A (Neo-)Bohrian Approach to the Foundations of Quantum Mechanics

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Wednesday, June 19, 2024

Workshop on the Work and Legacy of Niels Bohr,
Niels Bohr Institute, Copenhagen, Denmark

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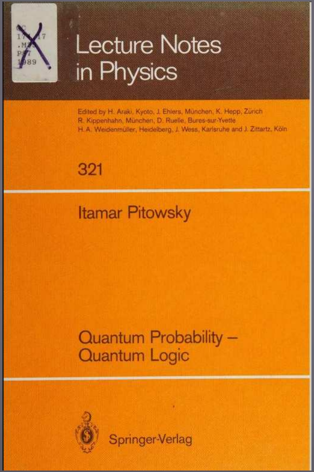
- a.k.a. “information-theoretic,” “informational,” etc.
- However, many approaches to interpretation have gone by that name. Thus, I mean more specifically . . .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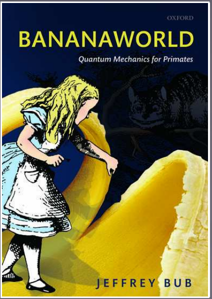
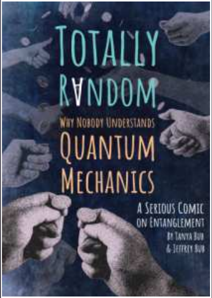
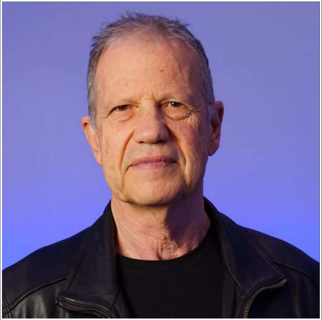
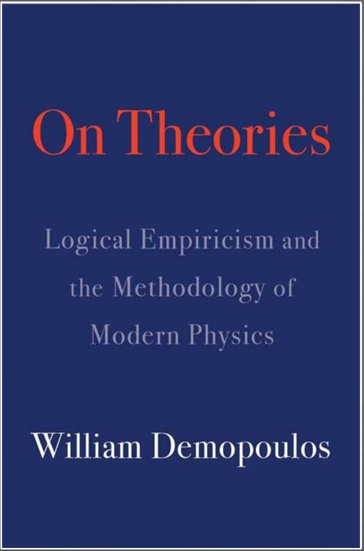
321
Itamar Pitowsky
Quantum Probability – Quantum Logic
Springer-Verlag

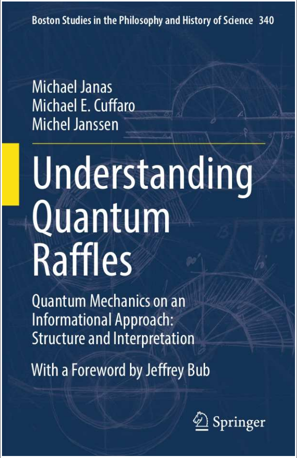




(with Tanya Bub)




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



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

See also:

- M. E .C., The Measurement Problem Is a Feature, Not a Bug—Schematising the Observer and the Concept of an Open System on an Informational, or (neo-)Bohrian, Approach. *Entropy 25* (2023): 1410.
- Janas, M., and Janssen, M., Broken Arrows: Hardy-Unruh Chains and Quantum Contextuality. *Entropy 25* (2023): 1568.

Other similar views:

- Časlav Brukner's view*; also (perhaps) Anton Zeilinger's

Other more distantly related views:

- QBism (Chris Fuchs, Rüdiger Schack, David Mermin, and others)†
- Relational Quantum Mechanics version 1 (Carlo Rovelli)‡

Other even more distantly related views:

- Relational Quantum Mechanics version 2 (Emily Adlam and Carlo Rovelli)§
- Pragmatist interpretation (Richard Healey)¶

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* Brukner, C. On the Quantum Measurement Problem. In Bertlmann & Zeilinger (eds.), *Quantum [Un]Speakables II*, Springer (2017): 95–117.

