The Measurement Problem is a Feature, Not a Bug – Quantum Mechanics on an Informational, or (Neo-)Bohrian, Approach

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The Quantum Reconstruction Program and Beyond,
University of Graz, Austria

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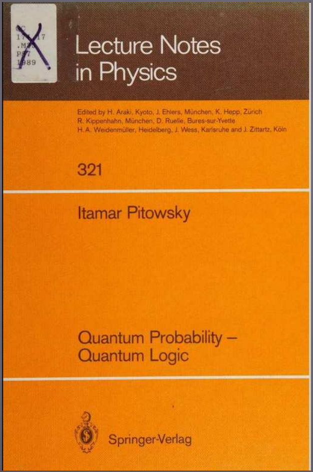
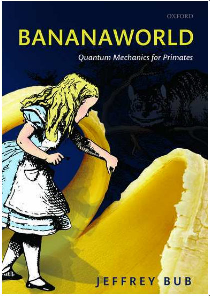
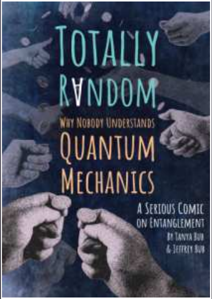
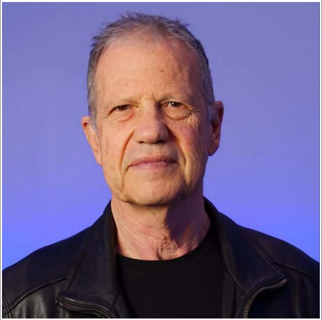
Which informational interpretation?

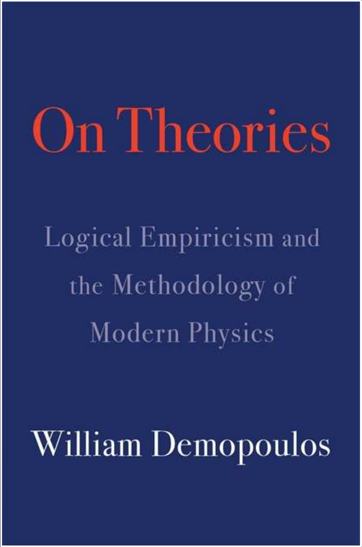

Lecture Notes in Physics
Edited by H. Araki, Kyoto, J. Ehlers, München, K. Hepp, Zürich
R. Kippenhahn, München, D. Ruelle, Bures-sur-Yvette
H. A. Weidenmüller, Heidelberg, J. Wess, Karlsruhe and J. Zittartz, Köln
321
Itamar Pitowsky
Quantum Probability –
Quantum Logic
Springer-Verlag

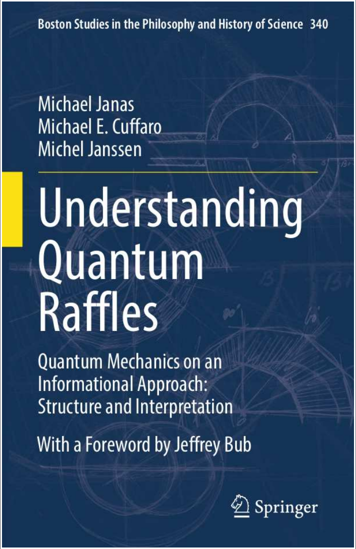




(with Tanya Bub)




On Theories
Logical Empiricism and
the Methodology of
Modern Physics
William Demopoulos

The "Three Mikes"
(at Al's Breakfast in Dinkytown)

Other (we think) similar views:

- Časlav Brukner, Anton Zeilinger

Other more distantly related views:

- Pragmatist interpretation (Richard Healey), QBism (Chris Fuchs, Rüdiger Schack, and others)

Other even more distantly related views:

- Relational interpretation (Carlo Rovelli; Emily Adlam and Rovelli)

What does "(neo-)" in "(neo-)Bohrian" mean?

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- Our view is a (neo-)Bohrian position in the sense of amounting to a defense of Bohr—or at least what we take to be essential about Bohr’s view—and an elaboration of how to make sense of what we have learned about the world since Bell in (neo-)Bohrian terms.

