# QBism by von Baeyer

December 5, 2018

# Cube factory

> *A precision tool factory produces iron cubes with edge length $\leq 2$ cm. What is the probability that a cube has length $\leq 1$ cm given that it was produced by that factory?*

Van Frassen's point was that you could "naturally" chose between a uniform distribution of the side length, the face area, or the volume of the cube. Each choice of course yields a different answer.

- Point is that it's not so easy to determine a probability distribution from simple information about the world.

from `https://physics.stackexchange.com/questions/414689/significance-of-cube-factory-paradox`

# Chances versus credences

Chances

- Smokers have a greater chance of getting cancer than non-smokers have.
- This coin toss is unbiased: it has equal chances of landing heads and tails.

Credences

- I think it will probably rain tonight.
- I'll bet you 4:1 that Pink Gin doesn't win the Derby.

from D. H. Mellor, *Probability: A Philosophical Introduction*

# Marcus Appleby's parable

> *Bob tosses a coin a hundred times, obtains a sequence of heads and tails that consists of about fifty heads and fifty tails in seemingly random order, and concludes that the coin is fair.*

Bob must:

- assume coin tosses are independent,
- assume the probability of heads is the same for every toss, and
- calculate the likelihood of getting his particular sequence of 100 tosses for each assumed value of single-toss probability and choose the single-toss probability (hopefully 1/2) that maximizes that likelihood.

# Cancer and testing

- 0.5% of the population has cancer
- 1.0% of tests are wrong

| | cancer | no cancer | total |
|---|---|---|---|
| positive test | 0.495% | 0.995% | 1.490% |
| negative test | 0.005% | 98.505% | 98.510% |
| total | 0.500% | 99.500% | 100.000% |

$$p(+) \times p(+ \to ☹) = p(☹) \times p(☹ \to +)$$
$$1.490\% \times p(+ \to ☹) = 0.500\% \times 99\%$$

$$p(+ \to ☹) = 33\%$$

# Bayes' law

$$p(I \to E) = \frac{p(E \to I)}{p(I)} p(E)$$

- $p(E)$ is the *prior* probability
- $p(I \to E)$ is the *posterior* probability

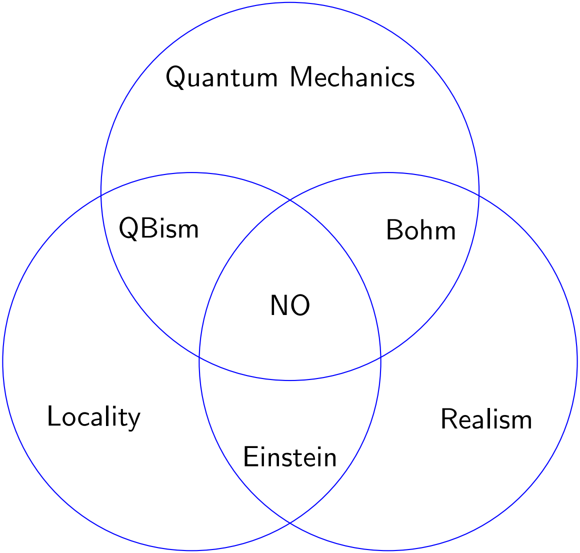
Notice that $\frac{p(E \to I)}{p(I)}$ could be greater than one (in which case our degree of belief in $E$ increases) or less than one (in which case our degree of belief in $E$ decreases).

# Cancer example

$$p(I \to E) = \frac{p(E \to I)}{p(I)} p(E)$$

$$33\% = \frac{99\%}{1.49\%}(0.5\%)$$

# Pick any two



Quantum Mechanics
QBism
Bohm
NO
Locality
Realism
Einstein

# 3 entangled electrons

Electron 1

| | $-1$ | $1$ |
|---|---|---|
| $\Sigma_1$ | $\leftarrow$ | $\rightarrow$ |
| $\Sigma_2$ | $\downarrow$ | $\uparrow$ |

Electron 2

| | $-1$ | $1$ |
|---|---|---|
| $\Xi_1$ | $\leftarrow$ | $\rightarrow$ |
| $\Xi_2$ | $\downarrow$ | $\uparrow$ |