† Fuchs, C. A., Notwithstanding Bohr, the Reasons for QBism, *Mind and Matter 15* (2017): 245–300.

‡ Rovelli, C., Relational Quantum Mechanics, *International Journal of Theoretical Physics 35* (1996): 1637–1678; Rovelli, C., *Helgoland*, Riverhead Books (2020).

§ Adlam, E. & Rovelli, C., Information is Physical: Cross-Perspective Links in Relational Quantum Mechanics. *Philosophy of Physics 1* (2023): 4.

¶ Healey, R. *The Quantum Revolution in Philosophy*, Oxford University Press (2017). Healey, R. Securing the Objectivity of Relative Facts in the Quantum World. *Foundations of Physics 52* (2022): 88.

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- Our view is (neo-)Bohrian in the sense that it amounts to a defense of Bohr—or at least what we take to be essential about his 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, *per se*, 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 are 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 Como paper). . . ."

* In Aaserud, F. (gen. ed.) and Kalckar, J. (ed.), *Niels Bohr, Collected Works, Volume 6*, North-Holland/Elsevier, 1985, pp. 45–46.

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Niels Bohr to Paul Dirac, March 24, 1928 (cont'd):*

"... What has been in my mind above all [, rather,] 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."

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Outline

1. The Necessary Conditions for Making Any Use of Observational Results
2. Quantum Mechanics as a Natural Generalisation of Ordinary Causal Description
    i. The New Kinematics of Quantum Mechanics
    ii. The Subjective Character of the Idea of Observation–Schematising the Observer as a Postulate
    iii. The Classical Idea of Isolated Objects and the Quantum-Mechanical Concept of an Open System
3. The View in a Nutshell

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What are “observational results”?

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

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*.

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* 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."*

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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	$\ldots$	E_n
0	0	$\ldots$	1
0	1	$\ldots$	0
$\vdots$	$\vdots$	$\vdots$	$\vdots$

General algorithm

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

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

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- Determine the (linear) inequalities associated with its facets.

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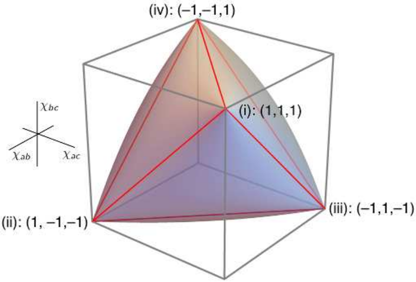
Special case: Bell inequalities (see Pitowsky 1994, 103–104)



General (nonlinear) constraint on the correlations between three balanced random variables:*

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

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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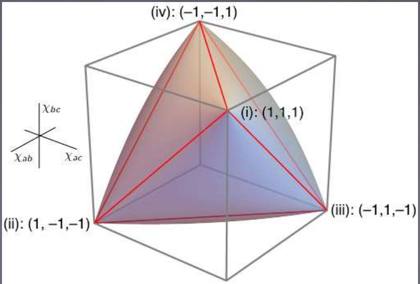

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$$\left\langle \left(v_1 \frac{X}{\sigma_X} + v_2 \frac{Y}{\sigma_Y} + v_3 \frac{Z}{\sigma_Z} \right)^2 \right\rangle \geq 0. \tag{2}$$

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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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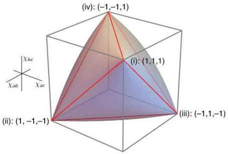
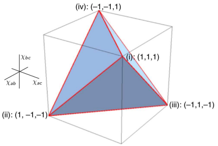
General elliptope:



Classical tetrahedron (2 values per ticket):



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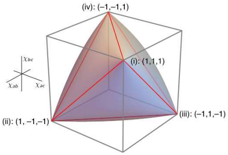
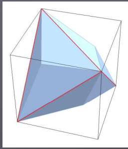


Classical polyhedron (3 values per ticket):



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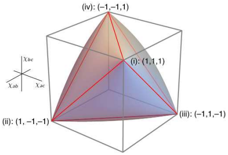
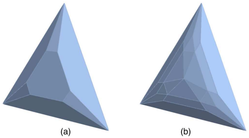


Classical polyhedra (4 and 5 values):



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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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* Michael Janas, M. E. C., and Michel Janssen, *Understanding Quantum Raffles: Quantum Mechanics on an Informational Approach: Structure and Interpretation*, Springer, 2022.

