Methodological Realism and Quantum Mechanics

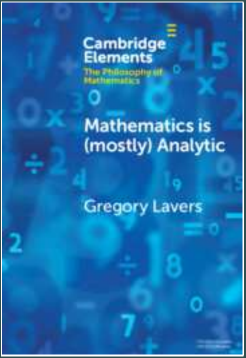
Michael E. Cuffaro[†]

[†]Munich Center for Mathematical Philosophy, LMU Munich,
Michael.Cuffaro@lmu.de

Sunday, May 25, 2025

Empiricism and the Methodology of Modern Physics
The University of Western Ontario
London, Ontario, Canada

Powered by LaTeX



Gregory Lavers (1974–1925)

From Mehra & Rechenberg's conversations with Heisenberg:

> Heisenberg: "the fact that XY was not equal to YX was very disagreeable to me. I felt this was the only point of difficulty in the whole scheme, otherwise I would be perfectly happy."*

* Mehra, J., and Rechenberg, H. (1982), *The Historical Development of Quantum Theory, Volume 3: The Formulation of Matrix Mechanics and Its Modifications*. New York: Springer, p. 94.

From Mehra & Rechenberg's conversations with Heisenberg:

> Heisenberg: "the fact that XY was not equal to YX was very disagreeable to me. I felt this was the only point of difficulty in the whole scheme, otherwise I would be perfectly happy." What this taught him, he continued: "If one finds a difficulty in a calculation which is otherwise quite convincing, one should not push the difficulty away; one should rather try to make it the centre of the whole thing."*

* Mehra, J., and Rechenberg, H. (1982), *The Historical Development of Quantum Theory, Volume 3: The Formulation of Matrix Mechanics and Its Modifications*. New York: Springer, p. 94.

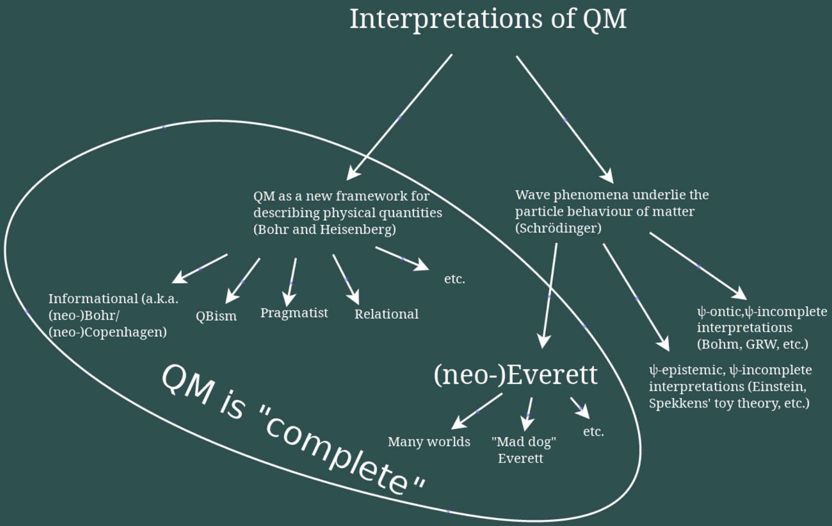


*Image source: MEC and Hartmann, S. (2025), Quantum Theory is About Open Systems. In MEC & Hartmann, S. (eds.), *Open Systems: Physics, Metaphysics, and Methodology*. Forthcoming.

"Completeness"

- QM provides us with, at least in principle, a complete description of physical reality.
  - (Neo-)Everett and related approaches

“[T]here is a concept of completeness that generalizes the classical concept and which was shown by Gleason to apply to the quantum theory. This concept does not require that an irreducibly statistical theory should derive its probability measures from a level of description that corresponds to Einstein’s real factual situations.”*

* Demopoulos, W. (2022), *On Theories*. Cambridge, MA: Harvard University Press, p. 178.

“[T]here is a concept of completeness that generalizes the classical concept and which was shown by Gleason to apply to the quantum theory. This concept does not require that an irreducibly statistical theory should derive its probability measures from a level of description that corresponds to Einstein’s real factual situations. Rather, completeness in the generalized sense established by Gleason requires that the quantum theory should generate all possible positive real-valued measures that are classical probability measures on Boolean subalgebras of the algebra of properties that the theory associates with a physical system.”*

---

*Demopoulos, W. (2022), *On Theories*. Cambridge, MA: Harvard University Press, p. 178.

