Title: The Minimal Modal Interpretation of Quantum Theory

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Abstract: A persistent mystery of quantum theory is whether it admits an interpretation that is realist, self-consistent, model-independent, and unextravagant in the sense of featuring neither multiple worlds nor pilot waves. In this talk, I will present a new interpretation of quantum theory -- called the minimal modal interpretation (MMI) -- that aims to meet these conditions while also hewing closely to the basic structure of the theory in its widely accepted form. The MMI asserts that quantum systems -- whether closed or open -- have actual states that evolve along kinematical trajectories through their state spaces, and that those trajectories are governed by specific (if approximate) dynamical rules determined by a general new class of conditional probabilities, and in a manner that differs significantly from the de Broglie-Bohm formulation. The MMI is axiomatically parsimonious, leaves the usual dynamical content of quantum theory essentially intact, and includes only metaphysical entities that are either already a standard part of quantum theory or that have counterparts in classical physics. I will also address a number of important issues and implicit assumptions in the foundations community that I believe merit reconsideration and re-evaluation going forward.

Outline

1. Introduction
   - Basic Features
   - Why a New Interpretation?
   - Why Not Instrumentalism?
2. Our Interpretation
   - Motivation from Classical Physics
   - Traditional Formulation of Quantum Case
   - Our Picture
3. Detailed Treatment
   - Minimal Modal Interpretation (MMI)
   - Classical Realism
   - Classical vs. Quantum Realism
   - Quantum Conditional Probabilities
4. Conclusion
   - Summary

Basic Features

- New realist interpretation → goes beyond instrumentalism
- Standard formalism → based on density matrices, dynamics intact
- Definite measurement outcomes → "one world" interpretation
- Quantum trajectories → even for improper mixtures
- Model independent → encompasses all systems (relativistic or not)
- No exotic ingredients → metaphysically minimal (only objects in traditional quantum or with classical parallels)

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VONNEGUT LIST

Source: Thomas Fuchs

- Highlight general points *transcending* our interpretation...
  - ...but helped *motivate* it
- Any interpretation should be expected to address/explain them

STATES AND OBSERVERS

- Ultimate meaning of *state vector* of system? $|\Psi\rangle$?
  - Represents experimenter's knowledge?
  - Objective probability distribution?
    - Trouble with PBR no-go theorem
  - Irreducible ingredient of reality?
    - Like state of classical system?
- What constitutes *observer*?
  - Talk about state of observer within formalism?

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$$|\Psi\rangle \ ?$$

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Pure State Problem

- No realistic system ever perfectly free of external entanglements, or truly describable by state vector!
- Apparent breakdown in popular depiction of quantum theory
  - Every particle described by specific wave function in 3D space?
- No-collapse interpretations often presume existence of maximal closed system in exactly pure state evolving unitarily
  - "Universal wave function" (e. g., dBB, MWI)
  - Safe assumption given possibility of eternal inflation?
  - Without prior assumption of linear CPT dynamics, not generally possible to embed evolving quantum system in universal wave function
- *Our interpretation*: no need for these assumptions

Instrumentalism in General

Source: Les Chatfield

- Ingredients: system, agent, measurements, outcomes, outcome probabilities forming a distribution
- Basic framework:
  - Probability distribution evolves according to some dynamical rule
    - e. g., Markov process, Liouville equation, Von Neumann equation
  - Agent (?) performs measurement (?) and obtains some outcome
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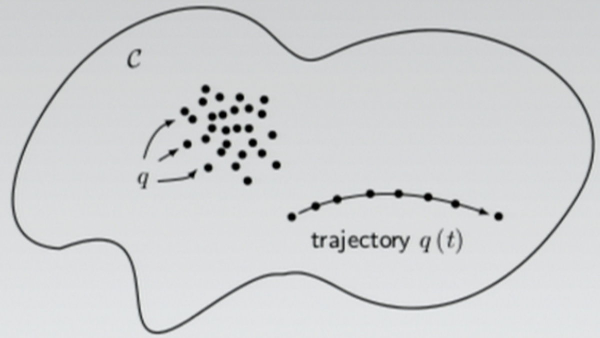
    - e. g., Bayesian update, Von Neumann-Lüders rule

Shuffling Around the Mysteries

- Instrumentalism incomplete
- Replacing "observers" and "Heisenberg cut" with "agents" not progress → just shuffles around the mysteries!
  - Physical requirements for constituting an agent?
  - What counts as an agent? People? (Half-awake/sleeping/comatose people?) Monkeys? Dogs? Ants? Paramecia? (Nano)robots? Why?
- Physical requirements for constituting a measurement?
- Does system have some underlying "ontic" state? (Does agent?)
- Probabilities of outcomes, also probabilities of underlying ontic states?