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- That said, the intention isn’t to make a contribution to the historical scholarship on Bohr. So if you agree that the view captures what is essential to Bohr’s view, you may call it Bohrian, otherwise you may feel free to call it neo-Bohrian. (Ultimately, as a group, such labels not really our concern.)

Niels Bohr to Paul Dirac, March 24, 1928:

"I quite appreciate your remarks that in dealing with observations we always witness through some permanent effects a choice of nature between the different possibilities. However, it appears to me that the permanency of results of measurements is inherent in the very idea of observation; whether we have to do with marks on a photographic plate or with direct sensations the possibility of some kind of remembrance is of course the necessary condition for making any use of observational results. It appears to me that the permanency of such results is the very essence of the ordinary causal space-time description. This seems to me so clear that I have not made a special point of it in my article (= the complementarity paper). . . ."

Niels Bohr to Paul Dirac, March 24, 1928 (cont'd):[1]

"... What has been in my mind above all was the endeavour to represent the statistical quantum theoretical description as a natural generalisation of the ordinary causal description and to analyze the reasons why such phrases like a choice of nature present themselves in the description of the actual situation. In this respect it appears to me that the emphasis on the subjective character of the idea of observation is essential. Indeed I believe that the contrast between this idea and the classical idea of isolated objects is decisive for the limitation which characterises the use of all classical concepts in the quantum theory. Especially in relation with the transformation theory the situation may, I think, be described by saying that any such concepts can be used unaltered if only due regard is taken to the unavoidable feature of complementarity."

[1] In Jørgen Kalckar (ed.), *Niels Bohr, Collected Works, Volume 6*, North-Holland/Elsevier, 1985, pp. 45–46.

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What are “observational results”?

What are “observational results”? E.g., Newton’s phenomena:[2]

1. “The circumjovial planets, by radii drawn to the center of Jupiter, describe areas proportional to the times, and their periodic times—the fixed stars being at rest—are as the $^3/_2$ powers of their distances from that center.”
2. “The circumsaturnian planets ...”
3. “The orbits of the five primary planets—Mercury, Venus, Mars, Jupiter, and Saturn—encircle the sun.”
4. “The periodic times of the five primary planets and of either the sun about the earth or the earth about the sun—the fixed stars being at rest—are as the $^3/_2$ powers of their mean distances from the sun.”
5. “The primary planets, by radii drawn to the earth, describe areas in no way proportional to the times but, by radii drawn to the sun, traverse areas proportional to the times.”
6. “The moon, by a radius drawn to the center of the earth, describes areas proportional to the times.”

Upshot: *Physical phenomena can be mathematised*.

[2] Isaac Newton, *Mathematical Principles of Natural Philosophy*, I. B. Cohen (ed.), Berkely and Los Angeles: University of California Press, 1999 [1687], pp. 797–801.

George Boole's "Conditions of Possible Experience" (of statistical data)

"When satisfied they indicate that the data *may* have, when not satisfied they indicate that the data *cannot* have resulted from an actual observation."[3]

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- Given the rational numbers $p_1, \ldots, p_n$, representing the relative frequencies of n (logically connected) events $E_1, \ldots, E_n$:
- What are the necessary and sufficient conditions under which the p_i can be realised as probabilities corresponding to the (logically connected) E_i in some probability space?

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General algorithm

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- Write down the corresponding (propositional) truth table.

E_1	E_2	$\dots$	E_n
0	0	$\dots$	1
0	1	$\dots$	0
$\vdots$	$\vdots$	$\vdots$	$\vdots$

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- Given the logically connected events $E_1, \ldots, E_n$,
- Write down the corresponding (propositional) truth table.
- Associate each row with a vector of (extremal) probabilities $(p_1, \ldots, p_n)$.

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- Take the convex hull of these vectors to yield a polytope.