"Completeness"

- QM provides us with, at least in principle, a complete description of physical reality.
  - (Neo-)Everett and related approaches
- QM provides us with all of the conceptual resources we need to describe any given (in general, probabilistic) physical phenomenon to whatever level of detail we like (as established by Gleason's theorem)
  - (Neo-)Bohr and related approaches

"Completeness"

- QM provides us with, at least in principle, a complete description of physical reality.
  - (Neo-)Everett and related approaches
- QM provides us with all of the conceptual resources we need to describe any given (in general, probabilistic) physical phenomenon to whatever level of detail we like (as established by Gleason's theorem)
  - (Neo-)Bohr, and (on my reading), Brukner, Zeilinger, Fuchs & Schack, Healey, Rovelli (but perhaps not Adlam & Rovelli)
  - Differences mainly concern the interpretation of probability and, generally, how to characterize the conditions under which probability assignments can be made.

"Completeness"

- QM provides us with, at least in principle, a complete description of physical reality.
  - (Neo-)Everett and related approaches
- QM provides us with all of the conceptual resources we need to describe any given (in general, probabilistic) physical phenomenon to whatever level of detail we like (as established by Gleason's theorem)
  - (Neo-)Bohr, and (on my reading), Brukner, Zeilinger, Fuchs & Schack, Healey, Rovelli (but perhaps not Adlam & Rovelli)
  - Differences mainly concern the interpretation of probability and, generally, how to characterize the conditions under which probability assignments can be made.
    - Healey: "decoherence context" (physical)
    - Rovelli: "observer system" (physical)
    - Fuchs & Schack: "rational agent" (radically subjective)
    - (Neo-)Bohr: "Boolean frame" (objective, epistemic)

"Completeness"

- QM provides us with, at least in principle, a complete description of physical reality.
  - (Neo-)Everett and related approaches
- QM provides us with all of the conceptual resources we need to describe any given (in general, probabilistic) physical phenomenon to whatever level of detail we like (as established by Gleason's theorem)
  - (Neo-)Bohr, and (on my reading), Brukner, Zeilinger, Fuchs & Schack, Healey, Rovelli (but perhaps not Adlam & Rovelli)
  - Differences mainly concern the interpretation of probability and, generally, how to characterize the conditions under which probability assignments can be made.
    - Healey: "decoherence context" (physical)
    - Rovelli: "observer system" (physical)
    - Fuchs & Schack: "rational agent" (radically subjective)
    - (Neo-)Bohr: "Boolean frame" (objective, epistemic)
      - (cf. Myrvold's concept of 'epistemic chance')*

* Myrvold, W. C. (2021). *Beyond Chance and Credence: A Theory of Hybrid Probabilities*. Oxford: Oxford University Press.

"(Neo-)Bohrian"

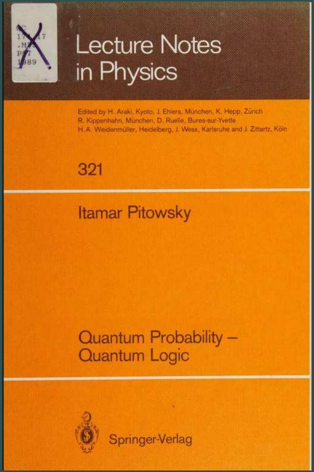
- a.k.a. "information-theoretic," "informational," etc.

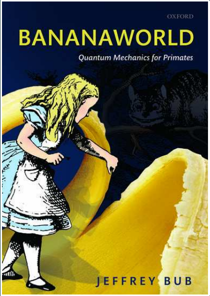
“(Neo-)Bohrian”

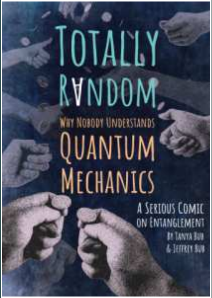
- a.k.a. “information-theoretic,” “informational,” etc.
- Amounts to a defense of Bohr—or at least what we take to be essential about his view—and an elaboration of how to make sense of what we have learned about the world since Bell in (neo-)Bohrian terms.