Motivation from Classical Physics

- General theoretical structure of classical physics:
  - Classical system has specific *ontic state* in config space
  - Ontic state evolves via some (possibly stochastic) dynamical rule



- Dynamical rule for system's underlying ontic state:
  - Exists even if ontic state beneath evolving probability distribution (*epistemic state*) on config space
  - Consistent with *overall* evolution of epistemic state
    - Epistemic dynamics = probabilistic ensemble over ontic dynamics
- *Our interpretation:* seek a similar picture for quantum theory!

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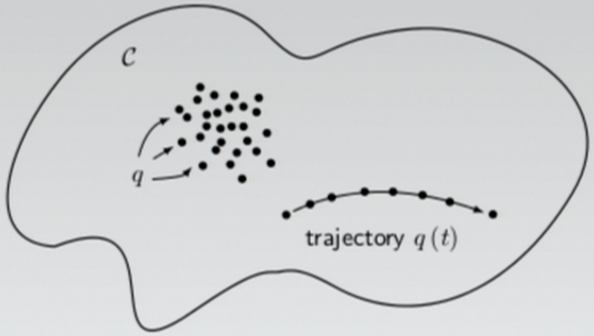

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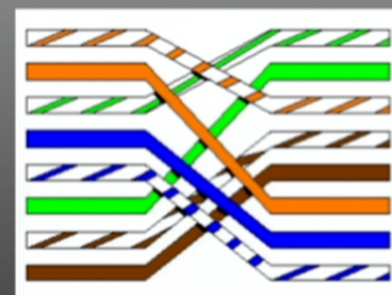
Insufficiency of Epistemic Dynamics

- Without dynamical rule for system's underlying ontic state itself:
  - Ontic state free to fluctuate drastically/discontinuously between macroscopically distinct configurations with appropriate frequency ratios



Source: learn44.com

- Any realist interpretation—including psi-epistemic—that fails to specify ontic dynamics is exposed!
  - Hidden variables need hidden dynamics!
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  - "Smoothness condition" for physical configuration over time

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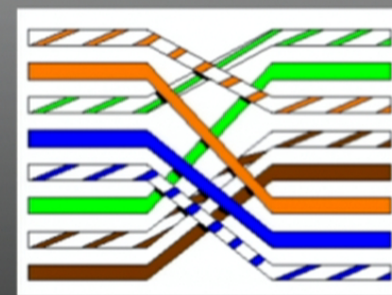

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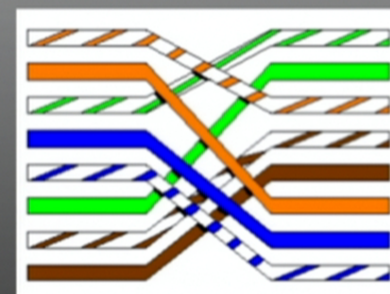

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  - Hidden variables need hidden dynamics!
- *Our interpretation*: provides ontic dynamics
  - "Smoothness condition" for physical configuration over time

Our Picture

Source: Lucie Winsky

- Systems (closed *or* open) have actual ontic states that evolve along kinematical trajectories through their state spaces
- Those trajectories are governed by specific (if approximate/emergent) dynamical rules

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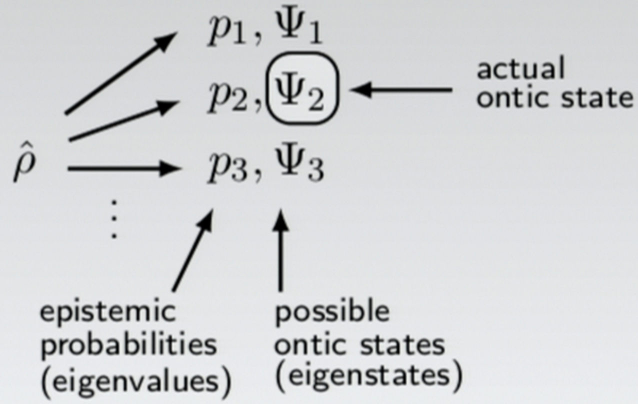
Minimal Modal Interpretation (MMI): Concept Summary