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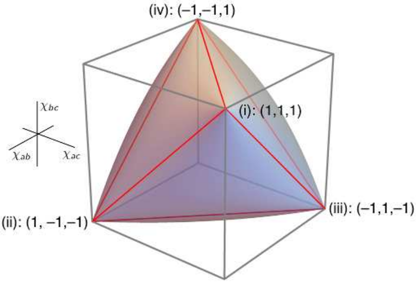
Special case: Bell inequalities (see Pitowsky 1994, 103–104)



General (nonlinear) constraint on the correlations between three balanced random variables:[4]

$$1 - \rho_{XY}^2 - \rho_{XZ}^2 - \rho_{YZ}^2 + 2\,\rho_{XY}\,\rho_{XZ}\,\rho_{YZ} \geq 0, \qquad (1)$$

where $\rho_{XY} = \frac{\langle XY \rangle}{\sigma_X\,\sigma_Y}$ is the *Pearson correlation coefficient* for two balanced random variables X and Y and σ_X, σ_Y are the standard deviations of X and Y.

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Derivation of Eq. (1) relies on the fact that:

$$\left\langle \left(v_1 \frac{X}{\sigma_X} + v_2 \frac{Y}{\sigma_Y} + v_3 \frac{Z}{\sigma_Z} \right)^2 \right\rangle \geq 0. \tag{2}$$

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Modelling this relation in a local-hidden variables theory (LHVT):

- Requires a joint probability distribution over the values of X, Y, Z.

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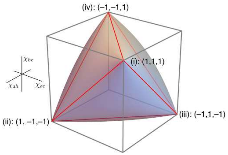
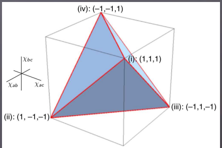
- Saturation of the elliptope only as # outcomes per variable $\rightarrow \infty$.

General elliptope:



Classical tetrahedron (2 values per ticket):



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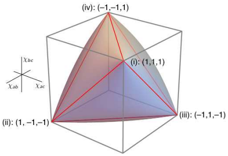
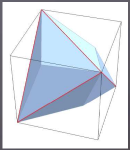


Classical polyhedron (3 values per ticket):



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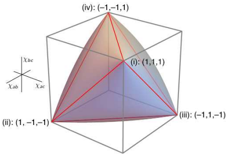
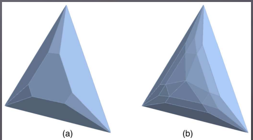


Classical polyhedra (4 and 5 values):



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Modelling this relation in quantum mechanics (QM):

- Saturation of the elliptope for all values of spin.
- Reason: In QM we can assign a value to a sum without assigning values to the summands.

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Assigning a value to a sum without assigning values to the summands:

- Not possible in classical theory.
- The kinematics of QM are less restrictive (consider the operator $\hat{S} \equiv \hat{S}_a + \hat{S}_b + \hat{S}_c$).[5]
- Kinematical constraints (broad sense):[6] constraints imposed by a theoretical framework on our physical description of a system independently of the specifics of its dynamics.

[5] See von Neumann, J., "Wahrscheinlichkeitstheoretischer Aufbau der Quantenmechanik," *Königliche Gesellschaft der Wissenschaften zu Göttingen. Mathematisch-physikalische Klasse. Nachrichten*, p. 249, n. 9.

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In essence, this is what we mean when we claim that: "QM is all about information" / "QM is all about probabilities."

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- This is a claim about where the conceptual novelty of QM lies:[7]
  - In the way that the kinematical constraints of QM constrain probability assignments.
- The slogan also conveys the idea that QM is a framework[8] that can in principle be applied to any type of physical system; e.g., computational systems, the fictitious "quantum bananas" of Jeff Bub's *Bananaworld*, the "quoins" of *Totally Random*, and so on.

[7] *Understanding Quantum Raffles*, sec. 6.3; see also Demopoulos, W., *On Theories*, Harvard University Press, 2022, ch. 4.

