THE DEATH OF LOCAL REALISM, AND YET THE EXISTENCE OF EPISTEMICS

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OUTLINE:

Death of Locality

- What is locality
- Bell violation via CHSH
- Contextuality and Mermin Square
- PBR

Life in Epistemics

- What is 'epistemics'
- Quantum mechanics as information...and a little more
- Specken's toy model, a local hidden variable theory

LOCALITY: WHAT IS IT?

- Locality:
  - Measurement on one system is unaffected by a distant system. [1]
  - Classical local action:
    - Objects can only act on their nearest neighbors --- no teleportation or effecting the state of a far-off system (eg. kicking a ball vs using the force to move a ball)
    - Consequence: given a complete set of initial conditions, you could predict time evolution of a system <u>exactly</u>.
      - Deterministic

One often hears that quantum Mechanics is **non-local**, but why?

LOCALITY: WHAT IS IT?

Take two spin ½ particles with a state described as:

$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|10\rangle + |01\rangle\right)$$

Imagine particle b is then shot off to mars, with particle a still here on earth.

- We then measure particle a and find it is in the state: $|\psi_a\rangle = |1\rangle$
- We know then that partible b is in the state $|\psi_b\rangle = |0\rangle$ without having to go to Mars.

This is a <u>non-local update in information</u>: we know the state of particle b without interacting with the particle in any way.

Important: non-locality in information <u>only</u>
we are not making particle b do anything, we only have a correlation in the information

LOCALITY: WHY IS IT WEIRD?

- Einstein coined ‘spooky action at a distance’ to the previous example.
- Seemingly, this knowledge of particle b violates relativity
  - faster than light transfer of information.
- This is the setup for the Einstein, Podolsky, Rosen (EPR) paradox:
  - How can you have simultaneous knowledge of system b solely due to knowing system a?
- Conclusion by EPR: quantum mechanics MUST be an incomplete theory…
  - Possible solution using realist intuitions?
  - Hidden variables

HIDDEN VARIABLE THEORIES(HVT)

- HVTs postulate that there are variables that when known would make quantum mechanics essentially a statistical mechanics system which evolves deterministically.
- Positive:
  - Would make quantum mechanics consistent with classical ideas.
- However, we would then all be out of a job…so how did people go about showing quantum mechanics is different from classical mechanics?

By proving a death in either locality or realism (local realism)

BELL AND CHSH

- Bell wrote in 1964 [1]
  - The first concrete paper disproving local hidden variables
    - ‘attempts [to disprove locality] have been examined elsewhere and found wanting.’
  - Any theory with hidden variables must have a non-local structure
    - The theory for quantum mechanics must uphold this phenomenon of non-locality in some way, either through qm as we know it, or a non-local hidden variable theory.
- Clausser, Horne, Shimony, and Holt (CHSH) in 1969 [2]
  - Generalized Bell’s findings to ‘realizable’ experiments, i.e., addresses uncertainty in experimental setup.
  - From paper derive the CHSH inequality: $|\langle QR\rangle + \langle RS\rangle + \langle RT\rangle - \langle QT\rangle| \leq 2$

Let’s look at a proof via coloring.

COLORING PROOF

- Let us look again at two entangled particles spatially separated, particle 1 will be measured in the two bases Q and R, and particle 2 in S and T.

Using realism and locality we will define two characteristics:

- (locality) The outcomes of Q,R have no impact on S,T, and vice versa
- (realism) Q,R,S,T can only take on values of ±1 in which they keep through the entire game.

Define the CHSH quantity:

$$S = Q(S-T) + R(S+T)$$

COLORING PROOF

Classically we can derive:

$$S = Q(S-T) + R(S+T) = \pm 2$$

$$\underset{1}{Q}\;\underbrace{(S-T)}_{-2} + \underset{-1}{R}\;\underbrace{(S+T)}_{0} = -2$$

e.g. $Q = 1$, $S = -1$, $R = -1$, $T = 1$

And that if we take the norm of the expectation value ranging over all the possible assignments of ±1 :

$$|\langle S \rangle| = |\langle QS \rangle - \langle QT \rangle + \langle RS \rangle + \langle RT \rangle| \leq 2$$

This is our classical bound imposed by local realism – the CHSH inequality.