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

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 $\hat{S} \equiv \hat{S}_a + \hat{S}_b + \hat{S}_c$).*
- Kinematical constraints (broad sense):† constraints imposed by a theoretical framework on our physical description of a system independently of the specifics of its dynamics.

* 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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- Not an ontological claim but a slogan.
- This is a claim about where the conceptual novelty of QM lies:*
  - In the way that the kinematical constraints of QM constrain probability assignments.
- The slogan also conveys the idea that QM is a framework† 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.

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† 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:*

- 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.*

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* *Understanding Quantum Raffles*, sec. 6.4.

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- This is simultaneously true of <u>all</u> 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:*

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In QM, states fail to be truthmakers in two senses:*

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.

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   - 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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(Slightly) more formally

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?

Outline

1. The Necessary Conditions for Making Any Use of Observational Results
2. Quantum Mechanics as a Natural Generalisation of Ordinary Causal Description
    i. The New Kinematics of Quantum Mechanics
    ii. The Subjective Character of the Idea of Observation–Schematising the Observer as a Postulate
    iii. The Classical Idea of Isolated Objects and the Quantum-Mechanical Concept of an Open System
3. The View in a Nutshell

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."*

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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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- The approach is instrumentalist in the sense that:
  - Ultimately the goal of even a so-called fundamental physical theory is to represent phenomena in a systematic way. Physical theory is, in this sense, a tool.
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  - However instrumentalism, in that sense, is compatible with realism on a more reasonable (methodological) construal of what it means to be a realist.
  - The important question is not whether, but how, to assign physical properties to what one takes to be the system of interest responsible for a given phenomenon.*

* *Understanding Quantum Raffles*, pp. 8–10; Cf. Perović, S., *From Data to Quanta – Niels Bohr's Vision of Physics*, University of Chicago Press (2021), p. 118.

Methodological realism:

- This amounts to the demand that we be able to meaningfully account to one another how we have set up a particular experiment ("what we have done"), and what information it yields ("what we have learned") about an object that we model as able to interact with our experimental apparatus in a particular way.*

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- Providing an "ordinary causal description" of phenomena functions as a fundamental constraint in this sense.

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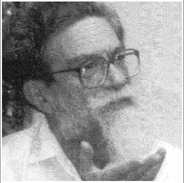
Howard Stein on the connection between observation and theory:



- The principal difficulty in making sense of the connection between the 'observational' and 'theoretical' parts of a physical theory is that of "how to get the laboratory inside the theory."*
  - i.e., how to account, theoretically, for observation.

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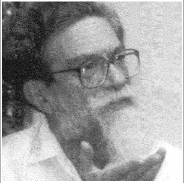

- The principal difficulty in making sense of the connection between the 'observational' and 'theoretical' parts of a physical theory is that of "how to get the laboratory inside the theory."*
  - i.e., how to account, theoretically, for observation.
- "It would ... be impossible to *understand* a theory, 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)."†

---

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- Not deductive: "there is no department of fundamental physics in which it is possible, in the strict sense, to *deduce* observations, or observable facts, from data and theory." (Stein, 1994, p. 638).

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- Not deductive: "there is no department of fundamental physics in which it is possible, in the strict sense, to *deduce* observations, or observable facts, from data and theory." (Stein, 1994, p. 638).
- Stein suggests that the only way to connect theory and observation is by "schematizing the observer within the theory" (ibid., p. 649)

Erik Curiel on schematizing the observer:

"We need a way to understand the substantive, physically significant contact—the epistemic continuity, as it were—between a precisely characterizable situation in the world of experience and the mathematical structures of what we usually think of as our theories. Such understanding should at a minimum consist of an articulation of the junctions where meaningful connections can be made between the two, and would thus ground the possibility of the epistemic warrant we think we construct for our theories from such contact and connection."*

* Curiel, E., Schematizing the Observer and the Epistemic Content of Theories, arXiv:1903.02182v3, p. 6.