[8] See: Aaronson, S., *Quantum Computing Since Democritus*, Cambridge University Press, 2013; Nielsen, M. A. and Chuang, I. L., *Quantum Computation and Information*, Cambridge University Press, 2016; Wallace, D., "On the Plurality of Quantum Theories: Quantum Theory as a Framework, and its Implications for the Quantum Measurement Problem," in S. French and J. Saatsi (eds.) *Realism and the Quantum*, Oxford University Press, 2019; *Understanding Quantum Raffles*, chs. 1, 6.

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Further examples of physical problems that seemed to call for dynamical solutions but that were solved simply by appealing to quantum theory's kinematics:[9]

- Accounting for the particle term in Einstein's 1909 formula for energy fluctuations in black-body radiation.
- Accounting for the formula for the electric susceptibility of diatomic gases.
- Accounting for why electron orbits seem to depend on which coordinates you choose to impose the quantization condition.

[9] *Understanding Quantum Raffles*, sec. 6.4.

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- This is simultaneously true of all observables. The state determines the answers to all questions concerning all observables in advance.

$\vec{p}_1$	$\vec{q}_1$	A in Δ_a?	B in Δ_b?	...
$v^1_{p_1}$	$v^1_{q_1}$	N	N	
$v^2_{p_1}$	$v^2_{q_1}$	N	Y	
$v^3_{p_1}$	$v^3_{q_1}$	N	Y	

etc. ...

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In QM, states fail to be truthmakers in two senses:[11]

1. The "big" measurement problem: Specifying $|\psi\rangle$ yields, in general, only the probability that the answer to a given experimental question will take on a given value.
   - Not as much of a departure from classicality as one might think. Conditional on the selection of an observable, observed statistics are describable by a classical probability distribution.

2. The "small" measurement problem: The classical probability distributions associated with individual observables cannot be embedded into a global classical probability distribution over all observables.
   - In QM one can only say that conditional upon inquiring about A, there is a particular probability distribution that one can use to characterise the possible answers to that question.
   - QM's unitary description of a measurement interaction does not, by itself, prefer any one of these (a.k.a. the preferred basis problem in the context of the Everett interpretation).

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Classical mechanics:

- An observable A is represented by $f_A(\omega)$ acting on the phase space of a system.

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How should we construe the wider significance of this?

The "traditional metaphysical picture":

- Dynamical variables like position, momentum, direction of spin, etc. are understood as manifestations of an underlying reality whose properties are such as to give rise to the values of the observable quantities that are revealed in our experiments with physical systems.
    - John S. Bell: "Observables are *made* out of beables."[12]

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  1. Posit further physical quantities over and above what is described by QM that can be so interpreted.
  2. Argue that, at least in principle, all of the (approximately) classical physical possibilities described by a given state vector are realised in some sense (Everett).

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- Instrumentalist, but need not be construed as anti-realist (it depends on what you mean by this!)
  - Cf. Howard Stein: "the issue between realism and instrumentalism seems to me not to be clearly posed; and what I really believe is that between a cogent and enlightened 'realism' and a sophisticated 'instrumentalism' there is no significant difference—no difference that *makes* a difference."[13]

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- The important question, for us, is not whether, but how to assign physical properties to what we take to be the external world.[14]

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[14] *Understanding Quantum Raffles*, pp. 8–10; Cf. Perović, S., *From Data to Quanta – Niels Bohr's Vision of Physics*, University of Chicago Press, p. 118.

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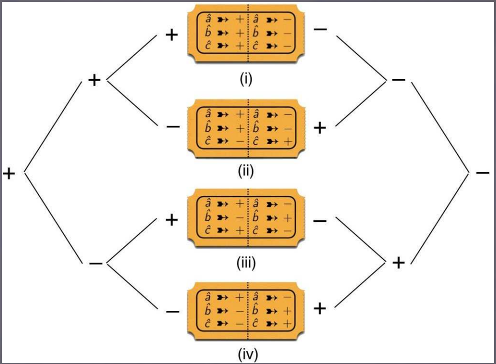

Modelling quantum correlations using raffle tickets.

What we take to be primary, rather, is the empiricist methodology through which we reason from the values revealed in experiments, carried out under precisely specified experimental conditions, to a picture of the world that is anchored in the contextual models one gives of phenomena under the dynamical assumptions characterising each.

