believing Bob interacts with his qubit

$\rightarrow (I \otimes U_{qB})\, \rho_0\, (I \otimes U_{qB}^{+})$

she measures, updates Bob & his qubit

$\rightarrow$ ρ_{qB} generally entangled

Example 2 cont.

Where in Alice's beliefs (i.e. quantum states) is any notion of clicks on Bob's side?

Her quantum states do not pierce into those systems.

They only refer to what she believes will be the consequences of her later interactions with Bob.

Comparison to an Everettian Take

"From the perspective of a given experimenter, of course, her experiment *does* have a unique, definite outcome, even in the Everett interpretation. But Bell's theorem requires more: it requires that from her perspective, her distant colleague's experiment also has a definite outcome. This is not the case in Everettian quantum mechanics – not, at any rate, until that distant experiment enters her past light cone. And from the third-person perspective from which Bell's theorem is normally discussed, no experiment has any unique definite outcome at all."

– David Wallace

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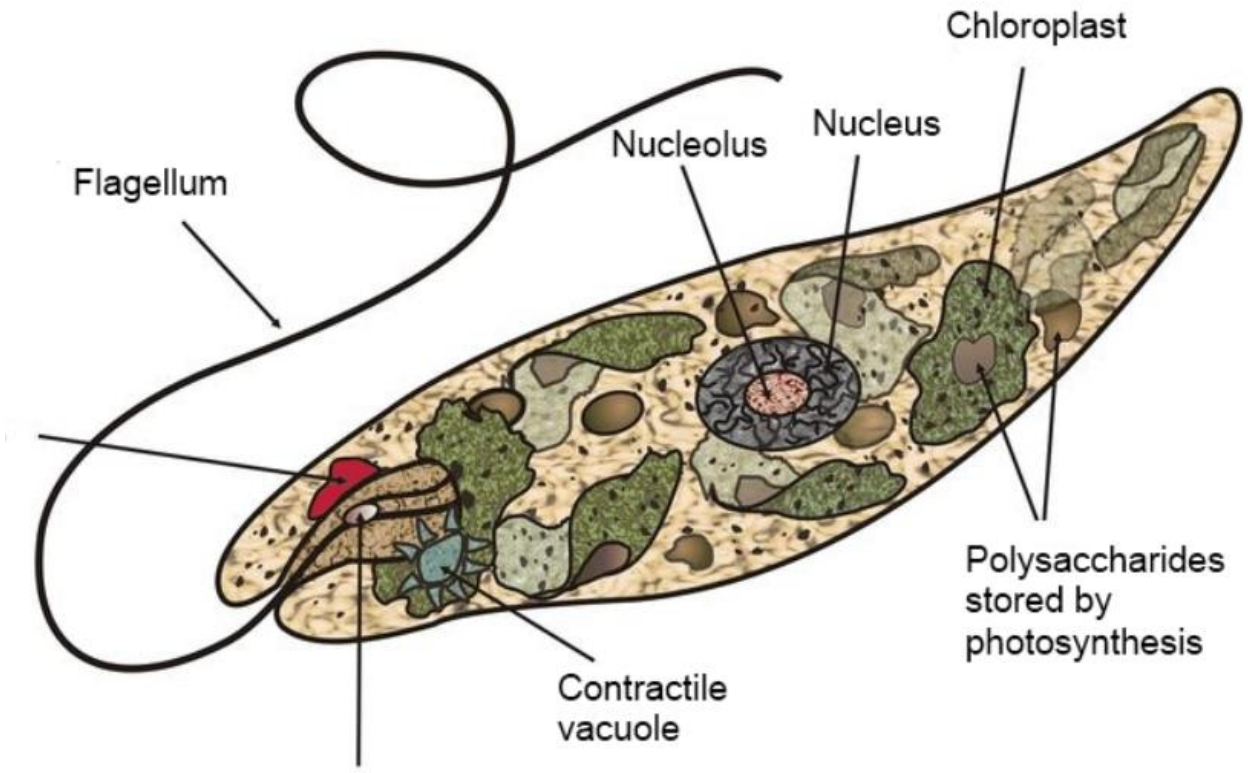
– David Wallace

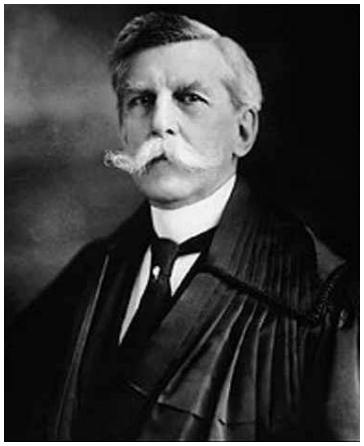
QBism don't do third-person.

(Not for this at least.)

A way to think about QBism …



Oliver Wendell Holmes and Bettabilitarianism



Holmes, 1841–1935

"The loss of certainty" is a phrase intellectual historians have used to characterize the period in which Holmes lived. But the phrase has it backward. It was not the loss of certainty that stimulated the late 19th century thinkers with whom Holmes associated; it was the *discovery* of uncertainty. Holmes was, in many respects, a materialist. He believed, as he put it, that "the law of the grub … is also the law for man." He was not a determinist, because he did not think that the course of human events was fixed. Complete certainty was an illusion; of that he was certain. There were only greater and lesser degrees of certainty, and that was enough. It was, in fact, better than enough; for although we always want to reduce the degree of uncertainty in our lives, we never want it to disappear entirely, since uncertainty is what puts the play in the joints. Imprecision, the sportiveness, as it were, of the quantum, is what makes life interesting and change possible. Holmes liked to call himself a "bettabilitarian": We cannot know what consequences the universe will attach to our choices, but we can bet on them, and we do it every day.

– Louis Menand

The discovery of quantum theory made us better bettabilitarians.

QBism = "Quantum Bettabilitarianism"*

AKA, goodbye Quantum Bayesianism!*

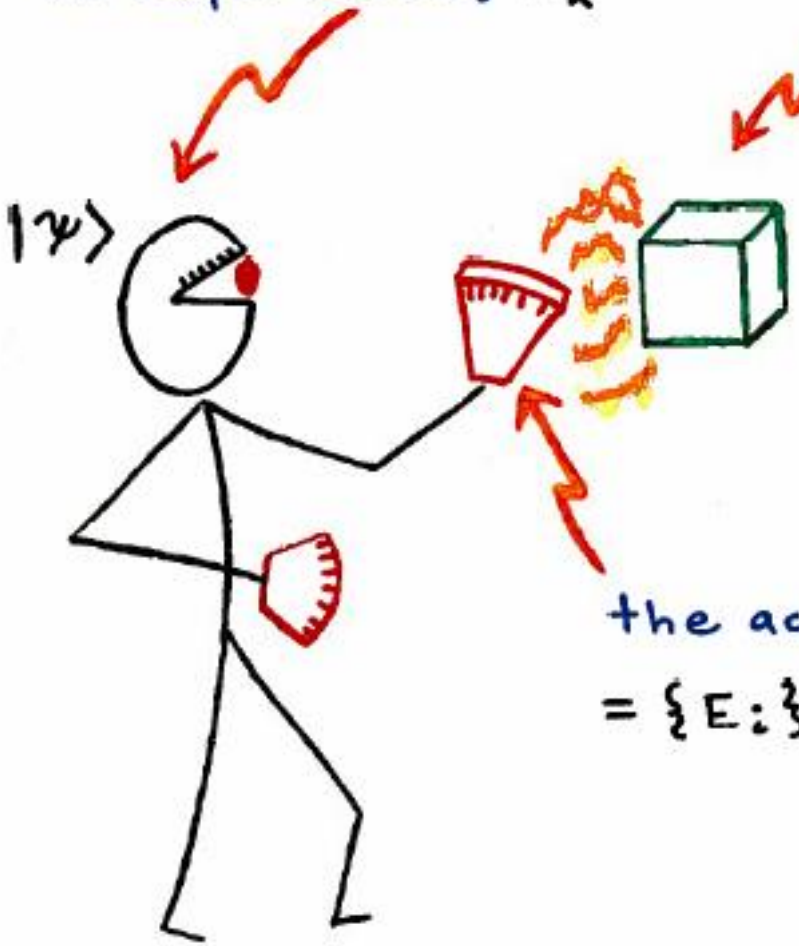
QBism
(The Full Monty)