Curiel (continued):

- "I mean something like: in a model of an experiment, to provide a representation of something like a measuring apparatus, even if only of the simplest and most abstract form, that allows us to interpret the model *as* a model of an experiment or observation." (ibid., p. 9).

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- "I mean something like: in a model of an experiment, to provide a representation of something like a measuring apparatus, even if only of the simplest and most abstract form, that allows us to interpret the model *as* a model of an experiment or observation." (ibid., p. 9).
- "[O]ne cannot even define physical quantities—e.g., temperature—without explicit schematic representation of the observer, much less have understanding of how to employ their representations in scientific reasoning in ways that respect the regime of applicability." (ibid., p. 14).

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Commenting (in the context of his discussion of Heisenberg's uncertainty relations) on the use of the superposition principle to explain particle-like quantum phenomena in terms of the concept of a 'wave packet', Bohr writes:

> "Indeed, a discontinuous change of energy and momentum during observation could not prevent us from ascribing accurate values to the space-time co-ordinates, as well as to the momentum-energy components before and after the process. The reciprocal uncertainty which always affects the values of these quantities is, as will be clear from the preceding analysis, essentially an outcome of the limited accuracy with which changes in energy and momentum can be defined, when the wave-fields used for the determination of the space-time co-ordinates of the particle are sufficiently small"*

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* Bohr, N., The Quantum Postulate and the Recent Development of Atomic Theory, *Nature 121* (1928): p. 583, emphasis mine.

On a (neo-)Bohrian approach, quantum mechanics is understood as elevating the idea—which Stein and Curiel have argued for on the grounds of practical and epistemic necessity—that it is required to "schematize the observer" in relation to the theoretical description of a system, in order to understand a theory as a theory of physics at all, to the level of a postulate.

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> "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. Disregard of this point has sometimes led to confusion, and in particular the use of phrases like 'disturbance of phenomena by observation' or 'creation of physical attributes of objects by measurements' is hardly compatible with common language and practical definition."
> (Bohr, 1958, pp. 392–393, my emphasis).

Schematizing the observer on a (neo-)Bohrian approach:

- An "observer"—or rather, an observational context—is represented as a 'Boolean frame' (*Understanding Quantum Raffles*, p. 213)—the Boolean algebra within which one represents the possible yes-or-no questions concerning a given observable, A, that can be asked about the system of interest:
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  - questions of the form "Is the value of A within the range Δ?"
- Given the schematic representation—to the relevant scale and for the relevant purposes—of an observer in this sense, one may then use the language of quantum mechanics to give a physical analysis of how the observed relative frequencies of outcomes of assessments of a measurement device will be (assuming the device is ideal*) describable using a particular classical probability distribution that can be thought of as determined in conformity with the dynamics of the system in interaction with the device (ibid., pp. 213–214).

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* Otherwise we can move back the 'Heisenberg cut' (*Understanding Quantum Raffles pp. 202–213.*).

Summing up:

- In classical mechanics, because the state is a truthmaker, as a matter of logic one can always argue (putting Curiel and Stein to one side for the moment) that including a representation of the observational context in one's analysis of a system's dynamics is superfluous, at least in principle.

Summing up:

- In classical mechanics, because the state is a truthmaker, as a matter of logic one can always argue (putting Curiel and Stein to one side for the moment) that including a representation of the observational context in one's analysis of a system's dynamics is superfluous, at least in principle.
- But this is not the case in quantum mechanics, where the introduction of a Boolean frame is required in order to interpret the outcome of a measurement interaction as providing us with information about the system of interest.