Let us see if we can beat it quantum mechanically

COLORING PROOF

Let us take 2 particles, each with two possible basis measurements with observables:

- Particle 1: $O_Q = \mathbb{Z} \otimes \mathbb{1}$ $\quad O_R = \mathbb{X} \otimes \mathbb{1}$
- Particle 2: $O_S = -\mathbb{1} \otimes \frac{1}{\sqrt{2}}(\mathbb{Z} + \mathbb{X})$ $\quad O_T = \mathbb{1} \otimes \frac{1}{\sqrt{2}}(\mathbb{Z} - \mathbb{X})$

The particles are entangled and prepared in the state: $|\psi_-\rangle = \frac{1}{\sqrt{2}}\left(|01\rangle - |10\rangle\right)$

COLORING PROOF

- Now we want to find what the expectation value after many many repetitions of the set up: (left as an exercise for the audience)

$$\langle S_1 \rangle = \langle QS \rangle + \langle RS \rangle + \langle RT \rangle - \langle QT \rangle = ?$$

- It turns out that with our quantum state, and with the observables, we find:

$$\langle QS \rangle = \langle RS \rangle = \langle RT \rangle = -\langle QT \rangle = 1/\sqrt{2}$$

- Leading to:

$$\langle S_1 \rangle = 2\sqrt{2} > 2$$

CONSEQUENCE OF PROOF

- We were able to violate the bound generated by the stipulations of local realism, what does this mean?
- Quantum mechanics must have a violation of *local realism*
- Information non-locality:
  - We can know information about systems without interacting with them.
  - In the assumption of realism, the far away particle has gone from a probability to a physical element of reality without being itself measured.
- Non-realism:
  - When we measure, we are bringing a quantity/object into existence - there is no underlying *thing* that we are finding.

CONTEXTUALITY [3]

<u>Contextuality</u>

- Dependence of the outcome of a measurement on the 'context' of your measurement.

<u>Non-contextual system</u>

- Simultaneously determine outcomes without contradiction

How does this relate?

- Idea of locality without having a concept of distance.
- Another way that a quantum system can have 'non-local' update in information, a way to study consistent assignments of values prior to measurement.

CONTEXTUALITY: MERMIN SQUARE

Let's play a game to get more comfortable with what contextuality is:
The game is called the Mermin square.

Take a 3x3 grid/matrix:

$$\begin{pmatrix} A & B & C \\ a & b & c \\ \alpha & \beta & \gamma \end{pmatrix}$$

The idea is to fill in the matrix such that you get the maximum value for the expectation value:

$$\langle PM \rangle = \langle ABC \rangle + \langle abc \rangle + \langle \alpha\beta\gamma \rangle + \langle Aa\alpha \rangle + \langle Bb\beta \rangle - \langle Cc\gamma \rangle$$

MERMIN SQUARE

Now these expectation values classically are defined as

<ABC> = prob(ABC = +1) - prob(ABC = -1)

$$\begin{pmatrix} A & B & C \\ a & b & c \\ \alpha & \beta & \gamma \end{pmatrix}$$

And the trick is, there must be only one entry which is -1

Suppose that we determine every value to be +1 except for 1 entry in the 3rd column, c_2, then 2 entries would flip sign:

let $\gamma = -1$ then $\langle Cc\gamma \rangle = \langle \alpha\beta\gamma \rangle = -1$

$$\langle PM \rangle = \langle ABC \rangle + \langle abc \rangle + \langle \alpha\beta\gamma \rangle + \langle Aa\alpha \rangle + \langle Bb\beta \rangle - \langle Cc\gamma \rangle$$

$$= 1 + 1 - 1 + 1 + 1 - (-1)$$

$$= 4$$

MERMIN SQUARE

It so happens that choosing an element in the third column to be negative is the best outcome *classically* with the Mermin square:

$$\begin{pmatrix} A & B & C \\ a & b & c \\ \alpha & \beta & \gamma \end{pmatrix}$$

let "a" be -1, then $\langle Aa\alpha \rangle = \langle abc \rangle = -1$

$$\langle PM \rangle = \langle ABC \rangle + \langle abc \rangle + \langle \alpha\beta\gamma \rangle + \langle Aa\alpha \rangle + \langle Bb\beta \rangle - \langle Cc\gamma \rangle$$

$$= 1 - 1 + 1 + 1 - 1 - 1$$

$$= 0$$

Thus classically: $\boxed{\langle PM \rangle \leq 4}$

CONTEXTUALITY: MERMIN SQUARE

So, can we beat it quantum mechanically? Yes!! Let's see how:

Let the Mermin square take the form of a 3x3 matrix with the entries:

$$\begin{pmatrix} \mathbb{Z}\,\mathbb{1} & \mathbb{1}\,\mathbb{Z} & \mathbb{Z}\,\mathbb{Z} \\ \mathbb{1}\,\mathbb{X} & \mathbb{X}\,\mathbb{1} & \mathbb{X}\,\mathbb{X} \\ \mathbb{Z}\,\mathbb{X} & \mathbb{X}\,\mathbb{Z} & \mathbb{Y}\,\mathbb{Y} \end{pmatrix}$$

Each row's/column's operators commute. So we can find, for each column/row, the complete set of eigenvectors, and each with have eigenvalues either ±1.

CONTEXTUALITY: MERMIN SQUARE

- Each row and column to represents a "context" which we will label as:

$$
\begin{array}{cccc}
c_0 & c_1 & c_2 & \\
\end{array}
$$

$$
\begin{pmatrix}
Z\mathbb{1} & \mathbb{1}Z & ZZ \\
\mathbb{1}X & X\mathbb{1} & XX \\
ZX & XZ & YY
\end{pmatrix}
\begin{array}{c} r_0 \\ r_1 \\ r_2 \end{array}
$$

where $\{c_0\} = \{ Z\mathbb{1}, \mathbb{1}X, ZX \}$, etc.

When we take the product of the operators in each context, we will get the following expectation values:

$$\langle c_{i\neq 2} \rangle = \langle \mathbb{1}\mathbb{1} \rangle$$

$$\langle c_2 \rangle = \langle -\mathbb{1}\mathbb{1} \rangle$$

$$\langle r_i \rangle = \langle \mathbb{1}\mathbb{1} \rangle$$

CONTEXTUALITY: MERMIN SQUARE

So what do we get for our value <PM>?

All columns and rows individually commute, and we have:

$$\begin{array}{ccc} c_0 & c_1 & c_2 \end{array}$$

$$\begin{pmatrix} Z\mathbb{I} & \mathbb{I}Z & ZZ \\ \mathbb{I}X & X\mathbb{I} & XX \\ ZX & XZ & YY \end{pmatrix} \begin{matrix} r_0 \\ r_1 \\ r_2 \end{matrix}$$

$$\left.\begin{aligned} \langle r_i \rangle &= \langle \mathbb{I}\mathbb{I} \rangle \\ \langle C_{i=2} \rangle &= \langle \mathbb{I}\mathbb{I} \rangle \\ \langle C_2 \rangle &= \langle -\mathbb{I}\mathbb{I} \rangle \end{aligned}\right\} \quad \begin{aligned} \langle PM \rangle &= 5\langle \mathbb{I}\mathbb{I} \rangle - \langle -\mathbb{I}\mathbb{I} \rangle \\ &= 6 \end{aligned}$$

A state independent value of 6!

Violating the classical bound implies that for a value assignment, there is a dependence on which context the operator is in.

CONTEXTUALITY

The conclusion to Mermin Square: that ‘the value-assignment [of ±1] must depend on which context the observable appears in’ is the phenomenon of quantum contextuality [3].

It would be natural to think of commutation here.

If you have commuting observables, you can have joint measurability,

This is the minimum requirement for a notion of a context. ---only in ideal, projective, measurement.

CONTEXTUALITY

Contextuality can be viewed from many hats (philosophy, physics, mathematics, comp sci, etc.) [3].

The contextuality that is widely used in QI is Kochen – Specker contextuality.

The requirement for only one value to have -1 in Mermin square comes with the framework for K-S contextuality:

Let $\{Q_i, \ldots, Q_d\}$ represent true/false propositions:

1. Q_i and Q_j cannot both be 'true' for $i \neq j$
2. $\{Q_i, \ldots, Q_d\}$ cannot be simultaneously false, one must be true.