- Type of *modal interpretation*
- Given "objective" density matrix
  - Eigenstates = possible, mutually exclusive ontic states
    - Sample space manifestly *contextual*!
  - Eigenvalues = "objective" epistemic probabilities that one *possible* ontic state is *actual* ontic state



- New general class of quantum conditional probabilities to sew together ontologies and give dynamical rules

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- Given "objective" density matrix arising solely via entanglement:
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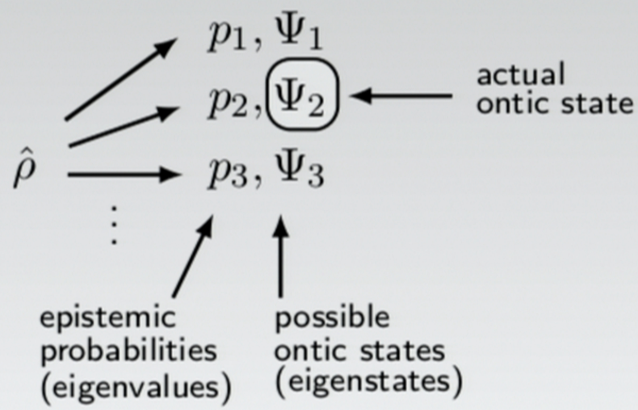

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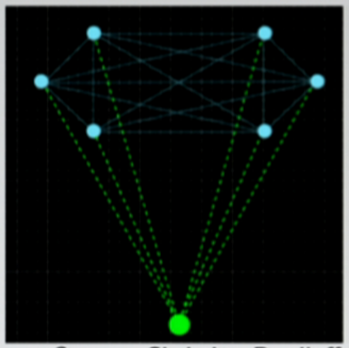
Hidden Variables?



Source: Christine Daniloff

- To extent that have hidden variables, just our ontic states
  - But on same footing as both *traditional quantum* states and *classical ontic* states
  - *Irreducibility* → our ontic states *not themselves* epistemic probability distributions over deeper level of hidden variables
- By contrast, dBB separates *state vector* from *ontic states/hidden variables* so that former is pilot wave for latter
- *Our interpretation:* unifies the two

Classical Realism in General

- Ingredients: system, ontic states from some configuration space, epistemic probabilities forming distribution
- Basic framework:
  - Ontic state evolves according to (possibly stochastic) dynamical rule
    - e. g., Markov process, Newton's second law, Maxwell equations
  - System may hide information about ontic state from outside world
    - Epistemic probability distribution (epistemic state) on config space
  - Epistemic evolution *compatible* with underlying ontic evolution
    - e. g., Markov process, Liouville equation
    - *Compatibility*: epistemic evolution = ensemble avg of ontic evolution
    - Tricky to implement in quantum theory $\rightarrow$ gives us strong constraints!

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Unstated Assumptions of Realism

- Numerous unstated, crucial assumptions even in *classical* realism
- Similar sort of trouble with unstated assumptions haunts certain other quantum interpretations
  - e. g., MWI, despite claims, not axiomatically simple or parsimonious!
- *Our interpretation:* when assumptions of classical realism made explicit, we will show they have natural correspondence with postulates of MMI → "quantum realism"

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Classical vs. Quantum Realism (MMI)

- Axiomatic content of MMI has natural correspondence to *often-unstated* ingredients of classical realism

- 1. Ontic states:
  - *Classical* $\rightarrow$ ontic states q represented by elements of configuration space $\mathcal{C}$
  - *Quantum (MMI)* $\rightarrow$ ontic states Ψ represented by elements $|\Psi\rangle$ of Hilbert space $\mathcal{H}$ (up to overall normalization)

Classical vs. Quantum Realism (MMI) (cont.)