Electron 3

| | $-1$ | $1$ |
|---|---|---|
| $\Theta_1$ | $\leftarrow$ | $\rightarrow$ |
| $\Theta_2$ | $\downarrow$ | $\uparrow$ |

# Connecting von Baeyer to Jordan

$$\rightarrow\rightarrow\uparrow$$

means

- $\Sigma_1$ has the definite value 1
- $\Xi_1$ has the definite value 1
- $\Theta_2$ has the definite value 1

| | $-1$ | $1$ |
|---|---|---|
| $\Sigma_1$ | $\leftarrow$ | $\rightarrow$ |
| $\Sigma_2$ | $\downarrow$ | $\uparrow$ |

| | $-1$ | $1$ |
|---|---|---|
| $\Xi_1$ | $\leftarrow$ | $\rightarrow$ |
| $\Xi_2$ | $\downarrow$ | $\uparrow$ |

| | $-1$ | $1$ |
|---|---|---|
| $\Theta_1$ | $\leftarrow$ | $\rightarrow$ |
| $\Theta_2$ | $\downarrow$ | $\uparrow$ |

# Showing that QM, locality, and realism cannot coexist

- Quantum mechanics says there is a state of three qubits in which
  - $\Sigma_1 \Xi_1 \Theta_2$ has the definite value 1,
  - $\Sigma_1 \Xi_2 \Theta_1$ has the definite value 1,
  - $\Sigma_2 \Xi_1 \Theta_1$ has the definite value 1, and
  - $\Sigma_2 \Xi_2 \Theta_2$ has the definite value $-1$.

  (Notice that every pair of matrices commutes, so they can have definite values together.)
- Locality and realism say that if
  - $\Sigma_1 \Xi_1 \Theta_2$ has the definite value 1,
  - $\Sigma_1 \Xi_2 \Theta_1$ has the definite value 1, and
  - $\Sigma_2 \Xi_1 \Theta_1$ has the definite value 1, then
  - $\Sigma_2 \Xi_2 \Theta_2$ has the definite value 1.

# Assuming realism

$$\downarrow\rightarrow\ \downarrow\rightarrow\ \uparrow\leftarrow$$

means

- $\Sigma_2$ has the definite value $-1$
- $\Sigma_1$ has the definite value 1
- $\Xi_2$ has the definite value $-1$
- $\Xi_1$ has the definite value 1
- $\Theta_2$ has the definite value 1
- $\Theta_1$ has the definite value $-1$

| | $-1$ | $1$ |
|---|---|---|
| $\Sigma_1$ | $\leftarrow$ | $\rightarrow$ |
| $\Sigma_2$ | $\downarrow$ | $\uparrow$ |

| | $-1$ | $1$ |
|---|---|---|
| $\Xi_1$ | $\leftarrow$ | $\rightarrow$ |
| $\Xi_2$ | $\downarrow$ | $\uparrow$ |

| | $-1$ | $1$ |
|---|---|---|
| $\Theta_1$ | $\leftarrow$ | $\rightarrow$ |
| $\Theta_2$ | $\downarrow$ | $\uparrow$ |

# Realism implies that all quantities have definite values

If $\Sigma_1$, $\Sigma_2$, $\Xi_1$, $\Xi_2$, $\Theta_1$, and $\Theta_2$ are just variables that can be $-1$ or 1 (unlike in quantum theory, where they are matrices), then

$$(\Sigma_1 \Xi_1 \Theta_2)(\Sigma_1 \Xi_2 \Theta_1)(\Sigma_2 \Xi_1 \Theta_1) = \Sigma_2 \Xi_2 \Theta_2$$

Therefore, if the three things on the left are 1, then the thing on the right is 1.