CONTEXTUALITY

This is generalized to projectors as:

In a d-dimensional Hilbert space H, consider d rank-1 projectors $P_1, \ldots, P_d$ associated with d orthogonal vectors in H which satisfy:

1. $P_i P_j = 0$ for any $i \neq j$ (Orthogonality)
2. $\sum_{i=1}^{d} P_i = \mathbb{1}$ (Completeness)

Now not all elements in the set may satisfy these conditions, and those which do satisfy occupy a context.

If you're more interested in this I would recommend reading Budras et al's paper Kochen – Specker Contextuality.

PBR

- Now, Bell and CHSH are not the only people thinking of local realism…
- Pusey, Barrett, and Rudolph (PBR) 2012 take the thought a step farther
  - Takes the question of the quantum state to what it would mean to be 'complete'
  - Argues that the quantum state must be ontic (state of reality) instead of epistemic (state of knowledge)
- The question of why this is important, i.m.o, comes from the interpretation of measurement.

PBR

Ontic (reality) state measurement collapse:

- A mysterious process – collapse of the wavefunction is shrouded in mystery for interpretation, especially in time [4].

Epistemic (knowledge) state measurement collapse:

- Essentially an ‘instantaneous Bayesian updating of probability distribution upon obtaining new information’ [4], benign and understood mathematically

PBR

What PBR argues for is that the quantum state is itself ontic (a state of reality), in the case that there is something ‘real’. (realists rejoice) [5]

Meaning: they show, using pure states and the assumption of realism, that the quantum state represents reality, not our ‘probabilistic knowledge of reality.’

So what does would be a next step?:

- We need to think about what measurement truly is: a true collapse, or every option does occur, or something else (?)

PBR

Now is the conversation over? Have the ontic believers won the battle?

Well not quite.

There are initial conditions to PBR -- a reliably creatable pure state, and the existence of ‘real’ things.

Immediately if you are a non-realist you can let out a breath of relief, PBR only rules out epistemics where the ‘knowledge’ referred to is about a real, true state of the system, if you are a non-realist then epistemics is still a valid idea to pursue.

In the world of these physics/philosophy topics there always toy models to play with…

PBR

In the original paper by PBR they quote Jaynes, and I think it is good to leave off my section:

'...our present formalism is not purely epistemological; it is a peculiar mixture describing part realities of Nature, in part incomplete human information about Nature --- all scrambled up by Heisenberg and Bohr into an omelette that nobody has seen how to unscramble. Yet we think that 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.'

REFERENCES

1. Bell, J. S. (1964). On the einstein podolsky rosen paradox. *Physics*, *1*(3), 195–200. https://doi.org/10.1103/physicsphysiquefizika.1.195
2. Clauser, J. F., Horne, M. A., Shimony, A., & Holt, R. A. (1969). Proposed experiment to test local hidden-variable theories. *Physical Review Letters*, *23*(15), 880–884. https://doi.org/10.1103/physrevlett.23.880
3. Budroni, C., Cabello, A., Gühne, O., Kleinmann, M., & Larsson, J.-Å. (2022). Kochen-Specker contextuality. *Reviews of Modern Physics*, *94*(4). https://doi.org/10.1103/revmodphys.94.045007
4. Pusey, M. F., Barrett, J., & Rudolph, T. (2012). On the reality of the Quantum State. *Nature Physics*, *8*(6), 475–478. https://doi.org/10.1038/nphys2309
5. Leifer, M. S. (2014). Is the quantum state real? an extended review of ψ-ontology theorems. *Quanta*, *3*(1), 67. https://doi.org/10.12743/quanta.v3i1.22

LIFE IN EPISTEMICS

- Quantum mechanical axioms are abstract

  ex: Quantum states correspond to density matrices in Hilbert space,

  Measurements correspond to POVMs E_d with outcome

  probabilities $tr(\rho E_d)$

  Etc…
- Is it possible to derive this structure through physical principles?
- Strategy to systematically discover these physical principles: "distill" down QM by separating information theoretic ideas from "pure physics" [1]

WHAT IS AN EPISTEMIC?

- Ontic state: state of reality
- Epistemic state: state of knowledge

Ex: point in phase space vs probability distribution over phase space

Many QM interpretations take the quantum state as an ontic,
but epistemic interpretation has led to recent progress in QIS research

WHY EPISTEMICS?