- 2. Epistemic states:
  - *Classical* $\to \{(p(q), q)\}_q$, where each $p(q) \in [0,1]$ corresponds to *possible* ontic state q, one of which is system's *actual* ontic state
  - *Quantum (MMI)* $\to \{(p_i, \Psi_i)\}_i$, where each $p_i \in [0,1]$ corresponds to *possible* ontic state Ψ_i, one of which is system's *actual* ontic state
    - Exists correspondence between *objective* epistemic states (i. e., due to entanglement, not subjective classical ignorance) and density matrices:

$$\{(p_i, \Psi_i)\}_i \leftrightarrow \hat{\rho} = \sum_i p_i |\Psi_i\rangle\langle\Psi_i|$$

    - *System-centric ontology*: determined by system's *own* density matrix

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Classical vs. Quantum Realism (MMI) (cont.)

- 3. Relationship between parent-system $W = Q + E$ epistemic states and subsystem Q, E epistemic states:
  - marginalization/partial sum:

$$\{(p_W(w), w)\}_w \implies p_Q(q) \equiv \sum_e p_W(w = (q, e))$$

  - *Quantum (MMI)* $\rightarrow$ Hilbert space $\mathcal{H}_W = \mathcal{H}_Q \otimes \mathcal{H}_E$, and partial trace

$$\{(p_W(w), \Psi_w)\}_w \implies \hat{\rho}_Q \equiv \mathrm{Tr}_E[\hat{\rho}_W] \iff \rho_Q(i, i') \equiv \sum_e \rho_W((i, e), (i', e))$$

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Classical vs. Quantum Realism (MMI) (cont.)

- 4. (a) *Kinematical* relationship between parent-system $W = Q + E$ ontic states and subsystem Q, E ontic states:
  - *Classical* $\rightarrow$ W has ontic state $w = (q, e)$

    $$\implies p_{Q,E|W}\left(i, e \middle| w = (q, e)\right) = 1$$

  - *Quantum (MMI)* $\rightarrow$ (derived from general new class of quantum conditional probabilities)

Classical vs. Quantum Realism (MMI) (cont.)

- 4. (b) *Dynamical* relationship between ontic states of system Q at initial time(s) and ontic states at final time:
  - *Classical* $\rightarrow$ assuming Q has well-defined dynamics, have ontic dynamical mapping:

    $$p_Q(\cdot;t'|(\cdot;t_1),\ldots):\underbrace{(q_1;t_1),\ldots}_{\text{initial data}}\mapsto\underbrace{(q';t')}_{\text{final data}}\mapsto\underbrace{p_Q(q';t'|(q_1;t_1),\ldots)}_{\text{conditional probabilities}},$$

    which lifts to linear epistemic dynamical mapping = ensemble average over ontic dynamical mapping:

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Outline

Linear CPT Dynamics

- *Linear CPT dynamical mappings* widely used in quantum chemistry/information science → *quantum operations/channels*
  - e. g., unitary dynamics for closed systems,
  - [illegible]
  - [illegible] postulate without post-selection)
- Buscemi → linear CPT dynamics ⟺ no backward flow of information into system from environment
  - Both classical and quantum → open subsystems do not generically have linear dynamics!
- *Not* proposing any fundamental modification (e. g., GRW or T violation) to dynamics of quantum theory
  - [illegible]

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  - measurement-induced decoherence ($\approx$Von Neumann-Lüders projection postulate without post-selection)
- Buscemi $\rightarrow$ linear CPT dynamics $\iff$ no backward flow of information into system from environment
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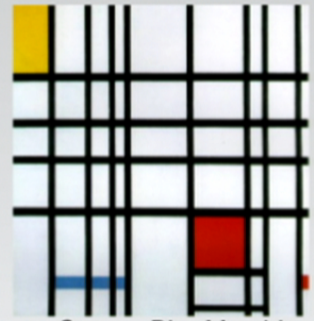
  - Both classical and quantum → open subsystems do not generically have linear dynamics!
- *Not* proposing any fundamental modification (e. g., GRW or T violation) to dynamics of quantum theory
  - Simply accommodating openness of generic meso/macroscopic quantum systems

BASIC SET-UP

- Suppose $W = Q_1 + \cdots + Q_n$ has approximately *linear CPT dynamics* $\mathcal{E}_W^{t' \leftarrow t}[\cdot]$ over given time interval $\Delta t \equiv t' - t \geq 0$:

$$\hat{\rho}_W(t) \mapsto \hat{\rho}_W(t') = \mathcal{E}_W^{t' \leftarrow t}[\hat{\rho}_W(t)]$$