# Realism vs. QM

- In a realist theory,

$$(\Sigma_1 \Xi_1 \Theta_2)(\Sigma_1 \Xi_2 \Theta_1)(\Sigma_2 \Xi_1 \Theta_1) = \Sigma_2 \Xi_2 \Theta_2$$

- In Quantum Mechanics,

$$(\Sigma_1 \Xi_1 \Theta_2)(\Sigma_1 \Xi_2 \Theta_1)(\Sigma_2 \Xi_1 \Theta_1) = -\Sigma_2 \Xi_2 \Theta_2$$

# GHZ state preparation

| | | | |
|---|---|---|---|
| $\rightarrow$ | $\rightarrow$ | $\uparrow$ | can occur |
| $\leftarrow$ | $\leftarrow$ | $\uparrow$ | can occur |
| $\rightarrow$ | $\leftarrow$ | $\downarrow$ | can occur |
| $\leftarrow$ | $\rightarrow$ | $\downarrow$ | can occur |
| $\rightarrow$ | $\rightarrow$ | $\downarrow$ | never occurs |
| $\leftarrow$ | $\leftarrow$ | $\downarrow$ | never occurs |
| $\rightarrow$ | $\leftarrow$ | $\uparrow$ | never occurs |
| $\leftarrow$ | $\rightarrow$ | $\uparrow$ | never occurs |

# 64 cases

- Assume locality and realism

| | | | |
|---|---|---|---|
| $\uparrow\rightarrow$ | $\uparrow\rightarrow$ | $\uparrow\rightarrow$ | ok |
| $\uparrow\rightarrow$ | $\uparrow\rightarrow$ | $\uparrow\leftarrow$ | not possible |
| $\uparrow\rightarrow$ | $\uparrow\rightarrow$ | $\downarrow\rightarrow$ | not possible |
| $\uparrow\rightarrow$ | $\uparrow\rightarrow$ | $\downarrow\leftarrow$ | not possible |
| | | $\vdots$ | |

- 8 of 64 cases are ok
- 56 of 64 cases are not possible

# Counting the cases

| | without order | number of orders | with order |
|---|---|---|---|
| All 3 same | 4 | 1 | 4 |
| 2 same, 1 different | 12 | 3 | 36 |
| All 3 different | 4 | 6 | 24 |
| Total cases | 20 | | 64 |

# 20 cases if we discount particle order

| | | | |
|---|---|---|---|
| $\uparrow\rightarrow$ | $\uparrow\rightarrow$ | $\uparrow\rightarrow$ | ok |
| $\uparrow\leftarrow$ | $\uparrow\leftarrow$ | $\uparrow\leftarrow$ | ok |
| $\downarrow\rightarrow$ | $\downarrow\rightarrow$ | $\downarrow\rightarrow$ | not possible |
| $\downarrow\leftarrow$ | $\downarrow\leftarrow$ | $\downarrow\leftarrow$ | not possible |

| | | | |
|---|---|---|---|
| $\uparrow\rightarrow$ | $\uparrow\leftarrow$ | $\downarrow\rightarrow$ | not possible |
| $\uparrow\rightarrow$ | $\uparrow\leftarrow$ | $\downarrow\leftarrow$ | not possible |
| $\uparrow\rightarrow$ | $\downarrow\leftarrow$ | $\downarrow\rightarrow$ | not possible |
| $\uparrow\leftarrow$ | $\downarrow\leftarrow$ | $\downarrow\rightarrow$ | not possible |

| | | | |
|---|---|---|---|
| $\uparrow\rightarrow$ | $\uparrow\rightarrow$ | $\uparrow\leftarrow$ | not possible |
| $\uparrow\rightarrow$ | $\uparrow\rightarrow$ | $\downarrow\rightarrow$ | not possible |
| $\uparrow\rightarrow$ | $\uparrow\rightarrow$ | $\downarrow\leftarrow$ | not possible |
| $\uparrow\leftarrow$ | $\uparrow\leftarrow$ | $\uparrow\rightarrow$ | not possible |
| $\uparrow\leftarrow$ | $\uparrow\leftarrow$ | $\downarrow\rightarrow$ | not possible |
| $\uparrow\leftarrow$ | $\uparrow\leftarrow$ | $\downarrow\leftarrow$ | not possible |
| $\downarrow\rightarrow$ | $\downarrow\rightarrow$ | $\downarrow\leftarrow$ | not possible |
| $\downarrow\rightarrow$ | $\downarrow\rightarrow$ | $\uparrow\rightarrow$ | not possible |
| $\downarrow\rightarrow$ | $\downarrow\rightarrow$ | $\uparrow\leftarrow$ | ok |
| $\downarrow\leftarrow$ | $\downarrow\leftarrow$ | $\downarrow\rightarrow$ | not possible |
| $\downarrow\leftarrow$ | $\downarrow\leftarrow$ | $\uparrow\rightarrow$ | ok |
| $\downarrow\leftarrow$ | $\downarrow\leftarrow$ | $\uparrow\leftarrow$ | not possible |