- Ontic proponent: QM isn't mysterious if you abandon preconcieved notions of reality
- Epistemics: many mysterious qualities of QM are more conceptually understandable and emerge naturally (No cloning, teleportation, measurement collapse and noncommuting measurements, entanglement…)

SPEKKENS TOY MODEL: INTRO

Spekkens [2] shows that some seemingly "quantum" qualities of QM can be derived by a locally real theory of epistemics, which describe knowledge of the ontics, satisfying the **Knowledge Balance Principle:**

An epistemic state of maximum knowledge is not a state of complete knowledge, and in this state the knowledge one has is equal in size to the knowledge one lacks about the system

Note this *cannot* exactly recreate QM, as Basie just showed us that QM is not locally real. Important thing is what *can* this recreate, and what is left behind that cannot be recreated?

WHY INCOMPLETE KNOWLEDGE?

Liouville mechanics: states of incomplete knowledge share similar behavior to quantum states:

- No cloning: Louisville thm. Preserves phase space overlap volume
- Impossibility of discriminating states with certainty
- Some features of entanglement

Better analogy between classical and quantum if complete knowledge was never achieved, i.e. if maximal knowledge is incomplete knowledge!

SPEKKENS TOY MODEL: INTRO

Knowledge Balance: in state of maximum knowledge, information one has about the system is equal size as information one lacks.

Canonical set: minimal # of Y/N questions sufficient to fully specify ontic

Knowledge: max # of questions for which answer is known

Ignorance: # questions - knowledge

SPEKKENS TOY MODEL: SIMPLEST SYSTEM?

2 ontics:

- Canonical set is 1 question (is the ontic 1 ?) → knowledge balance impossible, cannot have answer to ½ of a question

Clear that minimum number of questions possible in any canonical set is 2 for knowledge balance to hold → 4 ontics

- One possible canonical set: (is the ontic either 1 or 2?), (is the ontic either 1 or 3?), fully specifies ontic

YY → 1, YN → 2, NY →3, NN →4

SPEKKENS TOY MODEL: SINGLE SYSTEM

4 ontics: knowledge balance means 1 question of the 2 is answered → epistemic state of maximal knowledge reflects fact that ontic is either 1 of 2 states

Epistemic states of maximal knowledge ("v" : disjunction, read as "or")


1 v 2 ←→ $|0\rangle$


3 v 4 ←→ $|1\rangle$


1 v 3 ←→ $|+\rangle$


2 v 4 ←→ $|-\rangle$


3 v 4 ←→ $|+i\rangle$


1 v 4 ←→ $|-i\rangle$

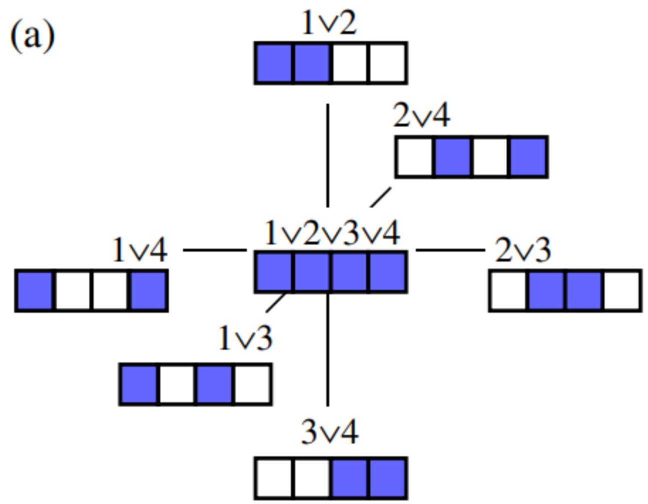
Only one epistemic state with less than maximal knowledge (both questions unanswered)


1 v 2 v 3 v 4 ←→ $\frac{1}{2}I$

SPEKKENS TOY MODEL: ORTHOGONALITY

Ontics consistent w/ epistemic form ontic support (ex: O.S. of 1 v 2 = {1,2})

Intersection of O.S. for pair of epistemics ←→inner product in QM



If union of O.S. for pair of epistemics forms O.S. of a valid epistemic, can combine epistemics through a **convex combo:**
(1 v 2) $+_{cx}$ (3 v 4) = 1 v 2 v 3 v 4
(1 v 2) $+_{cx}$ (1 v 3) = undefined