Source: Piet Mondrian

- Linear CPT approximation may break down for arbitrarily short time scales $\Delta t \ll \delta t_W$ relative to some physical characteristic δt_W for W
  - Naturally protects from technical issues involving eigenstate swap

Motivation for Quantum Conditional Probabilities

- Can trivially express epistemic probability $p_{Q_1}(i_1;t')$ for subsystem Q_1 to be in ontic state $\Psi_{Q_1}(i_1;t')$ as
- $p_{Q_1}(i_1;t') = \mathrm{Tr}_{Q_1}\left[\hat{P}_{Q_1}(i_1;t')\,\hat{\rho}_{Q_1}(t')\right]$
- $= \mathrm{Tr}_W\left[\left(\hat{P}_{Q_1}(i_1;t') \otimes \hat{1}_{Q_2} \otimes \cdots \otimes \hat{1}_{Q_n}\right)\hat{\rho}_W(t')\right]$
- $= \mathrm{Tr}_W\left[\left(\hat{P}_{Q_1}(i_1;t') \otimes \hat{1}_{Q_2} \otimes \cdots \otimes \hat{1}_{Q_n}\right)\mathcal{E}_W^{t' \leftarrow t}\left[\hat{\rho}_W(t)\right]\right]$
- $= \sum_w \mathrm{Tr}_W\left[\left(\hat{P}_{Q_1}(i_1;t') \otimes \hat{1}_{Q_2} \otimes \cdots \otimes \hat{1}_{Q_n}\right)\mathcal{E}_W^{t' \leftarrow t}\left[\hat{P}_W(w;t)\right]\right] p_W(w;t)$
- $= \sum_{i_2,\ldots,i_n,w} \underbrace{\mathrm{Tr}_W\left[\left(\hat{P}_{Q_1}(i_1;t') \otimes \hat{P}_{Q_2}(i_2;t') \otimes \cdots \otimes \hat{P}_{Q_n}(i_n;t')\right)\mathcal{E}_W^{t' \leftarrow t}\left[\hat{P}_W(w;t)\right]\right]}_{\text{looks like conditional probability for Bayesian propagation rule}} p_W(w;t)$

MOTIVATION FOR QUANTUM CONDITIONAL PROBABILITIES

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- $= \mathrm{Tr}_{W}\left[\left(\hat{P}_{Q_1}(i_1;t') \otimes \hat{1}_{Q_2} \otimes \cdots \otimes \hat{1}_{Q_n}\right)\hat{\rho}_{W}(t')\right]$
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Motivation for Quantum Conditional Probabilities

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Definition of Quantum Conditional Probabilities

- Motivates defining *quantum conditional probabilities* relating possible ontic states of subsystems $Q_1, \ldots, Q_n$ to those of parent system $W = Q_1 + \cdots + Q_n$ by

$$p_{Q_1,\ldots,Q_n|W}(i_1,\ldots,i_n;t'|w;t) \equiv \mathrm{Tr}_W\Big[\big(\hat{P}_{Q_1}(i_1;t')\otimes\cdots\otimes\hat{P}_{Q_n}(i_n;t')\big)\mathcal{E}_W^{t'\leftarrow t}\big[\hat{P}_W(w;t)\big]\Big]$$
$$\sim \mathrm{Tr}\Big[\hat{P}_{i_1}(t')\cdots\hat{P}_{i_n}(t')\mathcal{E}\big[\hat{P}_w(t)\big]\Big]$$

- In contrast to Born rule:
  - *Only* defined in terms of eigenprojectors representing system's possible ontic states—*not* in terms of *generic* state vectors
  - $\mathcal{E}_W^{t'\leftarrow t}[\cdot]$ acts to "parallel transport" $\hat{P}_W(w;t)$ from t to t' before

MIRACULOUS PROPERTIES

- Real numbers between 0 and 1:

$$p_{Q_1,\ldots,Q_n|W}\left(i_1,\ldots,i_n;t'|w;t\right)\in[0,1]$$

- Sum to 1 on first arguments:

$$\sum_{i_1,\ldots,i_n} p_{Q_1,\ldots,Q_n|W}\left(i_1,\ldots,i_n;t'|w;t\right)=1$$