the consequence

= an experience, E_k

the catalyst

= quantum system, ψ_d



the action

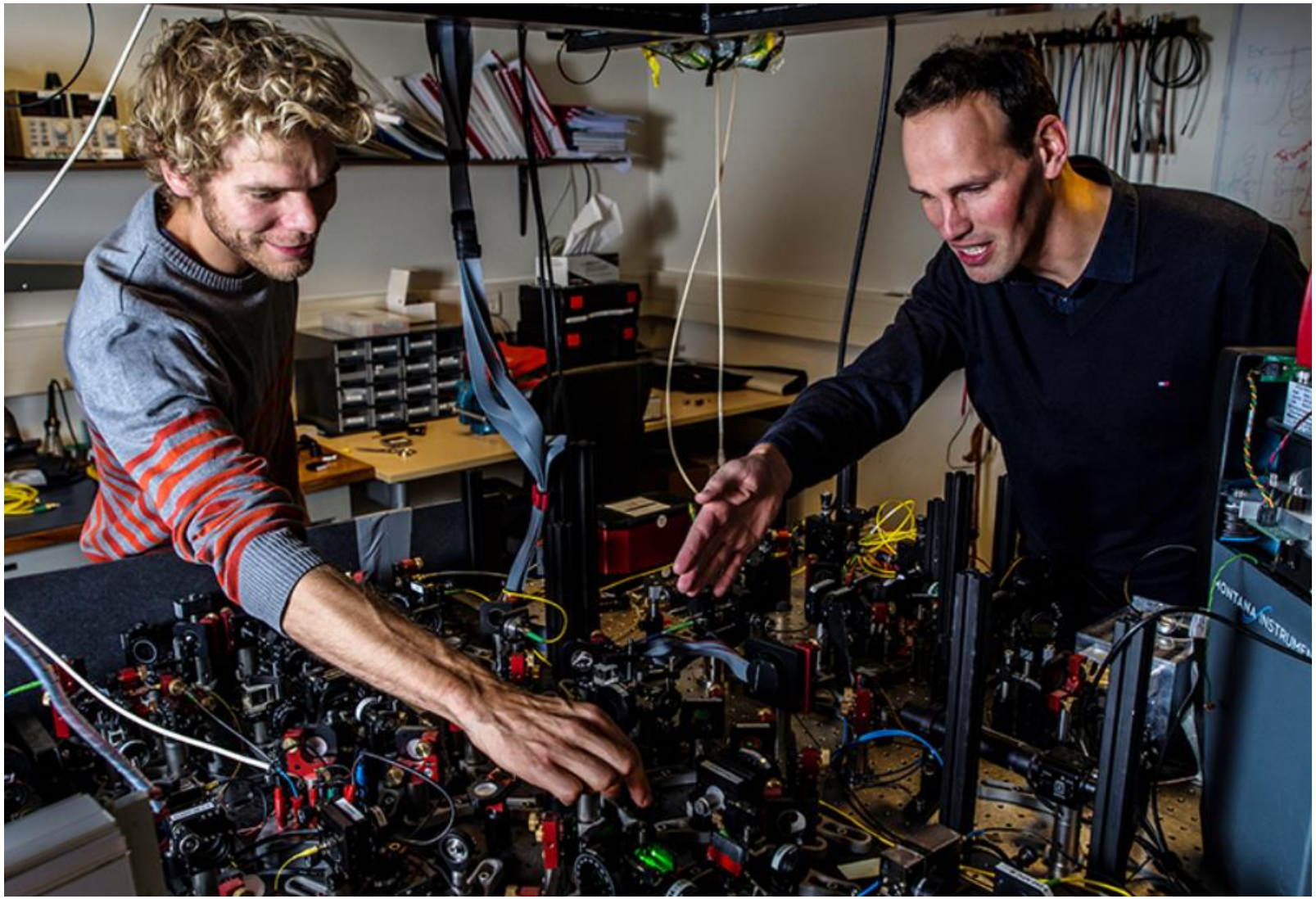
$= \{E_i\}$

Discussion from arXiv:1003.5209

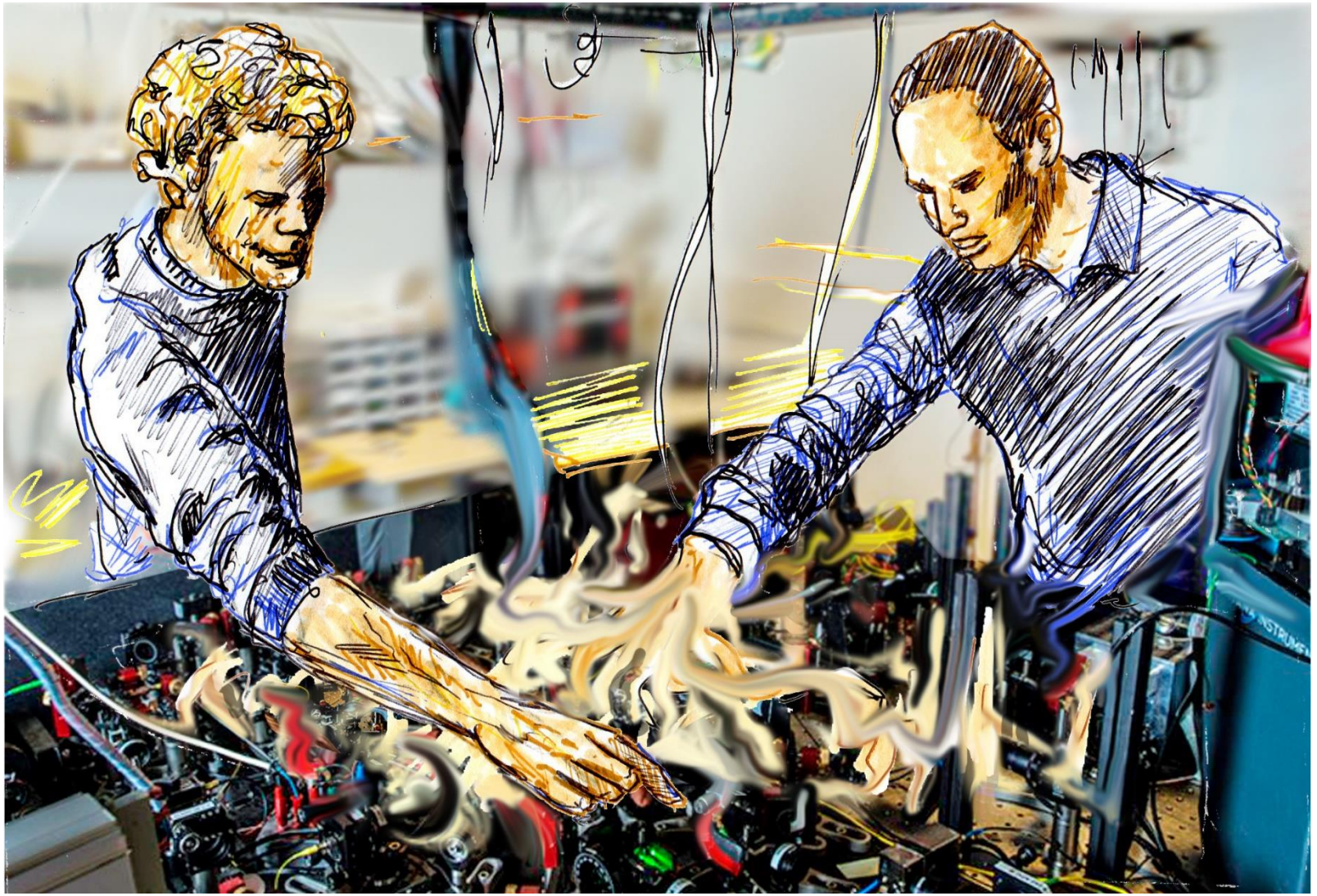
In contemplating a quantum measurement, one makes a conceptual split in the world: one part is treated as an agent, and the other as a kind of reagent or catalyst (one that brings about change in the agent itself). The latter is a quantum system of some finite dimension *d*. A quantum measurement consists first in the agent taking an *action* on the quantum system. The action is represented formally by a set of operators $\{E_i\}$---a positive-operator-valued measure. The action generally leads to an incompletely predictable *consequence* E_i for the agent. The quantum state Ψ makes no appearance but in the agent's head; for it captures his degrees of belief concerning the consequences of his actions, and, in contrast to the quantum system itself, has no existence in the external world. Measurement devices are depicted as prosthetic hands to make it clear that they should be considered an integral part of the agent. The sparks between the measurement-device hand and the quantum system represent the idea that the consequence of each quantum measurement is a unique creation within the previously existing universe. Two points are decisive in distinguishing this picture of quantum measurement from a kind of solipsism: 1) The conceptual split of agent and external quantum system: If it were not needed, it would not have been made. 2) Once the agent chooses an action $\{E_i\}$ to take, the particular consequence E_k of it is beyond his control---that is, the actual outcome is not a product of his whim and fancy.

An action is anything
from running across the street at L'Etoile …

… to a sophisticated quantum information experiment.



Conceptually, the lab equipment is part of the agent.



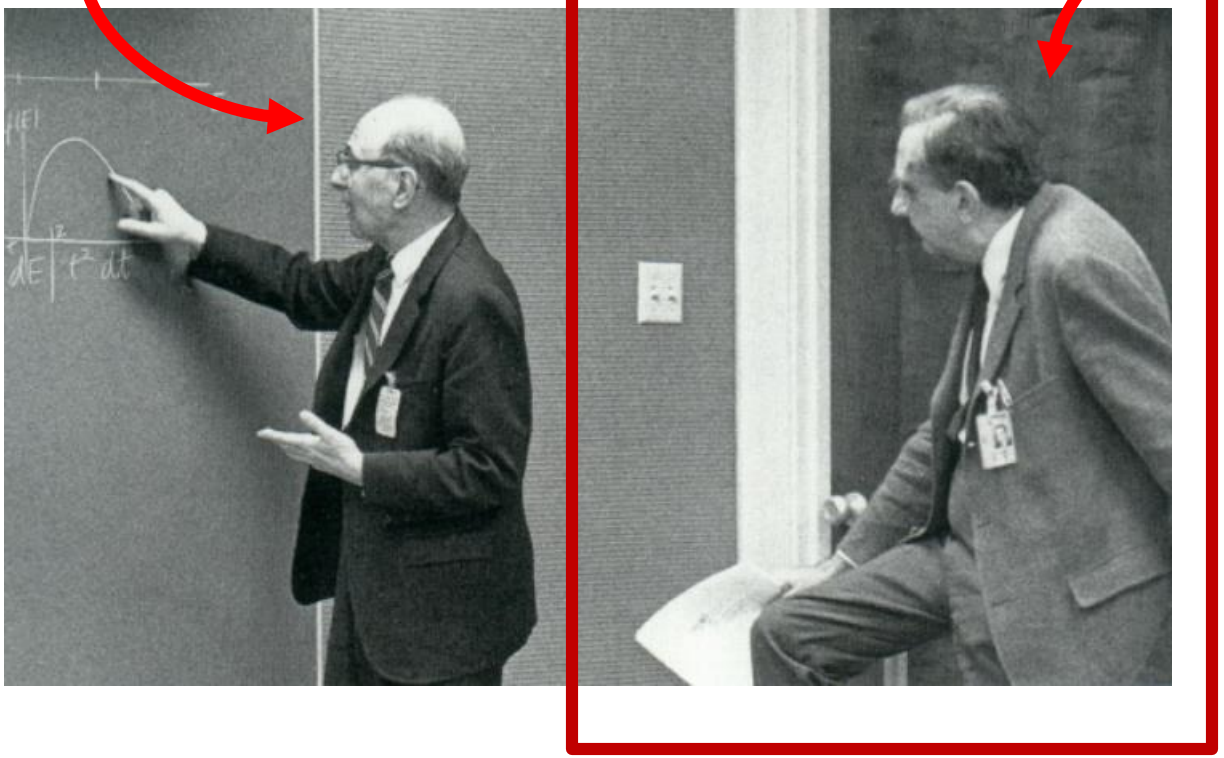
Artwork courtesy of Mark Staff Brandl

What does Wigner's friend bring to QBism?

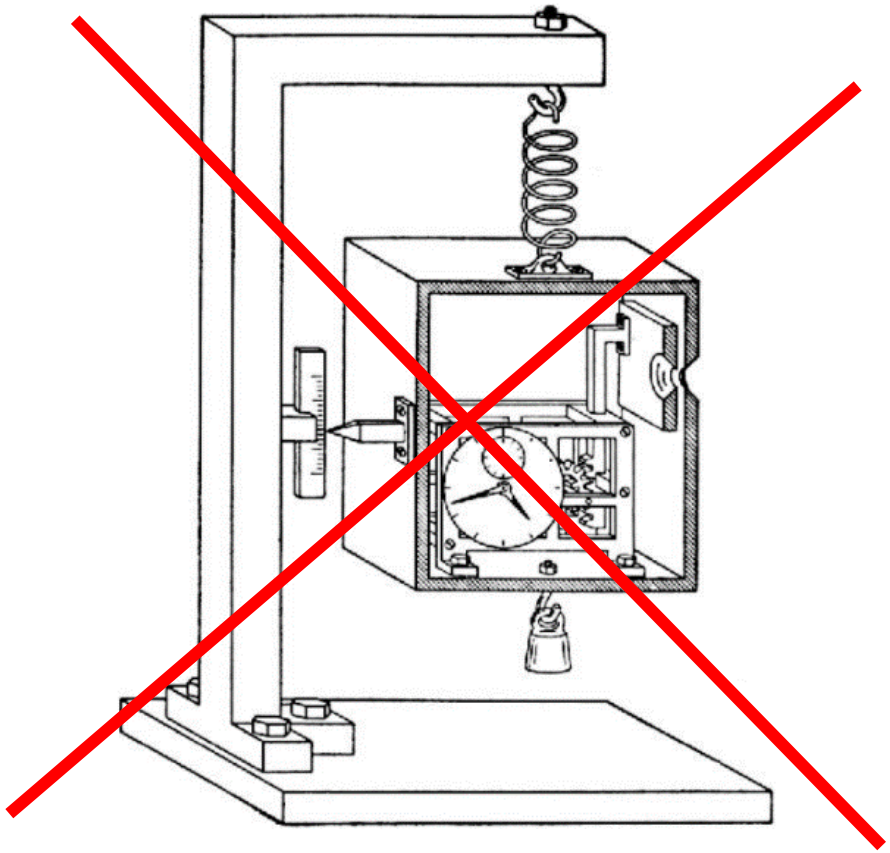
That measurement outcomes are personal.

Wigner

His Friend



Tenet 2: A quantum measurement is any action an agent takes upon the world, and its outcome *just is* the consequent personal experience this induces. Particularly, quantum measurement outcomes are *not*, to paraphrase Bohr, instances of "irreversible amplification objectively recorded for everyone to see in a device whose design is communicable in common language suitably refined by the terminology of classical physics."



Paraphrase from Rev. Mod. Phys. **85**, 1693 (2013)

We think the word *measurement* should be banished from fundamental discussions of quantum theory. Not because the word is "unprofessionally vague and ambiguous," as John Bell said. But because the word suggests a misleading notion of the subject matter of quantum mechanics.

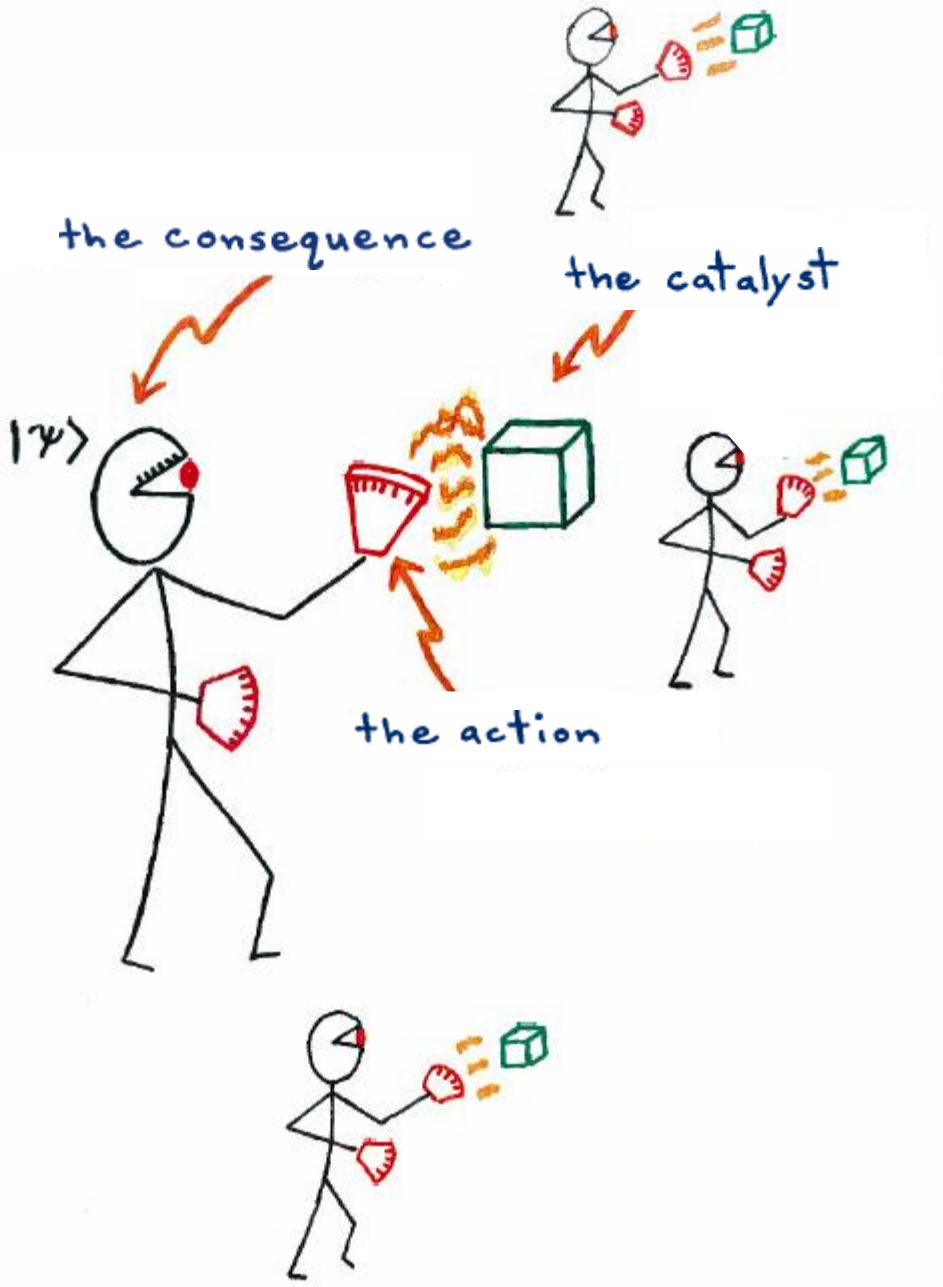
To make the point clear, put quantum theory aside for a moment and consider basic Bayesian probability theory. There the subject matter is an agent's expectations for various outcomes. For instance, an agent might write down a joint probability distribution for various mutually exclusive hypotheses and data values appropriate to some phenomenon. A major role of the theory is that it provides a scheme (Dutch-book coherence) for how these probabilities should be related any other probabilities the agent has for other phenomena. The theory also prescribes that if the agent is given a specific data value, he should update his expectations for everything else within his interest.

But what is this phrase "given a specific data value"? What does it really mean in detail? Should not one specify a mechanism or at least a chain of logical and/or physical connectives for how the raw fact signified by the data comes into the field of the agent's consciousness? And who is this "agent" reassessing his probabilities anyway? Indeed, what is the precise definition of an agent? How would one know one when one sees one? Can a dog be an agent? Or must it be a person? Maybe it should be a person with a PhD?