Mixed state: can be obtained by $+_{cx}$ of distinct epistemic pairs (1 v 2 v 3 v 4)
Epistemics which cannot be obtained by above are pure states
Analogous to QM

SPEKKENS TOY MODEL: SUPERPOSITIONS

Consider the possible binary operations that could combine two disjoint (no shared O.S) epistemics (a v b) and (c v d). 4 possibilities:

1. (a v b) $+_1$ (c v d) = a v c
2. (a v b) $+_2$ (c v d) = b v d
3. (a v b) $+_3$ (c v d) = b v c
4. (a v b) $+_4$ (c v d) = b v d

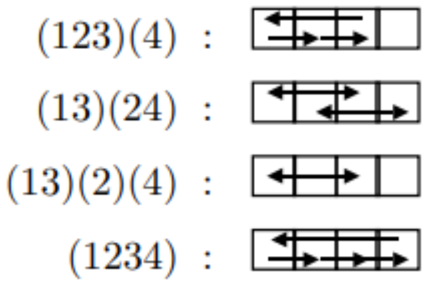
These operations are analogous to superpositions of quantum states with equal weights and relative phases defined by the binary operation ($+_1 = 0,\ +_2 = \pi,\ +_3 = \frac{\pi}{2},\ +_4 = \frac{3\pi}{2}$). For example:

(1 v 2) $+_1$ (3 v 4) = 1 v 3 $\leftrightarrow$ $\frac{1}{\sqrt{2}}(|0\rangle + |1\rangle) = |+\rangle$

Not exactly QM: Superposition not defined for arbitrary pair of states. No continuum of superpositions.

SPEKKENS TOY MODEL: TRANSFORMATIONS

Toy model transformations are 1:1 maps, sets of permutations of ontics
Seen as rotations/reflections on “Bloch sphere”, corresponding to unitaries/antiunitaries in QM



4! Possible permutations

QM: Only unitaries allowed, antiunitaries do not go over I in continuous time (Wigner’s theorem)

Toy model: discrete transformations = no constraint on antiunitaries

SPEKKENS TOY MODEL: NO UNIVERSAL STATE INVERTER

First example of a quantum effect recreated by toy theory

QM: transformation that maps every pure state to orthogonal state is not unitary and therefore cannot be physically implemented

Analogous task in toy theory: map every pure epistemic to disjoint epistemic

1 v 2 ←→ 3 v 4

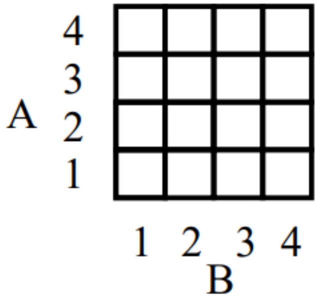
1 v 3 ←→ 2 v 4

2 v 3 ←→ 1 v 4

But first two lines together imply individual transformations 1 ←→ 4, 2←→3, contradiction with third line

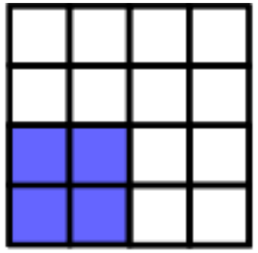
Not a possible permutation

SPEKKENS TOY MODEL: PAIR OF SYSTEMS

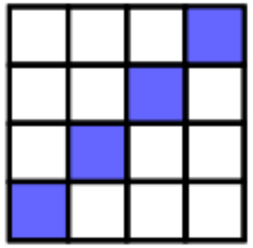


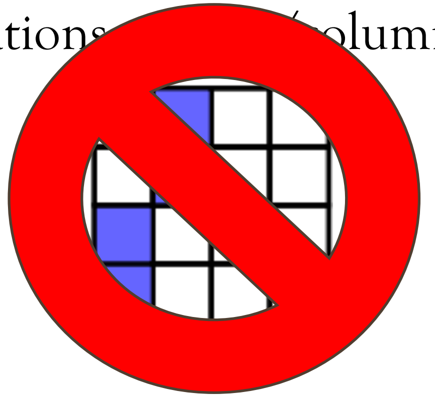
Individual system and composite sytems must both satisfy knowledge balance
4 questions in canonical set for composite system: no more than 2 question can be answered, max. knowledge epistemic made of 4 ontics

Only 2 epistemics satisfy above conditions (up to permutations … olumns among themselves)