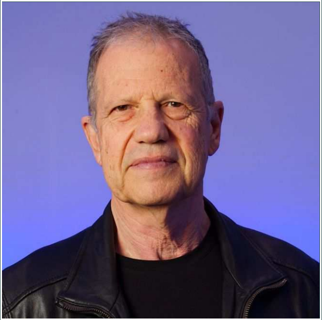
"(Neo-)Bohrian"

- a.k.a. "information-theoretic," "informational," etc.
- 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.
- That said, the intention isn't, *per se*, to make a contribution to the historical scholarship on Bohr—hence the "(Neo-)".

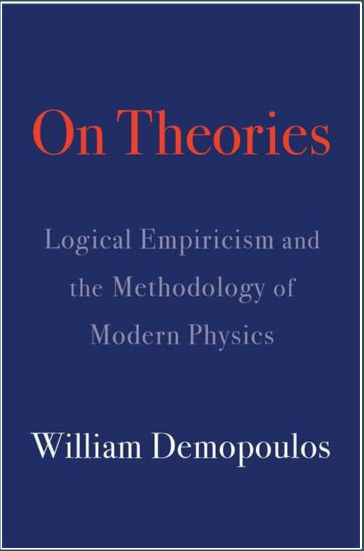

Lecture Notes in Physics
Edited by H. Araki, Kyoto, J. Ehlers, München, K. Hepp, Zürich
R. Kippenhahn, München, D. Ruelle, Bures-sur-Yvette
H. A. Weidenmüller, Heidelberg, J. Wess, Karlsruhe and J. Zittartz, Köln
321
Itamar Pitowsky
Quantum Probability – Quantum Logic
Springer-Verlag

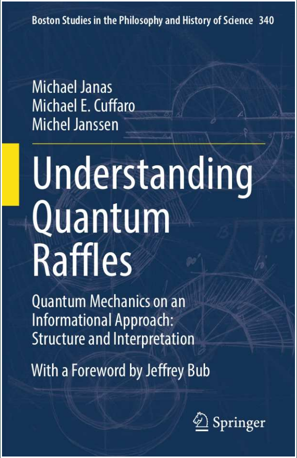






* See also, MEC. and Doyle, E., Essay Review of Bub & Bub's Totally Random. *Foundations Physics, 51* (2021), 28:1-28:16


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



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

See also:

- MEC., 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.
- MEC., Methodological Realism and Quantum Mechanics (working title). To appear in Johansson, L & Faye, J. (eds.), *How to Understand Quantum mechanics – 100 Years of Ongoing Interpretation*

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.

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.

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.

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.

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."

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

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."

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

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."

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

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."

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

Bohr on the primacy of classical concepts

Demopoulos:

‘By the “primacy of classical concepts” for our understanding of quantum mechanics I mean—and I take Bohr to have meant—their primacy in the description of experimental results pertinent to the development and confirmation of the theory.’*

* *On Theories*, p. 121.

Bohr on the primacy of classical concepts

Demopoulos:

'By the "primacy of classical concepts" for our understanding of quantum mechanics I mean—and I take Bohr to have meant—their primacy in the description of experimental results pertinent to the development and confirmation of the theory.'*

In other words,

- this is not a claim about the primacy of classical concepts w.r.t. the theoretical statements of any possible future physics.
- The primacy of classical concepts, for Bohr, is evidentiary.

---

* *On Theories*, p. 121.

"Understood as a thesis about the epistemic framework within which physical theories are evaluated, the thesis of the primacy of classical concepts is entirely compatible with the idea that the principles and presuppositions of the classical framework are radically mistaken and incapable of providing an adequate theoretical basis for physics."*

* *On Theories*, p. 122.

Example: Stokes law of fall.

- Relates the drag force experienced by a particle, as it falls through a fluid medium, to its density and to the density and viscosity of the medium.
- Stoke's law is only valid for small spherical objects that are assumed to produce only negligible effects on the fluid medium.

Example: Stokes law of fall.

- Relates the drag force experienced by a particle, as it falls through a fluid medium, to its density and to the density and viscosity of the medium.
- Stoke's law is only valid for small spherical objects that are assumed to produce only negligible effects on the fluid medium.

"The law guided Perrin's and Thomson's determinations of the properties of the molecular and subatomic constituents of matter, even though it was thought unlikely that the relation it expresses could be expected to hold for spherical objects of the dimensions required by their applications of it."*

* *On Theories*, p. 122.

Example: Stokes law of fall.