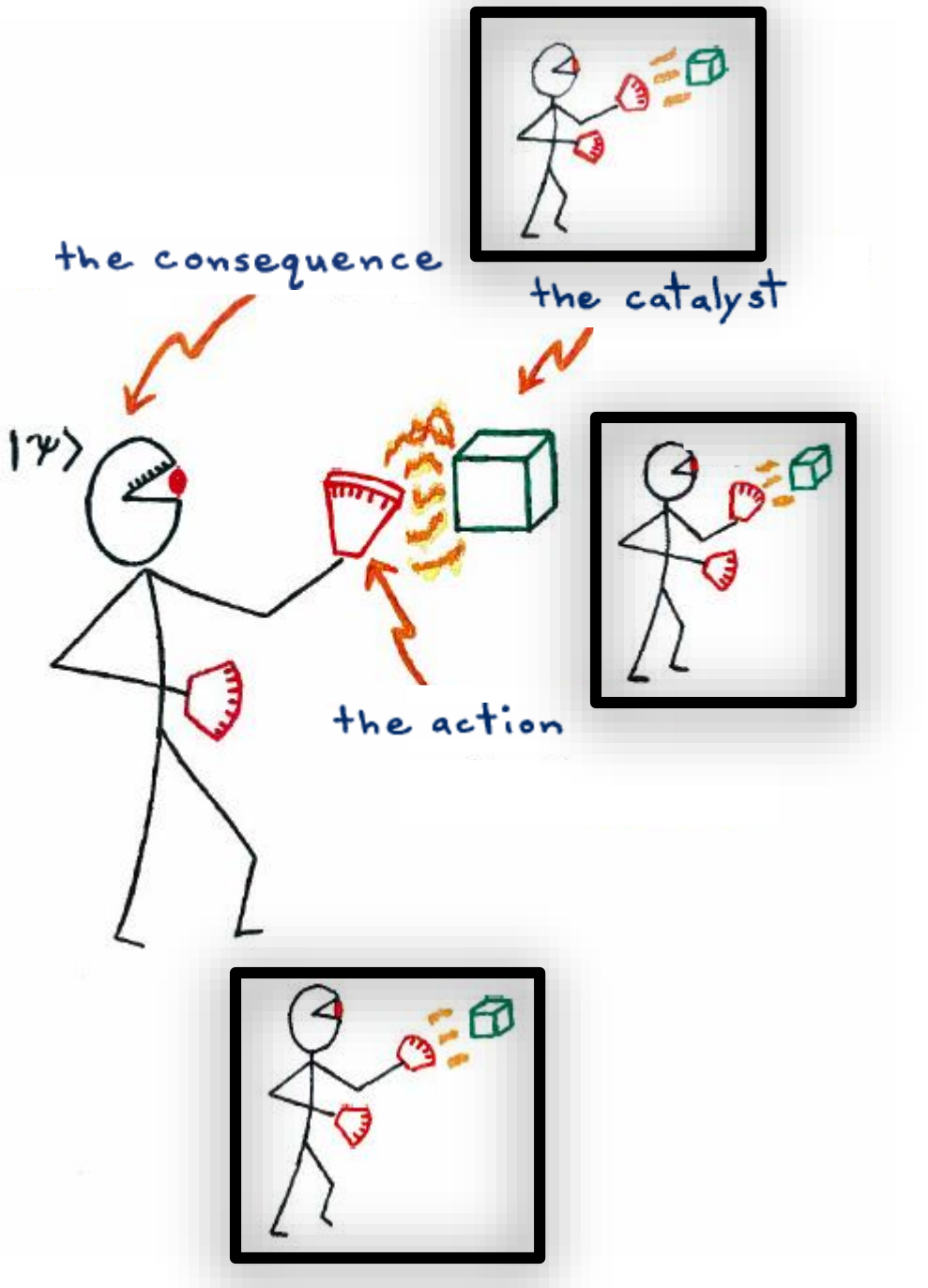
Probability theory cannot answer these questions because they are not questions within the subject matter of the theory. Within probability theory, the notions of agent and "given a data value" are primitive and irreducible. The whole theory is constructed to guide agents' decisions based on data. Agents and data are at the bottom of the structure of probability theory—they are not to be constructed from it, but rather agents are there to receive the theory's guidance, and data are there to designate the world external to the agent.

QBism says that, if all of this is true of Bayesian probability theory in general, it is true of quantum theory as well. As the foundations of probability theory dismiss the questions of where data come from and what constitutes an agent (these questions never even come to its attention) so can the foundations of quantum theory dismiss them too.

Quantum theory can be used by anyone.



But those other users, for the agent in focus, are physical systems like anything else.



The Born Rule

Given ρ and $\{E_i\}$,

$$p(i) = \mathrm{tr}\,\rho E_i$$

"The Born Rule"

NOT a law of nature.

RATHER something we should strive for.

Tenet 3: The Born Rule—the foundation of what quantum theory means for QBism—is a normative statement. It is an empirical addition to the coherent-ist paradigm and consequently about the decision-making behavior *any* individual agent should strive for; it is not a descriptive "law of nature" in the usual sense.

Not like

$$\vec{F} = m\vec{a}$$

Not like

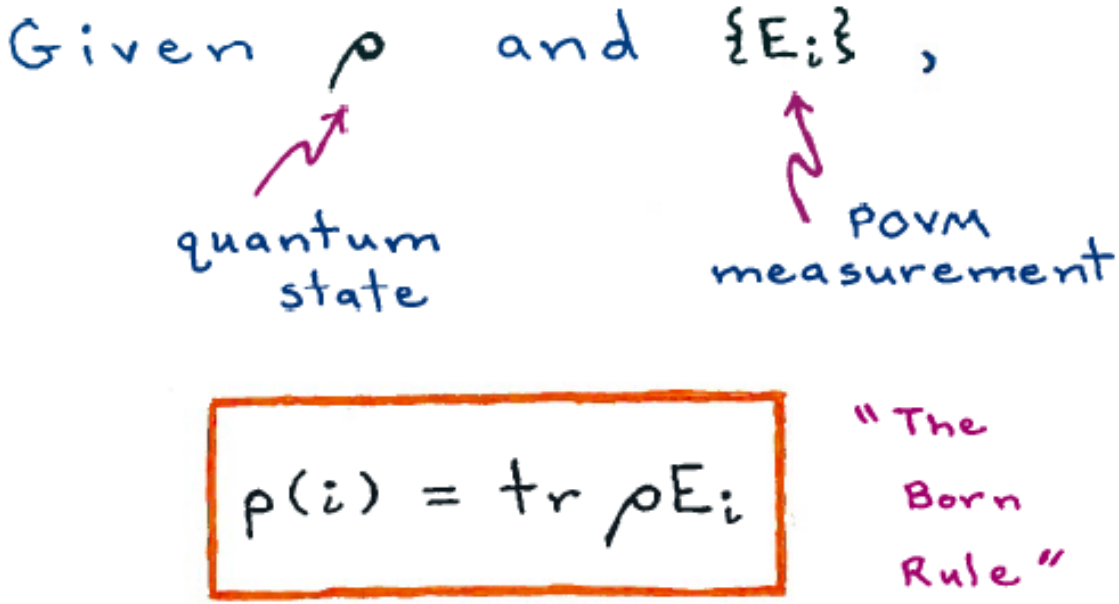
$$\vec{\nabla}\cdot\vec{E} = \frac{1}{\epsilon_0}\rho \qquad \vec{\nabla}\times\vec{E} = -\frac{\partial\vec{B}}{\partial t}$$

$$\vec{\nabla}\times\vec{B} = \mu_0\vec{J} + \mu_0\epsilon_0\frac{\partial\vec{E}}{\partial t} \qquad \vec{\nabla}\cdot\vec{B} = 0$$

Not like

$$G_{\mu\nu} = 8\pi T_{\mu\nu}$$

The Born Rule



The objective feature of the theory is that everybody should use the Born Rule.

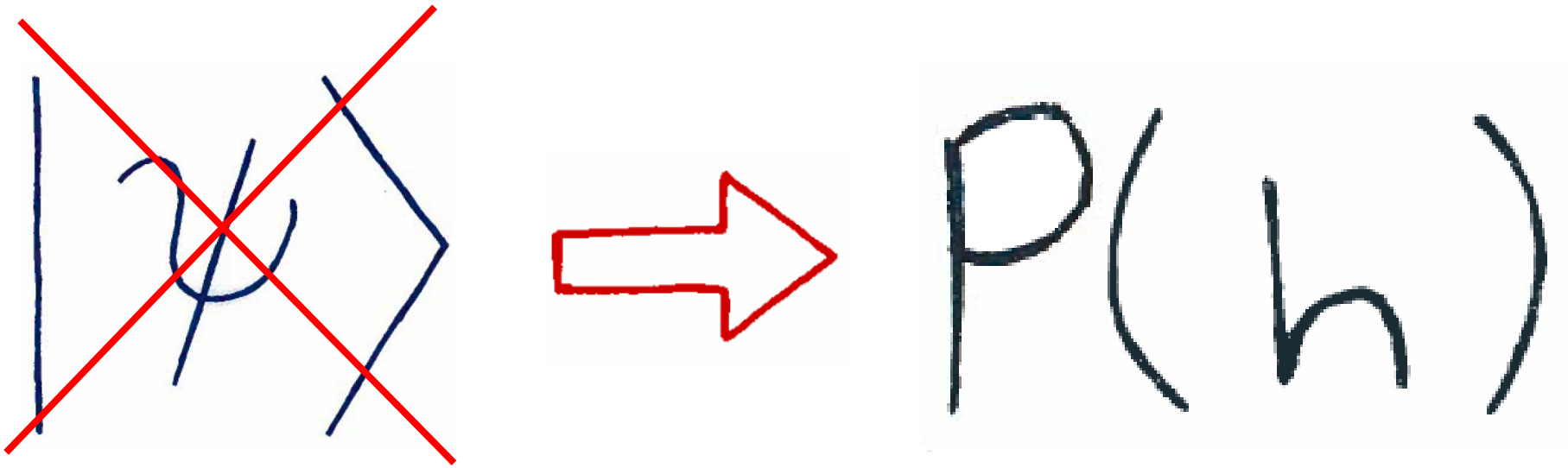
But we want more reality*!*

Tell us why the Born Rule.

E. T. Jaynes, 2 The Technical Side of QBism

"Of course, the QM formalism also contains fundamentally important and correct ontological elements … It seems that, to unscramble the epistemological probability statements from the ontological elements we need to find a different formalism, isomorphic in some sense but based on different variables; it was only through some weird mathematical accident that it was possible to find a variable ψ which scrambles them up in the present way."

Desire a Formalism That …



… denounces abstract quantum states and uses only probabilities.

A Very Fundamental Mmt ?

Suppose d^2 projectors $\Pi_i = |\psi_i\rangle\langle\psi_i|$ satisfying

$$\mathrm{tr}\,\Pi_i \Pi_j = \frac{1}{d+1} \quad , \quad i \neq j$$

exist. ← Called SIC.

Can prove:

1) the Π_i linearly independent

2) $\sum_i \frac{1}{d} \Pi_i = I$

So good for Bureau of Standards.

Also

$$p(i) = \frac{1}{d} \mathrm{tr}\,\rho \Pi_i$$

$$\boxed{\rho = \sum_i \left[(d+1)p(i) - \frac{1}{d}\right] \Pi_i}$$

CAF, Quant. Inf. Comp. **4**, 467 (2002)

[8] D. M. Appleby (2007), *Symmetric Informationally Complete Measurements of Arbitrary Rank*, Opt. Spect., **103**, pp. 416–428.

[9] D. M. Appleby, H. B. Dang and C. A. Fuchs (2007), *Symmetric Informationally Complete Quantum States as Analogues to Orthonormal Bases and Minimum Uncertainty States*, arXiv:0707.2071.

[10] O. Albouy and M. R. Kibler (2007), *A Unified Approach to SIC-POVMs and MUBs*, J. Russian Laser

[11] L. Hughston, *a* Seminar Talk October 2007. Av

[12] M. Grassl (200 ure Notes in Computer Science,

[13] M. Khatirineja , J. Algebr. Comb., **28** 333–349.

[14] C. Godsil and *A s, and Spin Models*, European J. C

[15] I. Bengtsson a *ge*, Open Syst. Inf. Dyn., **16**, pp. 1

[16] M. Fickus (200 ourier Anal. Appl., **15**, pp. 413–42

[17] D.M. Appleby *s in Prime Dimension*, arXiv:090

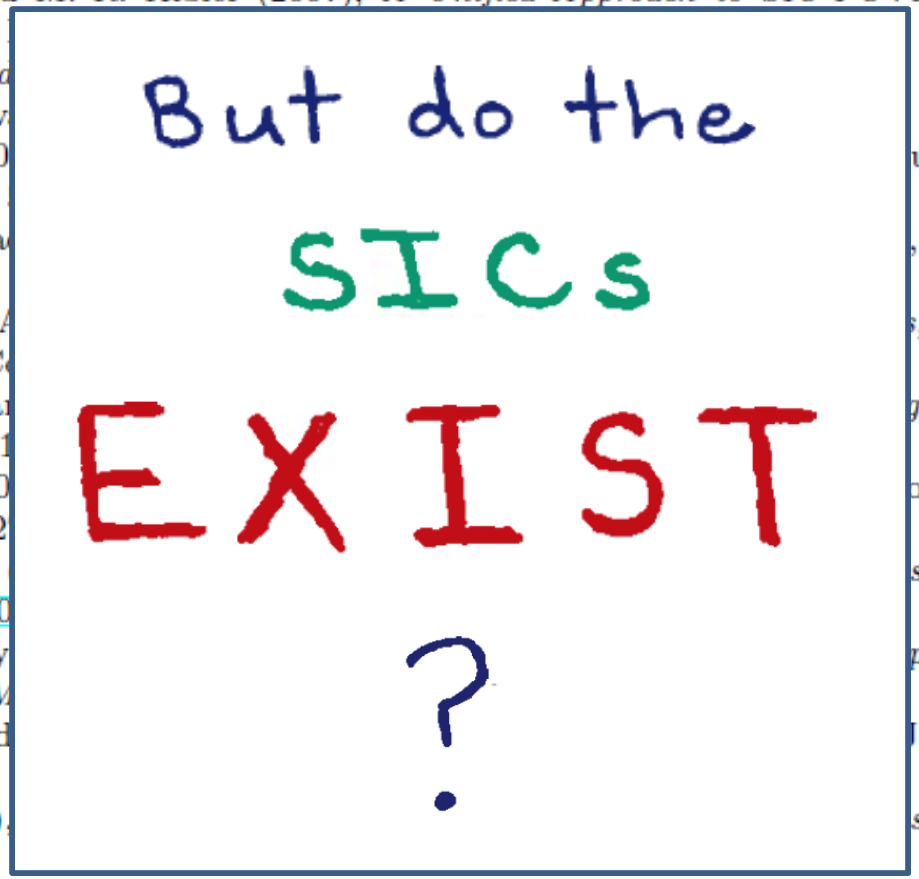
[18] D. M. Appleby *pplications to SIC-POVMs and M*

[19] A. J. Scott and J. Math. Phys., **51**, 042203.