- Give Bayesian propagation rule:

$$\sum_{i_1,\ldots(\text{no } i_\alpha)\ldots,i_n,w} p_{Q_1,\ldots,Q_n|W}\left(i_1,\ldots,i_n;t'|w;t\right)p_W\left(w;t\right)=p_{Q_\alpha}\left(i_\alpha;t'\right)$$

- Trivialize to deterministic result for unitary evolution:

$$p_{Q|Q}\left(i;t'|j;t\right)\equiv \mathrm{Tr}_Q\left[\hat{P}_Q\left(i;t'\right)\hat{P}_Q\left(j;t'\right)\right]=\delta_{ij}=\begin{cases}1 & \text{for } i=j,\\ 0 & \text{for } i\neq j\end{cases}$$

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Interpretive Step

- Mysterious quantities $p_{Q_1,\ldots,Q_n|W}\left(i_1,\ldots,i_n;t'|w;t\right)$ satisfying all these miraculous properties have existed in *formalism* all along

- *Our interpretation:* call them probabilities!

Knightian Uncertainty

- Possible concern: not every conceivable conditional probability definable in this framework!
  - e. g., *multiple* final times, *two* initial ontic states at *two* times, *non-disjoint* subsystems, *multiple* parent systems
  - Certain hypothetical statements for ontic states don't admit generally well-defined probabilities, despite lying behind veil of uncertainty
- Physicists often use "uncertainty" and "probabilistic" interchangeably, but not economists (c.f., Frank Knight, 1921)
- But no *a priori* reason why all uncertainty (especially unobservable!) should be constrained to obey long-run probability frequency-ratios!
  - No obvious logical reason why all outcome frequencies must "tend to" something or "settle down"
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Kinematical and Dynamical Smoothing

- Special cases $\rightarrow$ quantum conditional probabilities provide missing ingredients 4. (a), (b) in correspondence to classical realism

- 4. (a) *Kinematical* smoothing relationship between possible ontic states of $Q_1, \ldots, Q_n$ to those of $W = Q_1 + \cdots + Q_n$ at any *single* instantaneous moment in time

- 4. (b) *Dynamical* smoothing relationship between possible ontic states of *single* system Q *over time*
    - Formula coincides with Esposito-Mukamel *quantum transition rates* from unravelling, Leifer-Spekkens *conditional states*
    - Lifts to linear epistemic dynamical mapping $\Leftrightarrow$ ensemble average over

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Von Neumann Measurements, Born Rule, and Error-Entropy Bound

- Von Neumann measurements yield expected results for *Born-rule* outcome probabilities
- Intriguing $\exp(-S) \ll 1$ deviations from Born rule, where $S \approx$combined entropy of measurement device and subject system
- Similar *error-entropy bound* exists even for classical measurements: for measurement device with accuracy of n bits, correlational entropy with subject system grows by at least $\Delta S \sim \log n \leq S$, so

$$\text{minimum error} \sim 1/n \sim e^{-\Delta S} \geq e^{-S}$$

- Recent circumstantial evidence of similar error-entropy bound from black-hole thermodynamics (e. g., Maldacena)

Locality and Lorentz Invariance

- EPR/Bell + GHZ/Mermin:
  - Ontic dynamics non-local (can pinpoint where non-locally appears!), but fully in keeping with no-communication theorem
  - No observable violations of Lorentz invariance

Source: geekpause.com

- Unlike dBB, no preferred Lorentz frame selected
  - Evade no-go theorems of Vermaas, Dickson/Clifton, Hardy, Myrvold
  - Dickson/Clifton point out inadmissible assumptions about ontic property assignments in Hardy
  - Vermaas, Dickson/Clifton, Myrvold assume existence of joint epistemic probability distributions that do not exist in MMI

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Summary

Source: rhizome.org

- Presented new realist interpretation of quantum theory, called minimal modal interpretation (MMI):
  - Systems have ontic states
  - that evolve along trajectories in their Hilbert spaces
  - according to approximate/emergent ontic dynamical rules
- Introduced new general class of conditional probabilities that play central role in defining kinematical and dynamical structure of MMI
- Thank you!