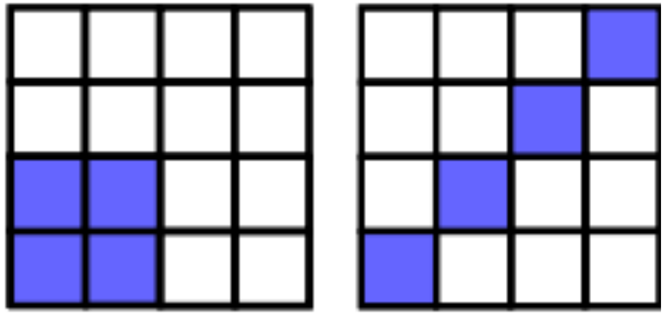


(1 v 2) · (1 v 2), read "·" as "and"





SPEKKENS TOY MODEL: PRODUCT STATES, ENTANGLED STATES



Analogous to product states and entangled states, respectively
Knowledge of individual systems vs relation b/n systems

Product state (1 v 2) · (1 v 2) = (1 · 1) v (1 · 2) v (2 · 1) v (2 · 2)
Measure A with {1 v 3, 2 v 4} → 1 v 3
Post measurement state (1 v 3) · (1 v 2), only marginal for A is updated

Entangled state (1 · 1) v (2 · 2) v (3 · 3) v (4 · 4) (Note cannot be separated into form A · B)
Marginal for each subsystem is maximally mixed 1 v 2 v 3 v 4
Measure A with {1 v 3, 2 v 4} → 1 v 3
Post measurement state (1 v 3) · (1 v 3) : collapses to product state

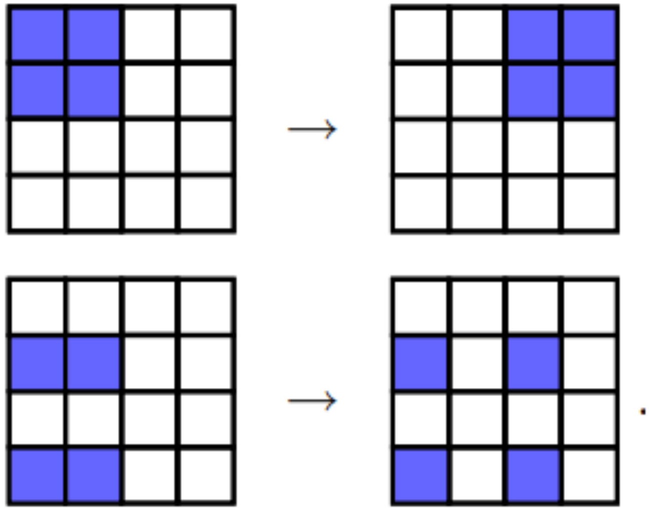
SPEKKENS TOY MODEL: NO CLONING

QM: want $|a\rangle|0\rangle \rightarrow |a\rangle|a\rangle$ for arbitrary $|a\rangle$
Assume $|a\rangle$ is either $|1\rangle$ or $|+\rangle$, then want $|10\rangle \rightarrow |11\rangle$, $|{+0}\rangle \rightarrow |{+}\,{+}\rangle$
Initial overlap $|\langle 10|{+0}\rangle|^2 = \frac{1}{2}$, final overlap $|\langle 11|+ +\rangle|^2 = \frac{1}{4}$
Cannot be unitary map

Toy theory: want (a v b) · (c v d) → (a v b) · (a v b)

Assume (a v b) is either (3 v 4) or (1 v 3)
then want (3 v 4) · (1 v 2) → (3 v 4) · (3 v 4),
and (1 v 3) · (1 v 2) → (1 v 3) · (1 v 3)

Initial overlap: 2/4, final overlap: 1/4
Permutation cannot change # places epistemics overlap



SPEKKENS TOY MODEL: FAILURES

Contextuality/Bell violations : toy theory is locally real and noncontextual. KS and Bell theorems prove that these *cannot* recreate QM, therefore nature of ontic states in QM must be different than toy theory

No continuum of states, measurements, or transformations. Would require continuum of ontics, but knowledge balance would then imply that you could encode an infinite number of bits

Convex combination and coherent superposition are separate operations, not defined for arbitrary pair of epistemic states like in QM

CONCLUSIONS

Knowledge balance principle is purely an information theoretic idea with no physics involved (assuming "physics" concerns only what is ontic). Therefore ideas presented in toy theory have nothing to do with physics if one takes epistemic standpoint.