[20] H. Zhu (2010), *s*, J. Phys. A, **43**, 305305.

[21] H. Zhu, Y. S. Teo and B. G. Englert (2010), *Two-Qubit Symmetric Informationally Complete Positive Operator Valued Measures*, Phys. Rev. A, **82**, 042308.

[22] S. N. Filippov and V. I. Man'ko (2011), *Symmetric Informationally Complete Positive Operator Valued Measure and Probability Representation of Quantum Mechanics*, J. Russian Laser Research, **31**, pp. 211–231.



The Latest Known on SIC Existence (*Holy fiducials, Batman!*)

- Exact solutions in 79 dimensions: d = 2 – 28, 30, 31, 35, 37 – 39, 42, 43, 48, 49, 52, 53, 57, 61 – 63, 67, 73, 74, 78, 79, 84, 91, 93, 95, 97 – 99, 103, 109, 111, 120, 124, 127, 129, 134, 143, 146, 147, 168, 172, 195, 199, 228, 259, 292, 323, 327, 399, 489, 844, 1299.

- High precision numerical solutions, many to 8,000 and 16,000 digits accuracy: d = 2 – 189, 192, 195, 199, 204, 224, 228, 255, 259, 288, 292, 327, 489, 528, 725, 844, 1155, 2208.

Most of this list found through the impressive efforts of M. Grassl (many not published yet); contributions also from D. M. Appleby, I. Bengtsson, T.-Y. Chien, S. T. Flammia, G. S. Kopp, A. J. Scott, and S. Waldron.

See CAF, M. C. Hoang, B. C. Stacey, Axioms **6**, 21 (2017) for an introduction.

It may be a very, very long project:

Most recently SIC existence has been discovered to be related to Hilbert's 12th Problem.*

But that only ups the ante*!***

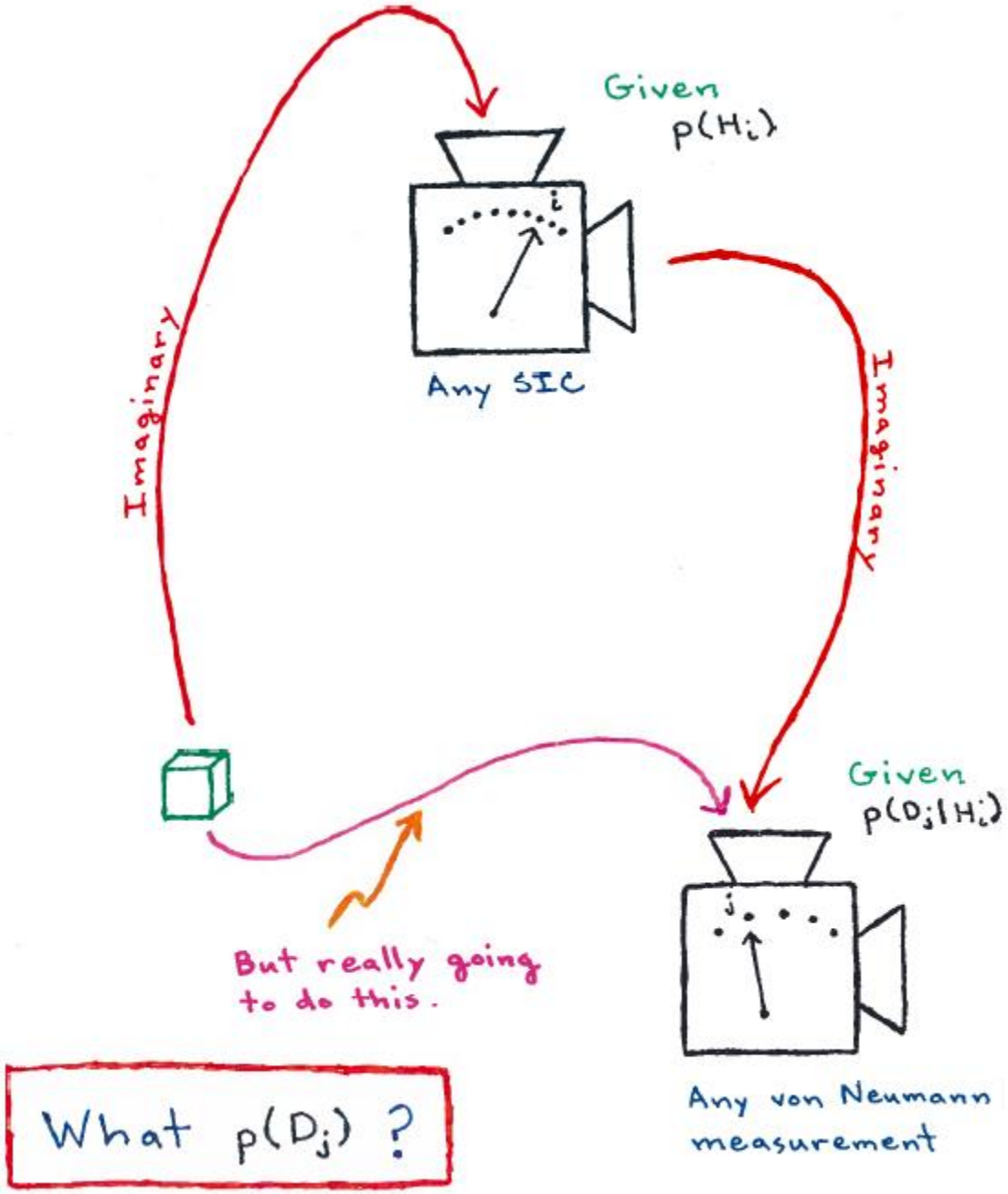
* See Appleby, Flammia, McConnell, Yard, arXiv:1604.06098.

** See, "Erwin Schrödinger on Responsible Physics" at end of talk.

How To See the Born Rule in SIC Terms

Discussion from arXiv:1003.5209

Any quantum measurement can be conceptualized in two ways. Suppose an arbitrary von Neumann measurement "on the ground," with outcomes $D_j = 1, \ldots, d$. Its probabilities $P(D_j)$ can be derived by cascading it with a fixed fiducial SIC measurement "in the sky" (of outcomes $H_i = 1, \ldots, d^2$). Let $P(H_i)$ and $P(D_j|H_i)$ represent an agent's probabilities, assuming the measurement in the sky is actually performed. The probability $P(D_j)$ represents instead the agent's probabilities under the assumption that the measurement in the sky is *not* performed. The Born Rule, in this language, says that $P(D_j)$, $P(H_i)$, and $P(D_j|H_i)$ are related nonetheless.


Given
$p(H_i)$
Any SIC
Imaginary
Imaginary
Given
$p(D_j|H_i)$
But really going to do this.
Any von Neumann measurement
What $p(D_j)$?

In this case,

$$p(D_j) \neq \sum_i p(H_i)\, p(D_j \mid H_i) .$$

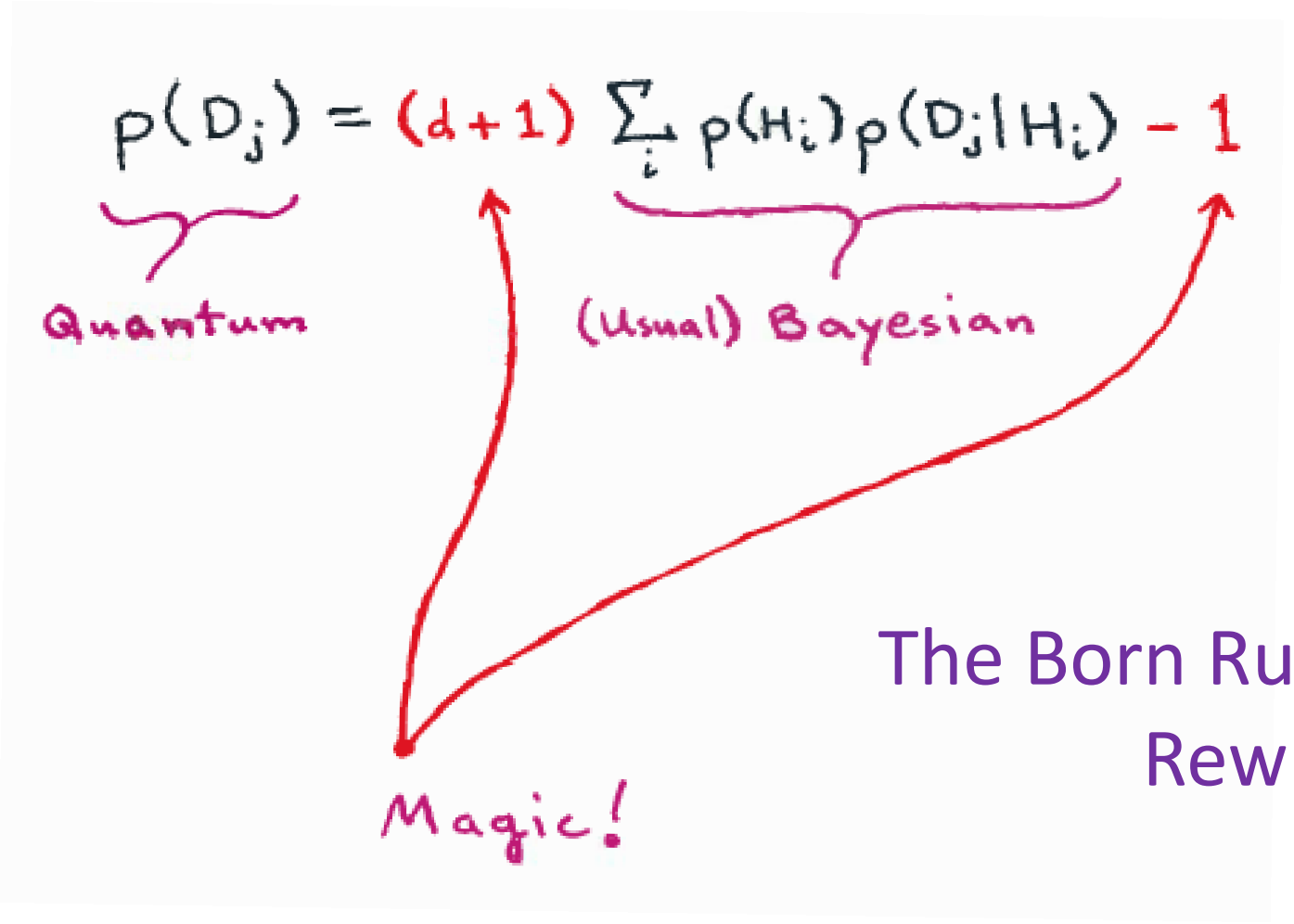
But this is not Dutch book incoherent.

As Ballentine (1986) points out, there are hidden conditionals

$p(D_j)$	really	$p(D_j \mid C_1)$
$p(H_i)$	really	$p(H_i \mid C_2)$
$p(D_j \mid H_i)$	really	$p(D_j \mid H_i, C_2)$

Dutch book coherence alone cannot demand equality.

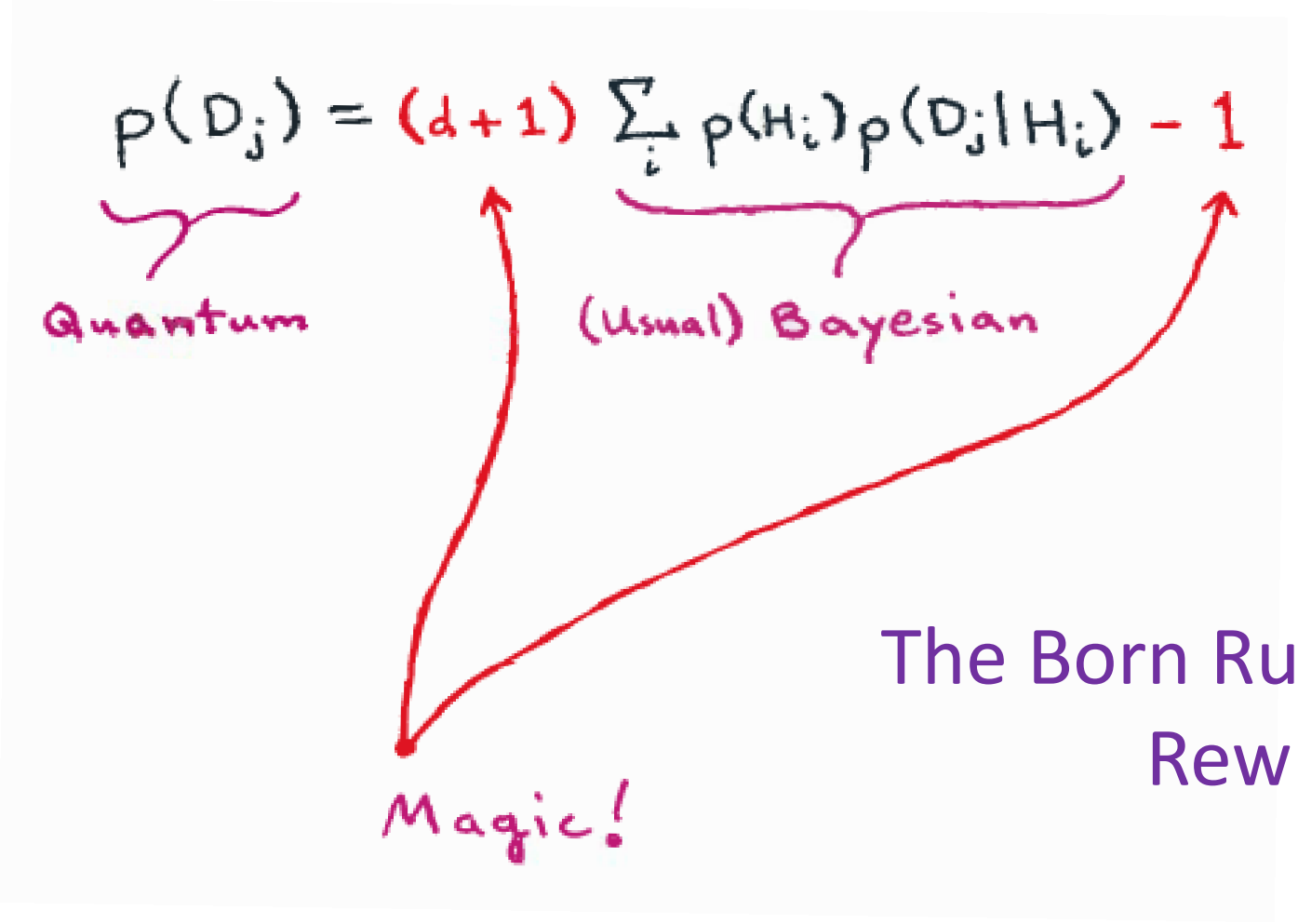
For QBism, the Born Rule Is an Addition to Dutch Book Coherence



The Born Rule Rewritten

CAF, Schack, Rev. Mod. Phys. **85**, 1693 (2013)

The Born Rule in transparently normative form.