For an informational interpreter, in other words, probabilities are (strictly speaking) always defined relative to a given experimental context; and the picture our theories build up of the world is in this sense essentially a contextual picture (which of course can admit of special cases, of which classical theory is one).

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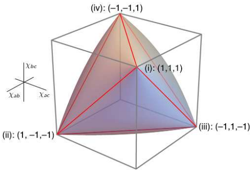
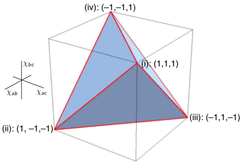


Classical tetrahedron (2 values per ticket):



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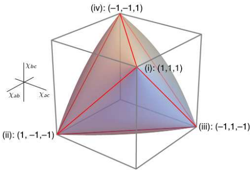

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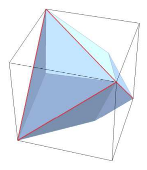

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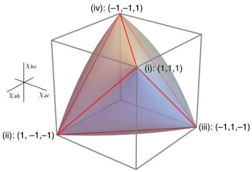
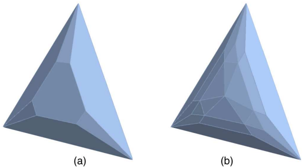


Classical polyhedra (4 and 5 values):



- What is exhibited by the quantum state is, on our view, not, *per se*, a collection of antecedently given properties possessed by a system, but rather the structure of and interdependencies among the (unitarily related) possible ways that one can effectively characterise a system in the context of a physical interaction.

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- Indeed this is no less true of a classical state description (cf. Erik Curiel's characterisation of an "abstract classical system"[15]).

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- The more complex structure of observables related by QM does not similarly invite the inference from the values of observable quantities to the properties of an underlying system in that sense.

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- Moreover, the probability distributions that one can assign in the various measurement contexts associated with a system, on the basis of a given state $|\psi\rangle$, are quantitatively related to one another in a consistent way that is constrained by the kinematical framework of quantum mechanics.

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- Does (b) depend, physically or metaphysically, on the existence of conscious observers?
  - No. Rather: a schematic representation of what (relevantly) constitutes an observer—a classical conditional probability distribution (a.k.a. "Boolean frame")—is being used as a formal tool with which to describe how the various dynamical possibilities ("propensities") that are implicit in the physical world are necessarily related to one another.[16]

[16] Cf. Curiel, E. "Schematizing the Observer and the Epistemic Content of Theories," *Studies in History and Philosophy of Modern Physics*, forthcoming (2022, arXiv:1903.02182v3).

Schematising the observer as a postulate

Howard Stein: "It would ... be impossible to *understand* a theory, as anything but a purely mathematical structure—impossible, that is, to understand a theory *as* a theory of physics—if we had no systematic way to put the theory into connection with observation (or experience)."[17]

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- In the context of classical theory, for all practical purposes, we need to employ a schematic representation of an observer if theoretical claims are to have epistemic content at all.
- On a (neo-)Bohrian understanding of quantum theory, QM should be understood as elevating this insight to the level of a postulate.

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For a (neo-)Bohrian:

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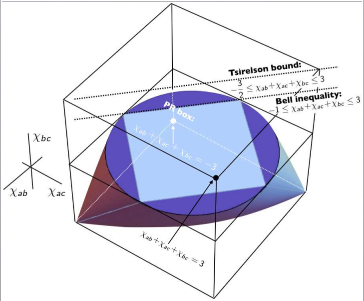

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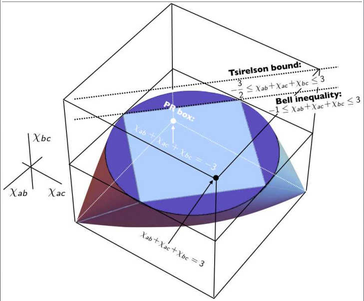

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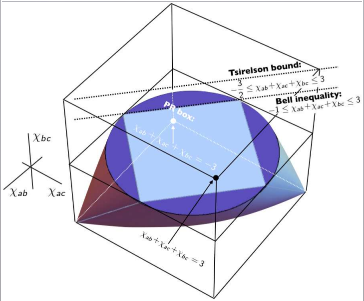

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- QM describes the relations between these in an in general *non-Boolean* way, which amounts to saying that the various probability distributions that we can use to effectively characterise the phenomena associated with commuting sets of observables cannot be embedded consistently into a global probability distribution over the simultaneous values of all observables.