Outline

1. The Necessary Conditions for Making Any Use of Observational Results
2. Quantum Mechanics as a Natural Generalisation of Ordinary Causal Description
   i. The New Kinematics of Quantum Mechanics
   ii. The Subjective Character of the Idea of Observation–Schematising the Observer as a Postulate
   iii. The Classical Idea of Isolated Objects and the Quantum-Mechanical Concept of an Open System
3. The View in a Nutshell

- What is exhibited by the quantum state, on a (neo-)Bohrian view?

- What is exhibited by the quantum state, on a (neo-)Bohrian view is not, *per se*, a collection of antecedently given properties possessed by a system.
- Rather, what is exhibited is the structure of and interdependencies among the 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"*).

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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"*).
- But because the probability distributions over the values of every classical observable are determined independently of whether a physical interaction through which one can assess those values is actually made, there is an invitation to think of them as originating in the properties of an underlying physical system that exists in a particular way irrespective of anything external.

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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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- Such a model does not suffer—in a given measurement context—from the "small" measurement problem (since the observables associated with that context commute).
- It does suffer from the "big" measurement problem. *However* in any given measurement context it will always be possible to effectively interpret the indeterminacy of individual measurement results, in a given experimental run, as stemming from our inability to precisely specify some relevant physical parameter in whatever dynamical model that we use to conceptualise the phenomena in that context.

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- It does suffer from the “big” measurement problem. *However* in any given measurement context it will always be possible to effectively interpret the indeterminacy of individual measurement results, in a given experimental run, as stemming from our inability to precisely specify some relevant physical parameter in whatever dynamical model that we use to conceptualise the phenomena in that context.
- 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 specific way, subject to the constraints imposed by the kinematical framework of quantum mechanics.

- But can nothing really be said, on the (neo-)Bohrian view, about what the world is like independently of the observational context?

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- On the contrary:
  (a) Non-dynamical quantities (mass, spin, charge, etc.): valid regardless of experimental context.
  (b) Dynamical quantities: The world is such that all of the effectively classical (i.e., Boolean) probabilistic pictures that one can draw of it, under the precisely specified experimental conditions corresponding to each of them, are precisely relatable to one another in the way described by quantum mechanics. That's not a trivial thing!

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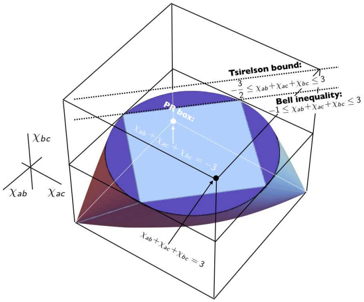
- Does (b) depend, physically or metaphysically, on the existence of conscious observers?
  - No. Rather: a schematic representation of what (relevantly) constitutes an observer—a classical conditional probability distribution (a.k.a. "Boolean frame")—is being used as a formal tool with which to describe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

For a (neo-)Bohrian:

- Physics is in the business of describing the true empirical relations that obtain in the world.



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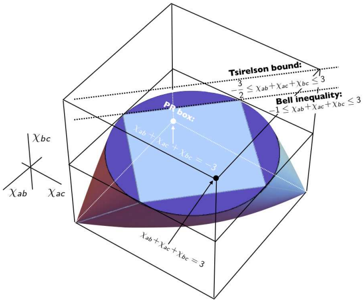
- Of course, that doesn't amount to the description of a substance existing in itself in the traditional metaphysical sense.*



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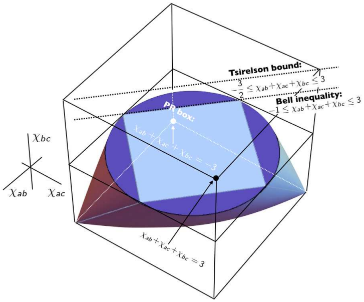
- But on the empiricist perspective embraced by the (neo-)Bohrian interpreter we were never committed to this.



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Our view in a nutshell:

- QM is, in the sense of what it objectively describes, about probabilities. These are understood to be (to use von Neumann's phrase) "given from the start",*
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  - i.e., as objectively (i.e., non-contextually) associated with a given concrete measurement context.
- 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.

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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.*

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* Cf. Pitowsky, 1994, p. 118.

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