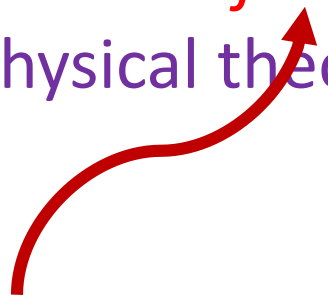
The Born Rule Rewritten

CAF, Schack, Rev. Mod. Phys. **85**, 1693 (2013)

Remember This?

Some (most!) elements of the formalism are *subjective*
—more subjective than Jaynes himself would ever go.

Whereas some relations in the formalism are *objective*
—as objective as one could want of a physical theory.

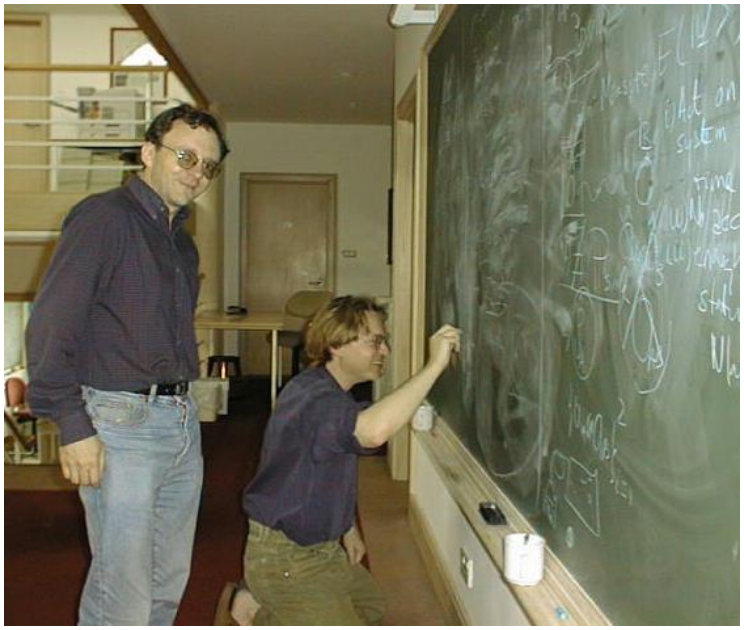


The Born Rule in this form is exactly one of those relations. Normative, but objective.

Nota bene,
one obtains this expression for the Born Rule if an only if a SIC exists in that dimension.

But with that as a proviso, supposing a SIC always does exist …

CAF to Sam Braunstein, 19 July 1996:



I don't think there's anything interesting to be gained from *simply* trying to redo [Cox's derivation of probability theory] but with complex numbers. It seems to me that it'll more necessarily be something along the lines of: "When you ask me, 'Where do all the quantum mechanical outcomes come from?' I must reply, 'There is no where there.'" (with apologies to [Gertrude Stein]!) That is to say, my favorite "happy" thought is that when we know how to properly take into account the piece of prior information that "there is no where there" concerning the origin of quantum mechanical measurement outcomes, then we will be left with "plausibility spaces" that are so restricted as to be isomorphic to Hilbert spaces. But that's just thinking my fantasies out loud.

Could we take diagram and modified Law of Total Probability

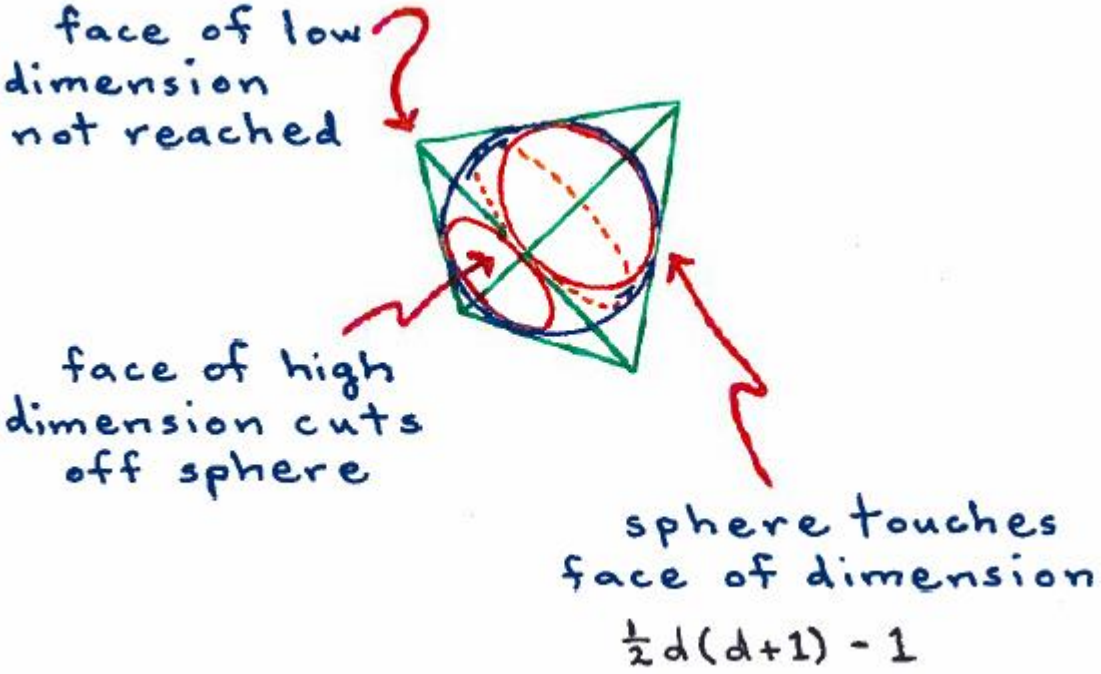
$$p(D_j) = (d+1)\sum_i p(H_i)\,p(D_j|H_i) - 1$$

as a fundamental postulate of quantum mechanics?

fundamental expression of the idea that quantum measurements generate novelty

CAF, Schack, Rev. Mod. Phys. **85**, 1693 (2013)
CAF, Schack, Found. Phys. **41**, 345 (2011)

Nearly the consistency of this equation alone implies a significant, nontrivial convex structure.



Appleby, CAF, Ericsson, Found. Phys. **41**, 564 (2011)

Compels this geometric notion:

Call a set $\mathcal{S} \subseteq \Delta_{d^2}$ within the probability simplex

a) consistent if for any $\vec{p}, \vec{q} \in \mathcal{S}$

$$\frac{1}{d(d+1)} \leq \vec{p} \cdot \vec{q} \leq \frac{2}{d(d+1)} ,$$

b) maximal if adding any further $\vec{p} \in \Delta_{d^2}$ makes it inconsistent

qplex

Example: If $\mathcal{S}$ is set of quantum states, it is consistent & maximal.

Problem: Characterize all such $\mathcal{S}$; compare to quantum.

One Theorem from arXiv:1612.03234

(D. M. Appleby, C. A. Fuchs, B. C. Stacey, H. Zhu)

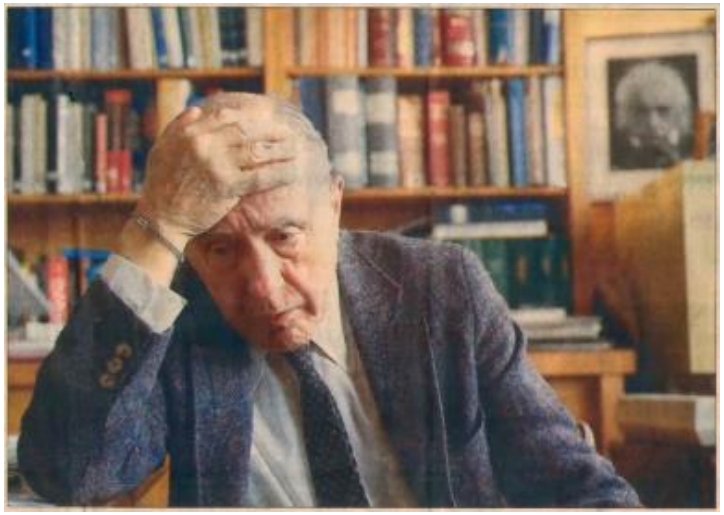
Theorem. The following statements are equivalent:

- A qplex is isomorphic to the quantum state space of a *d*-level system.
- The symmetry group of a qplex over d^2 outcomes is the projective unitary group.
- A SIC exists in dimension *d*.

But too cheap to be

the end of the story *!*

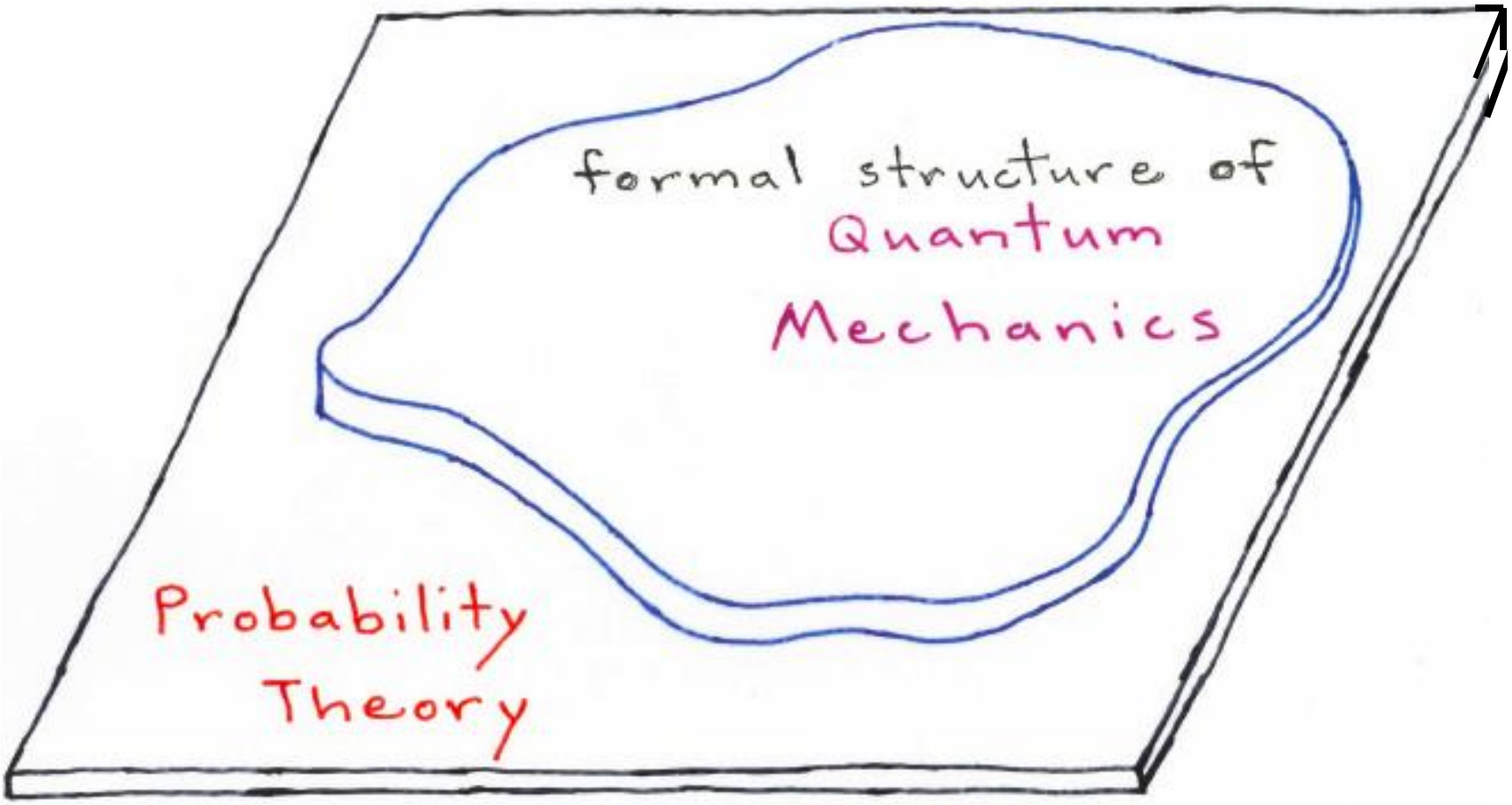
“Behind it all is surely an idea so simple, so beautiful, that when we grasp it – in a decade, a century, or a millennium – we will all say to each other, how could it have been otherwise?”



John Archibald Wheeler
1911 – 2008

Still, one obtains a clear vision of how to see quantum theory as an addition to probability theory.