# 4 of 20 cases follow the GHZ rule

| | | | |
|---|---|---|---|
| $\uparrow\rightarrow$ | $\uparrow\rightarrow$ | $\uparrow\rightarrow$ | ok |
| $\uparrow\leftarrow$ | $\uparrow\leftarrow$ | $\uparrow\leftarrow$ | ok |
| $\downarrow\rightarrow$ | $\downarrow\rightarrow$ | $\uparrow\leftarrow$ | ok |
| $\downarrow\leftarrow$ | $\downarrow\leftarrow$ | $\uparrow\rightarrow$ | ok |

- none of these are UUD
- first two are UUU, last two are DDU

# QM and realism

If realism demand definite values for all quantities, and QM represents quantities by matrices, isn't that already a contradiction?

# Interpretations of Quantum Mechanics

| Polkinghorne | von Baeyer |
|---|---|
| Irrelevance | |
| Large systems | Copenhagen |
| New physics | Spontaneous Collapse |
| Consciousness | |
| Many worlds | Many-Worlds |
| Determinism | Pilot-Wave |
| | QBism |

# Adan Cabello's classification of interpretations

| | $\psi$-Ontic | $\psi$-Epistemic |
|---|---|---|
| Type-I (intrinsic realism) | Bohmian mechanics [10, 11]<br>Many worlds [12, 13]<br>Modal [14, 15]<br>Bell's "beables" [16]<br>Collapse theories* [17, 18] | Einstein [19]<br>Ballentine [20]<br>Consistent histories [21, 22]<br>Spekkens [23] |

| | About knowledge | About belief |
|---|---|---|
| Type-II (participatory realism) | Copenhagen [24, 25]<br>Wheeler [26, 27]<br>Relational [28, 29]<br>Zeilinger [30, 3]<br>No "interpretation" [31]<br>Brukner [32] | QBism [33, 34, 35] |

- arXiv:1509.04711v2 (2016)

# Adan Cabello's classification of interpretations

- Type-I interpretations are defined as those in which the probabilities of measurement outcomes are determined by intrinsic properties of the observed system.
- Type-II interpretations are defined as those which do not view the probabilities of measurement outcomes of quantum theory as determined by intrinsic properties of the observed system. Type-II interpretations do not deny the existence of an objective world but, according to them, quantum theory does not deal directly with intrinsic properties of the observed system, but with the experiences an observer or agent has of the observed system.

# Type-I interpretations

Type-I interpretations can be

- "$\psi$-ontic" [36], if they view the quantum state as an intrinsic property of the observed system, or
- "$\psi$-epistemic" [36], if they view the quantum state as representing knowledge of an underlying objective reality in a sense somewhat analogous to that in which a state in classical statistical mechanics assigns a probability distribution to points in phase space.

# Type-II interpretations

Type-II interpretations can be

- "about knowledge" if they view the quantum state as an observer's knowledge about the results of future experiments, or
- "about belief" if they view the quantum state as an agent's expectations about the results of future actions.

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| | About knowledge | About belief |
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# Four Quantum Mysteries

- Quantization
  - Why do things come in lumps? (Photons, but also Stern-Gerlach outcomes)
  - Why can $\Sigma_1$ have only the values $-1$ and 1?
- Wave/Particle Duality
  - Why do electrons behave sometimes like waves and sometimes like particles?
  - Feynman called this "the only mystery", but others disagree.
- Quantum Entanglement
  - Why can we not have both locality and realism in a theory?
- Interpretation
  - What is quantum mechanics trying to tell us about the world?
  - Is the world non-local? (Some say yes; some say no.)
  - Are there objects with real properties? (Some say yes; some say no.)

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