Knowledge balance principle and epistemics seem to capture many phenomena, is it possible to derive knowledge balance from physical principle governing interactions between systems?

If quantum states are indeed like states of knowledge, what are the corresponding states of reality?

Is there a 2nd principle which can capture missing quantum phenomena? Best start is to try to capture contextuality/Bell inequality violations

Shows that "distillation" of information theoretic ideas from QM, leaving behind pure physics, is possible!

REFERENCES

[1] C. A. Fuchs, “Quantum Mechanics as Quantum Information (and only a little more)”

[2] R. W. Spekkens, “Evidence for the epistemic view of quantum states: A toy theory”

SPEKKENS TOY MODEL: MEASUREMENTS

Reproducible measurement = same outcome after repeated on system: epistemic after measurement must rule out all other ontics inconsistent with measurement outcome

Must satisfy knowledge balance: for 4 ontics, can only determine if ontic is 1 of 2 states

Sets of Y/N questions partitioning 4 ontics into 2 ontics (min allowed by knowledge balance)
{1 v 2, 3 v 4}, {1 v 3, 2 v 4}, {1 v 4, 2 v 3}
Analogous to Z, X, Y basis measurements

If epistemic has O.S. inside O.S. of measurement outcome, that outcome is certain
Otherwise outcome not determined by initial epistemic

SPEKKENS TOY MODEL: MEASUREMENT UPDATE RULE

Assume initial epistemic 1 v 2, measurement {1 v 3, 2 v 4} performed with measurement result 1 v 3
Can you determine the initial ontic?

Yes! Measurement outcome and initial state tell you initial ontic must have been 1.
But wait, doesn't this violate the knowledge balance principle?

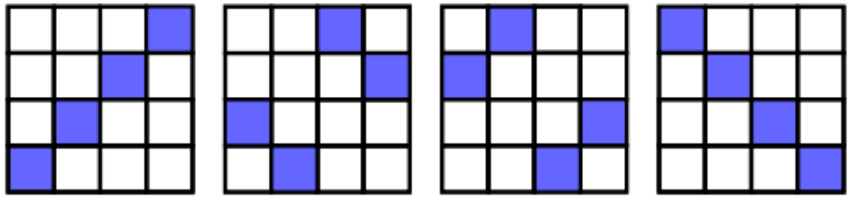
If measurement causes disturbance to system, so that post-meas. epistemic is 1 v 3, not just 1, then knowledge balance not violated

Though information about initial state is gained, measurement disturbs system so that O.S. of post-measurement state=O.S of measurement outcome
Analogous to QM wavefunction collapse to eigenvector associated with measurement outcome

SPEKKENS TOY MODEL: DENSE CODING

QM: sending 1 qubit communicates 1 bit of information, but…
sharing 2 qubit Bell state allows Alice and Bob to communicate 2 bits after Alice implements 1 of 4 transformations to same or other Bell states, then sends her qubit to Bob

Toy theory:
Alice and Bob share "entangled" epistemic, Alice encodes 1 of 4 messages through permutations to same or other entangled epistemics



Can be distinguished through joint measurement if Alice sends her system to Bob

SPEKKENS TOY MODEL: TRIPLET SYSTEMS

4 * 4 * 4 = 64 ontics
2^6=64 → 6 questions in canonical set
Only 3 questions can be answered = 8 ontics in epistemic of maximal knowledge

3 types of pure epistemics

1. No correlations → product states
2. Correlation between 2 systems → (Bell state) ⊗ (pure state)
3. Correlation between 3 systems → GHZ state

SPEKKENS TOY MODEL: MONOGAMY OF PURE ENTANGLEMENT

QM: if individual system is maximally entangled with another system, it cannot be entangled with any others!

Toy theory: suppose A, B, C are perfectly correlated, giving epistemic of the form
$(1 \cdot 1 \cdot 1) \vee (2 \cdot 2 \cdot 2) \vee (3 \cdot 3 \cdot 3) \vee (4 \cdot 4 \cdot 4)$

Contains 4 ontics, violating knowledge balance of composite system which requires a minimum of 8 ontics per epistemic