Probability theory comes first; quantum theory is added to the top of it.


formal structure of
Quantum
Mechanics
Probability
Theory

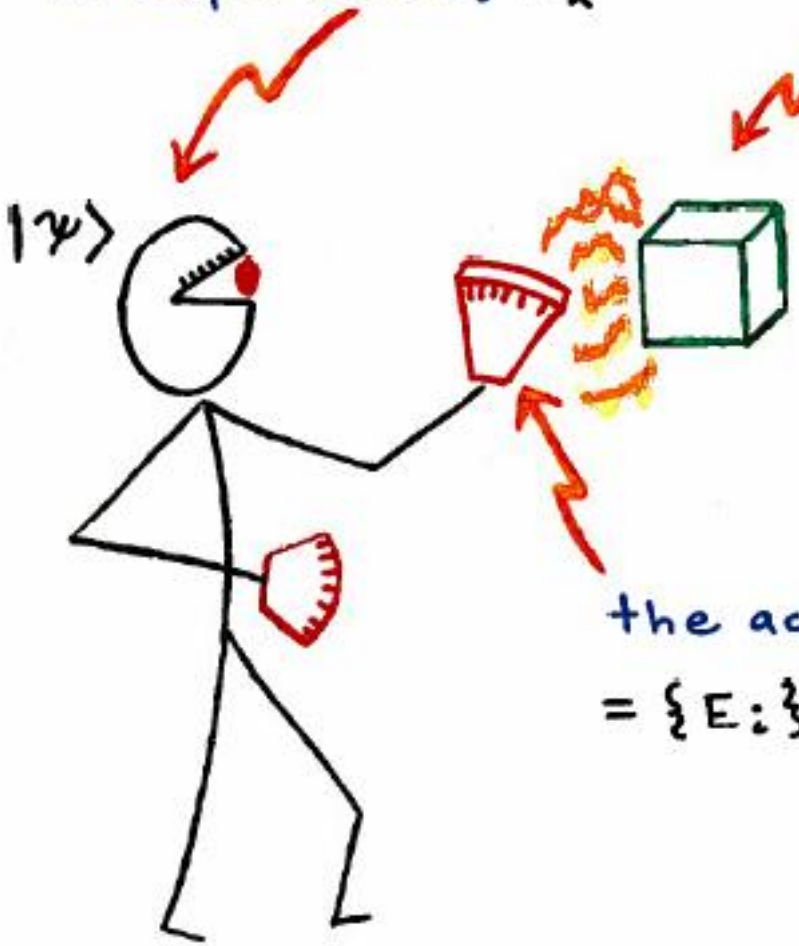
So, let’s go back to this …

the consequence

= an experience, E_k

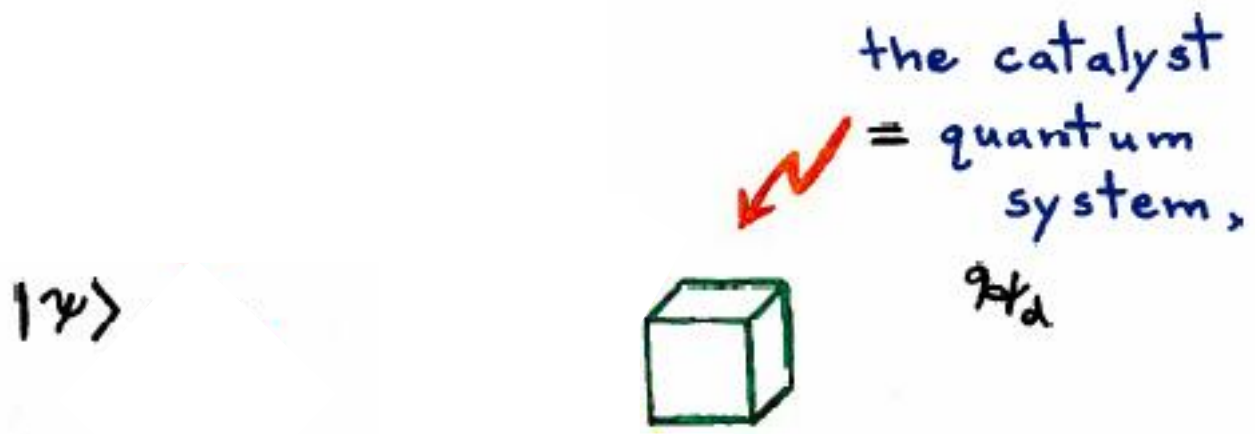
the catalyst

= quantum system, ψ_d

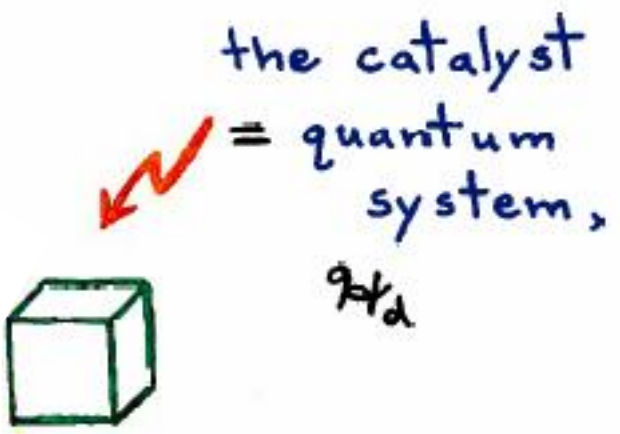


the action

$= \{E_i\}$

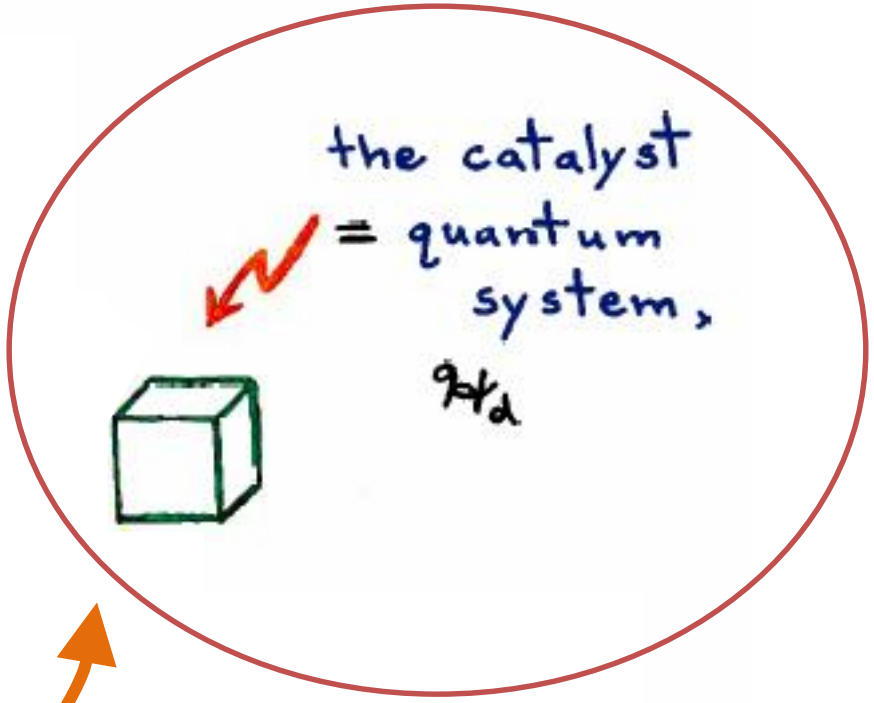


What happens if we wipe the agent out of the picture?



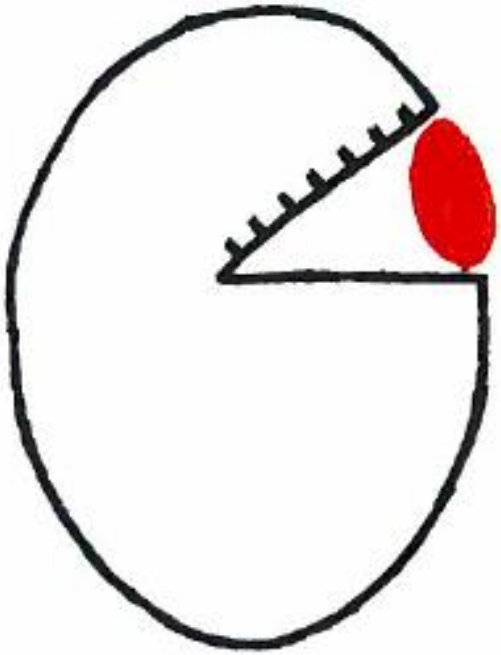
What happens if we wipe the agent out of the picture?

Poof!



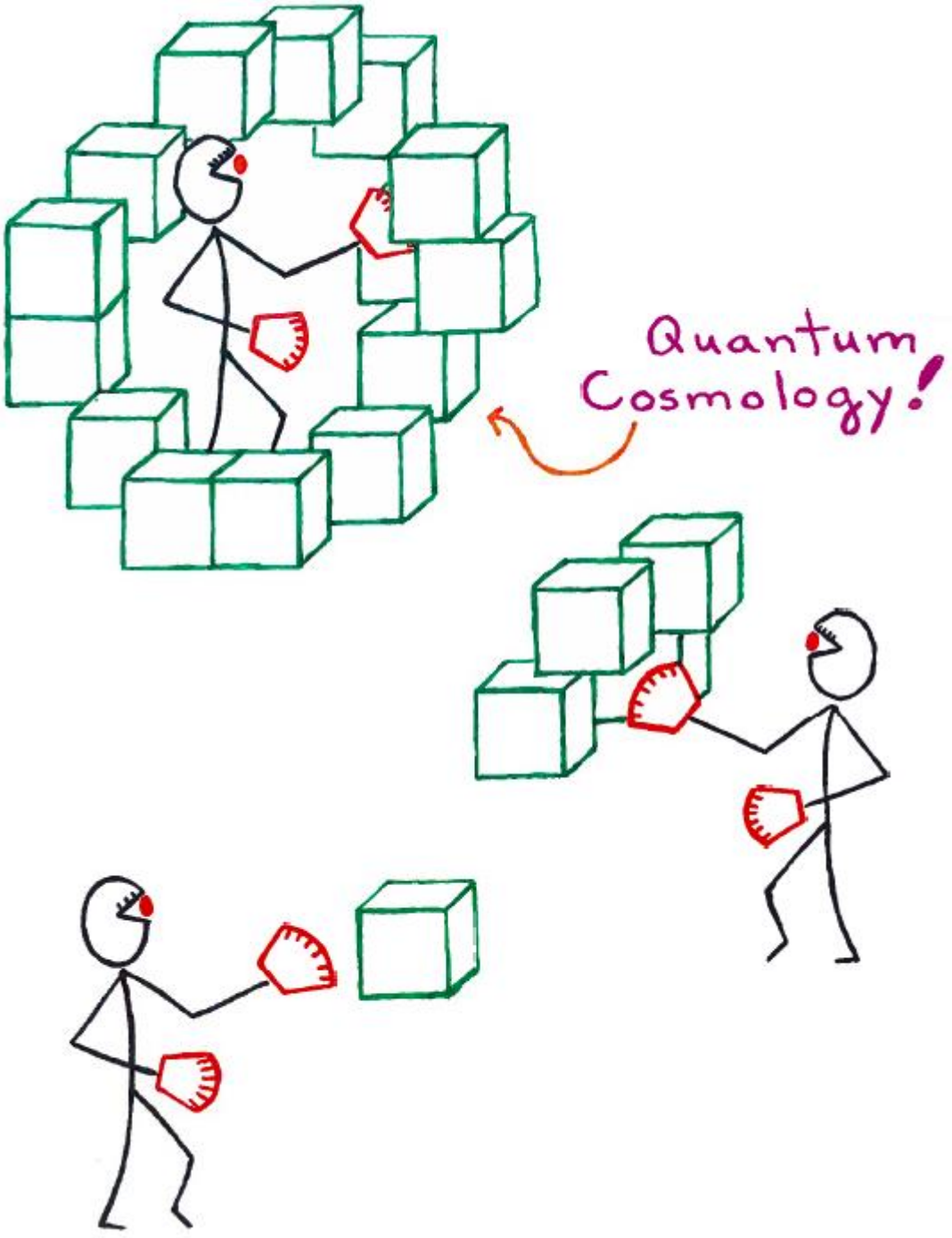
But this didn't
go Poof!

What QBism Is Not



I.e., it's not solipsism, Nicolas.*

*Nicolas Gisin, but I could have used in his place any of Philippe Grangier, Tim Maudlin, Travis Norsen, or Howard Wiseman.



Nothing to stop us from doing quantum cosmology either.

What of the Wavefunction of the Universe?

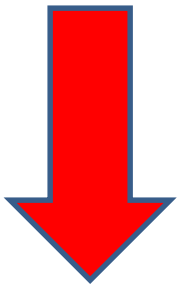
Discussion from arXiv:1003.5209

FIG. 6. **Quantum Cosmology from the Inside.** The agent in Figure 1 can consider measurements on ever larger systems. There is nothing in quantum mechanics to bar the systems considered from being larger and larger, to the point of eventually surrounding the agent. Pushed far enough, this is quantum cosmology! Why all this insistence on thinking that "an agent must be outside the system he measures" in the cosmological context should mean "outside the physical universe itself"? It means outside the system of interest, and that is the large-scale universe. Nor is there any issue of self-reference at hand. One would be hard pressed to find a cosmologist who wants to include his beliefs about how the beats of his heart correlate with the sidereal cycles in his quantum-state assignment for the external universe. The symbol $|\,\Psi_{\text{universe}}\,\rangle$ refers to the green boxes alone.

What Else Doesn't Go Poof.

(That's a statement, not a question.)

$$p(D_j) = (d+1) \sum_i p(H_i)\, p(D_j \mid H_i) - 1$$

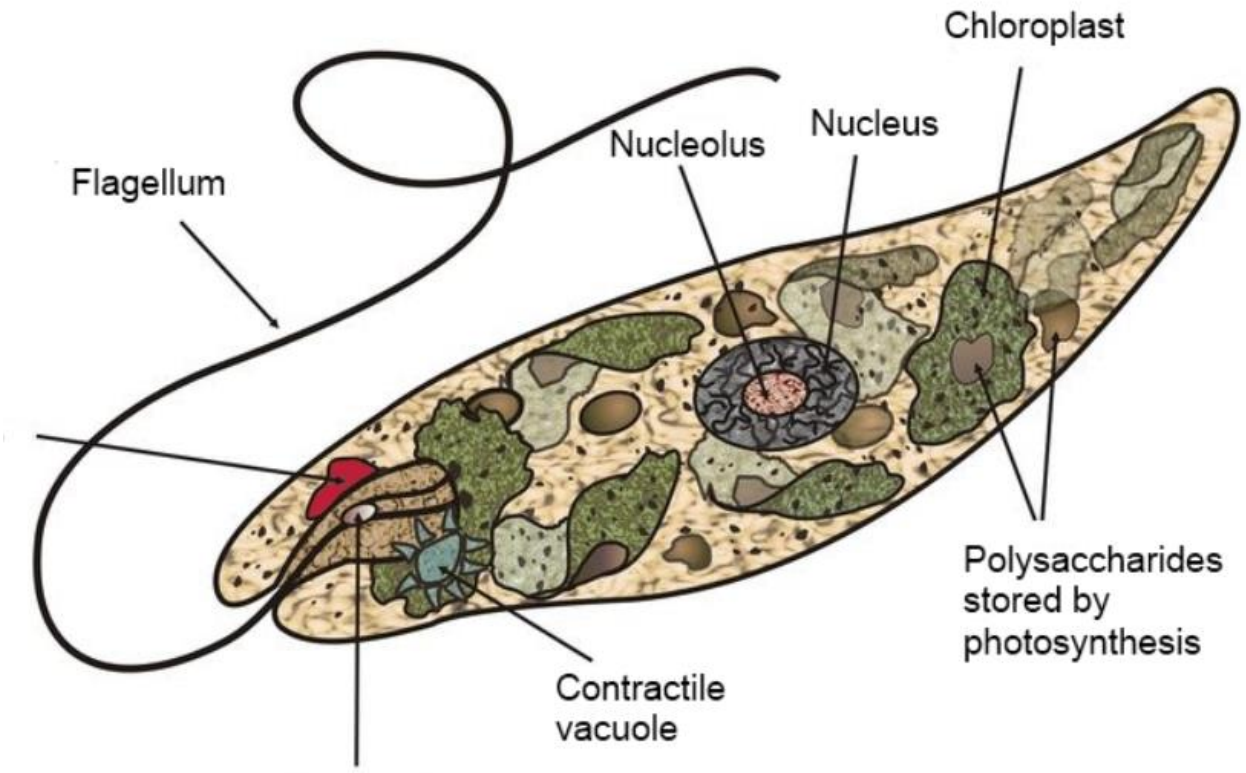


I.e., the relation as a normative rule stays behind!