[20] Quoted in Bub, Jeffrey, "Foreword," in *Understanding Quantum Raffles*, *op. cit.*, p. x.

Our view in a nutshell (cont'd):

- Despite this, QM provides, in any given measurement context, a recipe through which one can acquire information concerning a quantum system through interactions with objects whose relevant parameters can—effectively—be described using classical, i.e., *Boolean*, means, as being either "on" or "off" with a certain probability determined by the dynamical properties of the system according to the dynamical model that one constructs of it in that context.

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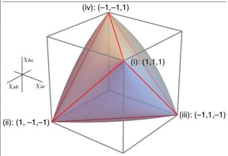
- In other words, QM allows us to do physics in much the same way as we always have.
- But it does not follow from any of this that nature itself must be such as to allow (in a natural way, at any rate) for a globally Boolean description of all aspects of all dynamical phenomena that physics is concerned to describe.[21]

[21] Cf. Pitowsky, 1994, p. 118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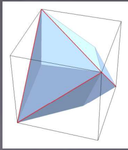

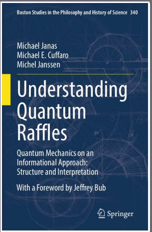
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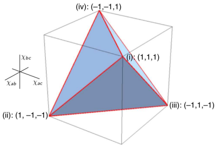
Understanding Quantum Raffles
Quantum Mechanics on an Informational Approach: Structure and Interpretation
With a Foreword by Jeffrey Bub
Springer

Thanks!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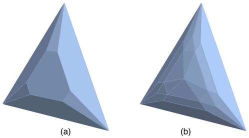
(a)
(b)

Extra slides

$$
\begin{aligned}
|\psi\rangle_{\mathcal{S}} &= \alpha|b_1^+\rangle + \beta|b_1^-\rangle \\
&= \alpha'|b_2^+\rangle + \beta'|b_2^-\rangle.
\end{aligned}
$$

What does this mean on the informational interpretation?

- Coupling the degrees of freedom of $\mathcal{S}$ to those of a further system $\mathcal{M}$ will yield a collection of unitarily-related conditional probability distributions over the possible outcomes of an assessment of $\mathcal{M}$ as described with respect to a particular basis b_m.

"In the treatment of atomic problems, actual calculations are most conveniently carried out with the help of a Schrödinger state function, from which the statistical laws governing observations obtainable under specified conditions can be deduced by definite mathematical operations. It must be recognized, however, that we are here dealing with a purely symbolic procedure, the unambiguous physical interpretation of which in the last resort requires a reference to a complete experimental arrangement."[22]

[22] Bohr, N., "Quantum Physics and Philosophy," in Klibansky, R. (ed.), *Philosophy in the Mid-Century: A Survey*, Firenze: La Nuova Italia Editrice, 1958, pp. 392–393.

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- What's important isn't that a particular system represented by $\mathcal{M}$ actually exists (in the same way that it's inessential for observers to actually exist as long as we can represent them schematically).

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- What's important is the dynamical context that $\mathcal{M}$ represents. It's always possible to imagine a dynamical physical interaction with the empirically accessible degrees of freedom of any physical system—because, conceptually, that is just what we mean when we say that a physical system is empirically accessible—regardless of that system's size.

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- The further question of whether it "really" makes sense to talk about the empirical accessibility of the universe as a whole is a philosophical question.
- But whatever one thinks about this issue, it makes no difference to the basic methodological point that, I want to argue, forms the core of the informational / (neo-)Bohrian view, which is that systems are modelled as open on such an interpretation whenever it makes sense to model a system at all.