Discussion from arXiv:1601.04360

It is worth noting that *in this aspect*, QBism bears a certain resemblance to structural realism. Imagine our universe at a time (if there ever was one) when there were no agents about to use the laws of probability theory as an aid in their gambles---i.e., no such agents had yet arrived out of the Darwinian goo. Were there any quantum states in the universe then? A QBist would say NO. It's not a matter of the quantum state of the universe waiting until a qualified PhD student came along before having its first collapse, as John Bell joked, but that there simply weren't any quantum states. Indeed, on earth there weren't any quantum states until 1926 when Erwin Schrödinger wrote the first one down. The reason is simple: The universe is made of something else than quantum states. But then, what of the Born Rule? To this, in contrast, a QBist would say, "Aha, now there's a sensible question." For the Born Rule is among the set of relations an agent should strive to attain in his larger mesh of probability assignments. That normative rule is still lying about even when there are no agents to make use of it. It's the normative rule which is nature's whisper, not the specific terms within it.

Back to the *Tale* of the Euglena. (Get it?)



So QBism = “Shut Up and Calculate”?

Anything but!

Blake Stacey

“Were the world a different way, would we not, after we shut up, calculate in a different fashion?”

B. C. Stacey, Theoria **34**, 149-151 (2019)

Discussion from arXiv:1601.04360

Any of us can use quantum theory, but only for ourselves. There's a little single-celled thing called a Euglena that has a tail coming off it. The tail arose from evolutionary pressures, so that the Euglena can move from environments where there are depleted nutrients to environments where there's an abundance of nutrients. It's a tool. Quantum mechanics is like the Euglena's tail. It's something we evolved in 1925 and since it's been shown to be such a good tool, we keep using it and we pass it on to our children. The tail is a single-user tail. But we can look at the tail and ask things like, what might we learn about the environment by studying its structure? We might notice the tail is not completely circular and that might tell us something about the viscosity of the medium it's traveling through. We might look at the ratio of the length of it to the width of it in various places and that might tell us about features of the environment. So quantum mechanics is a single-user theory, but by dissecting it, you can learn something about the world that all of us are immersed in.

Ultimately I view QBism as a quest to point to something in the world and say, that's intrinsic to the world. But I don't have a conclusive answer yet. Let's take the point of view that quantum mechanics is a user's manual. A user's manual ***for me***. A philosopher will quickly say, well that's just instrumentalism. "Instrumentalism" is always prefaced by a "just." But that's jumping too quickly to a conclusion. Because you can always ask – you should always ask – what is it about the world that compels me to adopt this instrument rather than that instrument? A quantum state is a user's manual of probabilities. But how does it determine the probabilities? Well there's a little mathematical formula called the Born Rule. And then you should ask, why that formula? Couldn't it have been a different formula? Yes, it might have been different. The fact that we adopt this formula rather than some other formula is telling us something about the character of the world as it is, independent of us. If we can answer the question "Why the Born Rule?" or John Wheeler's question "Why the quantum?" then we'll be making a statement about how the world is, one that's not "just" instrumentalism.

What might the tale of QBism be telling us?

Newton and the Law of Universal Gravitation

$$F = G\frac{m_1 m_2}{r^2}$$

Discussion from arXiv:1003.5209

An unparalleled example can be found in Newton's law of universal gravitation. What did Newton really find? Would he be considered a great physicist in this day when the most cherished goal of physics is a Theory of Everything? For the law of universal gravitation is hardly that! Instead, it *merely* says that every body in the universe tries to accelerate every other body toward itself at a rate proportional to its own mass and inversely proportional to their squared distance. Beyond that, the law says nothing else particular of objects, and it would have been a rare thinker in Newton's time, if any at all, who would have imagined that all the complexities of the world could be derived from that limited law. Yet there is no doubt that Newton was one of the greatest physicists of all time. He did not give a theory of everything, but a Theory of One Aspect of Everything. And only the tiniest fraction of physicists of any variety, much less the Theory-of-Everything seekers, have ever worn a badge of that more modest kind. Finding a theory of “merely” one aspect of everything is hardly something to be ashamed of: It is the loftiest achievement physics can have in a living, breathing nonreductionist world.

Quantum Theory as a Rubric for All That Is

Rubric = “a direction for the conduct of divine service”

Quantum Theory as a Rubric for All That Is

Rubric = "a direction for the conduct of divine service"

Instead:

Quantum Theory as the Expression of
Just One Feature of all Matter

Quantum Theory as the Expression of Just One Feature of all Nature

- In a way, quantum theory humbled.
- But in another way, that one feature of nature seems to encode that:

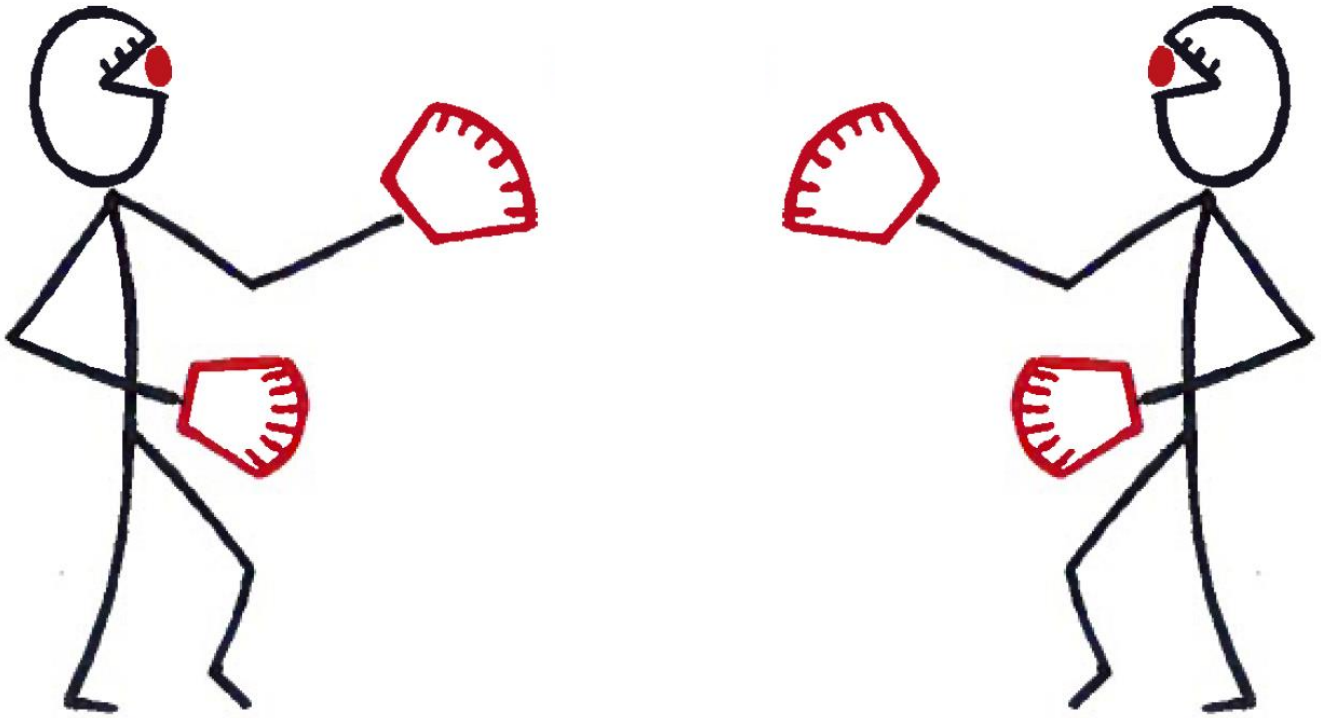
Our actions as agents genuinely matter.

Bad Pun: With every action an agent takes, the universe is Born Again.

But what more can be said of the ontology?

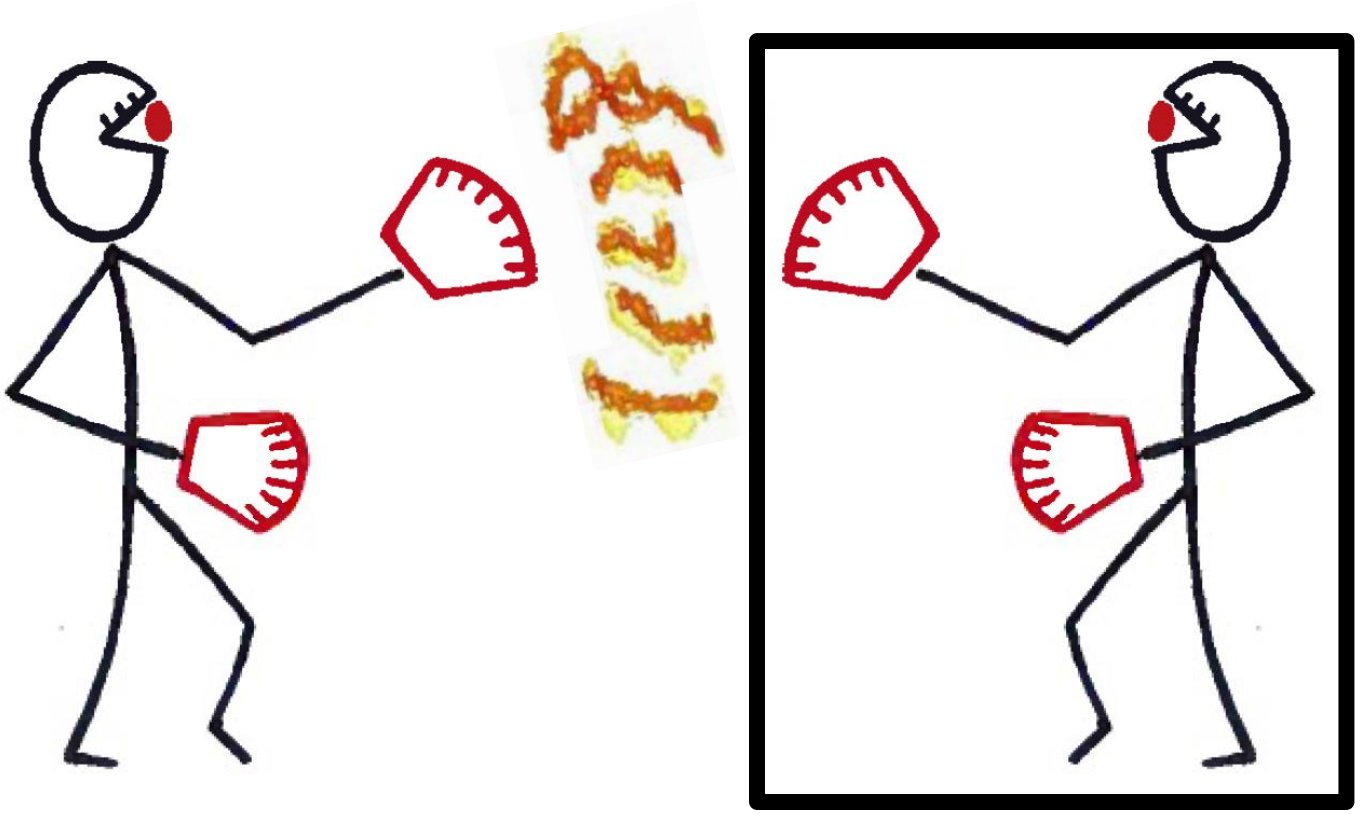
(Here's the part we're not sure of.)

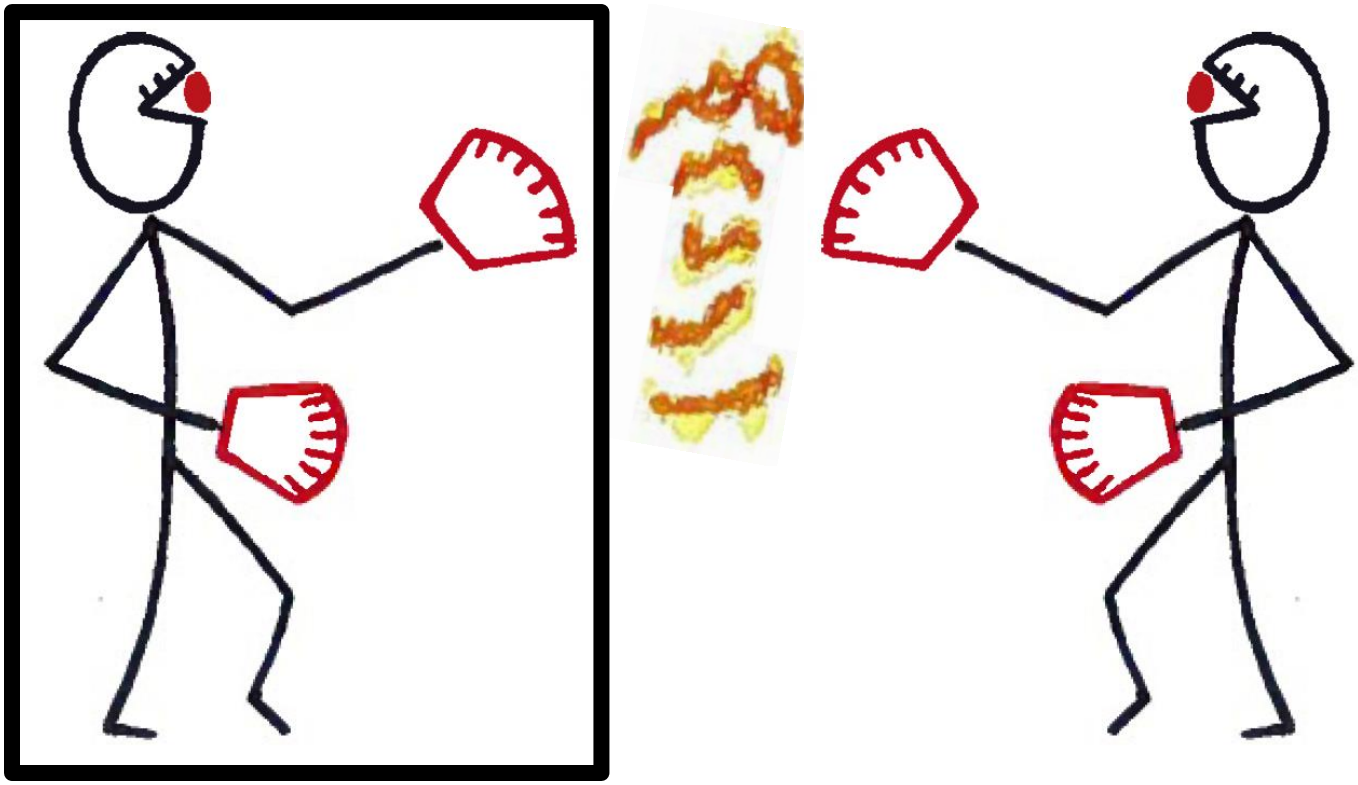
Consider This Symmetric Situation



Discussion from arXiv:1412.4209

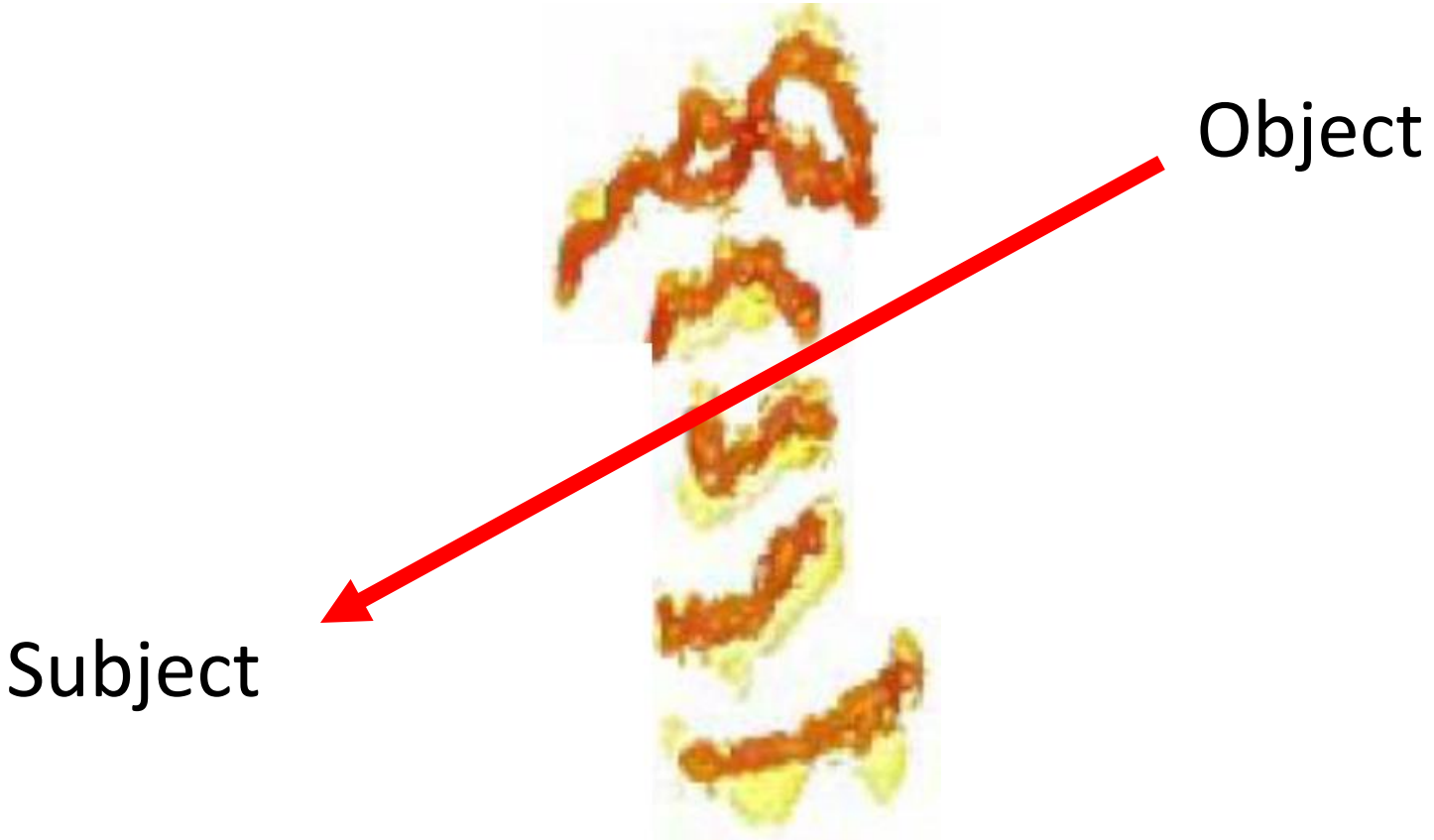
Of course, as a single-user theory, quantum mechanics is available to any agent to guide and better prepare her for her encounters with the world. And although quantum mechanics has nothing to say about another agent's personal experiences, agents can communicate and use the information gained from each other to update their probability assignments. In the spirit of the Paulian Idea, however, querying another agent means taking an action on him. Whenever "I" encounter a quantum system, and take an action upon it, it catalyzes a consequence in my experience that my experience could not have foreseen. Similarly, by a Copernican-style principle, I should assume the same for "you": Whenever you encounter a quantum system, taking an action upon it, it catalyzes a consequence in your experience. 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. Like with the Rubin vase, the best the eye can do is flit back and forth between the two formulations.





Suggests, perhaps, trying to abstract ***this*** element from the lessons of QBism.

Event of sorts, but ostensibly has a polarity, like Whitehead's "throbs of experience."

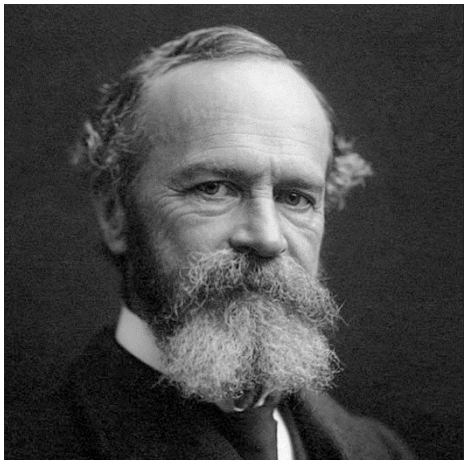


Whitehead *per se* cannot be exactly right.

His vision, his ontology was not tempered by the deep details of quantum theory.

To ask why the Born Rule is to construct a detailed picture of the characteristics of these “actual occasions” or “throbs of experience.”

“Here I take the bull by the horns, and … ask *why not?* Our acts, our turning-places, where we seem to make ourselves and grow, are the parts of the world to which we are closest, the parts of which our knowledge is the most intimate and complete. Why should we not take them at their face-value? Why may they not be the actual turning-places and growing-places, which they seem to be, of the world---why not the workshop of being, where we catch fact in the making, so that nowhere may the world grow in any other kind of way than this?”



William James
1842 – 1910

Usual Physicalism

Physics takes its start at some wholly dehumanized fundamental entity. Democritus had his atoms and void. Einstein had his hoped-for unified field.

The question then becomes how to recover conscious experience or agency out of the fundamental dehumanized ontology.

The traditional approach tries to proceed “up the chain.”

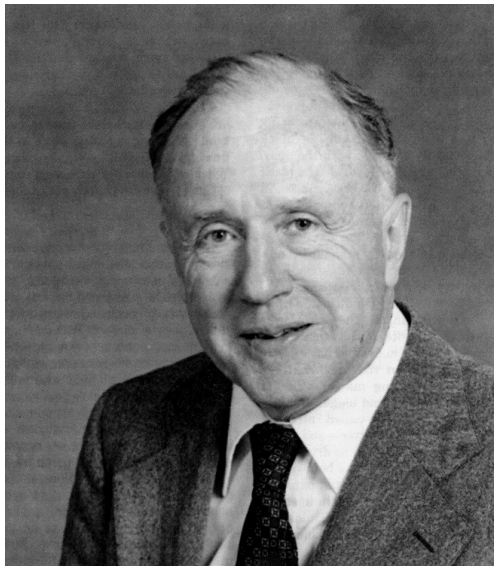
QBistic Physicalism

Quantum theory takes its very start at the agent using the formalism. Agential *actions* and *experience* are primitives of the theory. *Free will*, as Lequyer and Renouvier argued, comes first before any logic or science.

But then the question becomes how can physics really be like that? The greatest fruits of science have always *seemed* to come from removing the subjective, human element as much as possible.

QBism turns the usual physicalist chain upside down. It asks how far we might proceed by applying a Copernican Principle to its starting points.

WHEELER: It is difficult to escape asking a challenging question. Is the entirety of existence, rather than being built on particles or fields of force or multidimensional geometry, built upon billions upon billions of elementary quantum phenomena, those elementary acts of "observer-participancy," those most ethereal of all the entities that have been forced upon us by the progress of science?



John Archibald Wheeler
1911 – 2008

ELVEE: Dr. Wheeler, who was there to observe the universe when it started? Were we there? Or does it only start with our observation? Is the big bang here?

WHEELER: A lovely way to put it – "Is the big bang here?" I can imagine that we will someday have to answer your question with a "yes."

Each elementary quantum phenomenon is an elementary act of "fact creation." That is incontestable. But is that the only mechanism needed to create all that is? Is what took place at the big bang the consequence of billions upon billions of these elementary processes, these elementary "acts of observer-participancy," these quantum phenomena? Have we had the mechanism of creation before our eyes all this time without recognizing the truth? That is the larger question implicit in your comment.

But

QBism is a project.

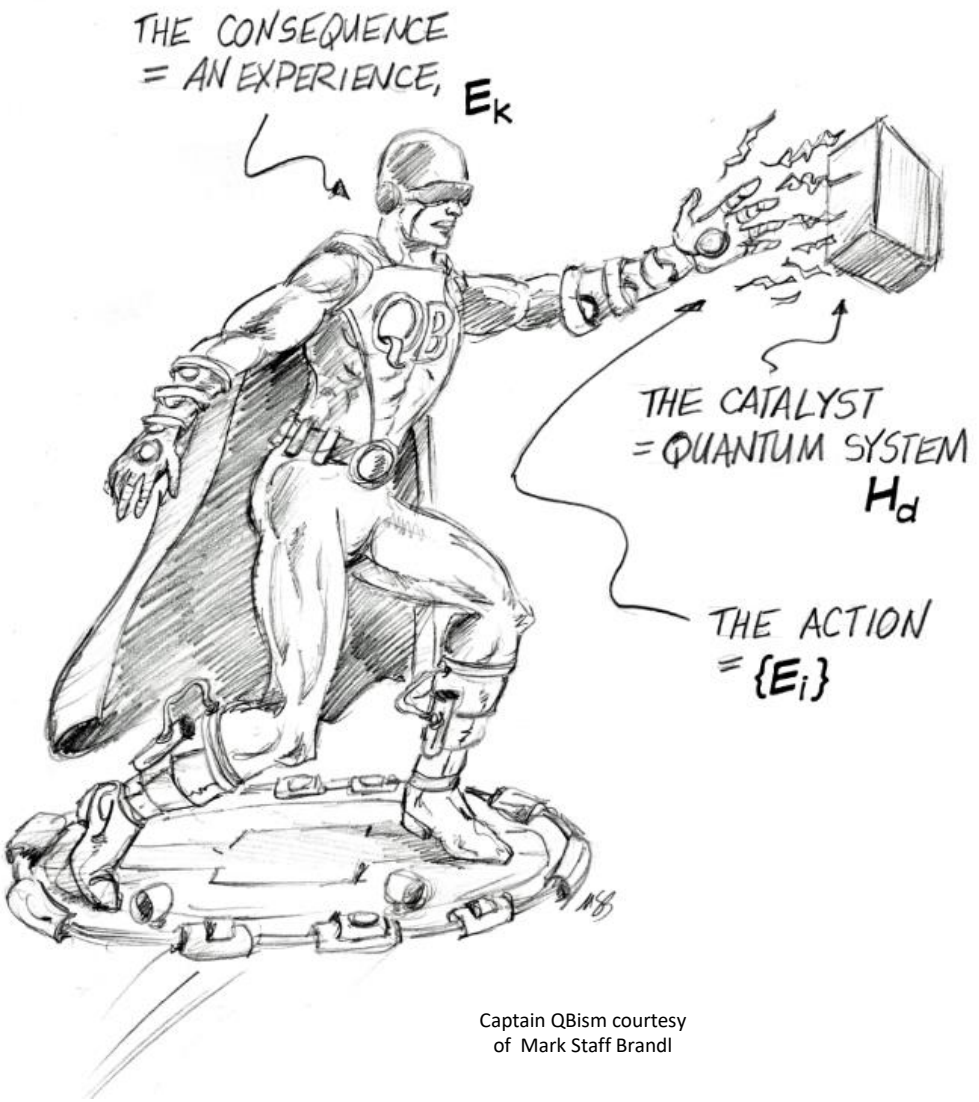
Erwin Schrödinger on Responsible Physics*

In an honest search for knowledge you quite often have to abide by ignorance for an indefinite period. Instead of filling a gap by guesswork, genuine science prefers to put up with it; and this, not so much from conscientious scruples about telling lies, as from the consideration that, however irksome the gap may be, its obliteration by a fake removes the urge to seek after a tenable answer. So efficiently may attention be diverted that the answer is missed even when, by good luck, it comes close at hand. The steadfastness in standing up to a *non liquet*, nay in appreciating it as a stimulus and a signpost to further quest, is a natural and indispensable disposition in the mind of a scientist. This in itself is apt to set him at variance with the religious aim of closing the picture, unless each of the two antagonistic attitudes, both legitimate for their respective purposes, is applied with prudence.

— Erwin Schrödinger, 1954

* This message sponsored by *QBists for Quantum Attitude Reform.*

Until the next episode …



Captain QBism courtesy
of Mark Staff Brandl