- Relates the drag force experienced by a particle, as it falls through a fluid medium, to its density and to the density and viscosity of the medium.
- Stoke's law is only valid for small spherical objects that are assumed to produce only negligible effects on the fluid medium.

"The law guided Perrin's and Thomson's determinations of the properties of the molecular and subatomic constituents of matter, even though it was thought unlikely that the relation it expresses could be expected to hold for spherical objects of the dimensions required by their applications of it. Nevertheless, Stokes's law isolates what, in Poincaré's terminology is a "true" relation—within a limited domain—between the rate of fall of spherical objects, density, and viscosity that is preserved under a change of application from the continuous media for which it was initially devised to discrete media."*

* *On Theories*, p. 122.

"It illustrates the fact that the presuppositions of the principles which underlie an evidentiary framework might be false—and even known to be false—and the principles themselves of only limited validity, without losing their effectiveness for probing the evidence for a theoretical claim, or refining the determination of a theoretical parameter."*

* *On Theories*, p. 122.

Slobodan Perović on Bohr on methodology*

Physical inquiry, for Bohr, proceeds in multiple inductive stages, associated with different layers of "hypotheses" of varying levels of generality.

* Perović, S. (2021), *From Data to Quanta – Niels Bohr's Vision of Physics*. Chicago: University of Chicago Press.

Slobodan Perović on Bohr on methodology*

Physical inquiry, for Bohr, proceeds in multiple inductive stages, associated with different layers of “hypotheses” of varying levels of generality.

- First stage: Formation of concrete hypotheses and models relating to specific experimental setups, whose validity is assumed to be limited to those particular setups.

* Perović, S. (2021), *From Data to Quanta – Niels Bohr's Vision of Physics*. Chicago: University of Chicago Press.

Slobodan Perović on Bohr on methodology*

Physical inquiry, for Bohr, proceeds in multiple inductive stages, associated with different layers of “hypotheses” of varying levels of generality.

- First stage: Formation of concrete hypotheses and models relating to specific experimental setups, whose validity is assumed to be limited to those particular setups.
- Second stage: Formation of abstract intermediate and ‘master-level’ hypotheses that unify and systematize our understanding of a given experimental domain.

* Perović, S. (2021), *From Data to Quanta – Niels Bohr’s Vision of Physics*. Chicago: University of Chicago Press.

First stage:

- Experimental particulars are observed and recorded.
- Characterized by the use of everyday language (e.g., that a spot was registered on this rather than that part of a screen), made further precise using the mathematical tools of classical physics.*

---

* *From Data to Quanta*, p. 34.

First stage:

- Experimental particulars are observed and recorded.
- Characterized by the use of everyday language (e.g., that a spot was registered on this rather than that part of a screen), made further precise using the mathematical tools of classical physics.*
- Results, in general, in an experimental account whereby we describe 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 assume is able to interact with our experimental apparatus in a particular way in accordance with some lower-level hypothesis relating to the setup.†

---

* *From Data to Quanta*, p. 34.
† ibid., p. 44.

Second stage:

- Aims to unify the experimental accounts produced in the first stage.

Second stage:

- Aims to unify the experimental accounts produced in the first stage.
- Unlike the first stage, neither everyday language nor its classical-mechanical precisifications directly constrain the second stage.*

* *From Data to Quanta*, pp. 39–41, 62.

Second stage:

- Aims to unify the experimental accounts produced in the first stage.
- Unlike the first stage, neither everyday language nor its classical-mechanical precisifications directly constrain the second stage.*
- But they do indirectly constrain it insofar as the ultimate aim of the second stage is to obtain a comprehensive, quantitative, grasp of the overall experimental domain of an area of inquiry.†

* *From Data to Quanta*, pp. 39–41, 62.
† ibid., pp. 50–51.

Second stage:

- Aims to unify the experimental accounts produced in the first stage.
- Unlike the first stage, neither everyday language nor its classical-mechanical precisifications directly constrain the second stage.*
- But they do indirectly constrain it insofar as the ultimate aim of the second stage is to obtain a comprehensive, quantitative, grasp of the overall experimental domain of an area of inquiry.†
- At least until new experiments are performed.‡ For despite the fact that an accepted master hypothesis will be implicit in any account of a given set of data,

---

* *From Data to Quanta*, pp. 39–41, 62.

† ibid., pp. 50–51.

‡ ibid., p. 60.

Second stage:

- Aims to unify the experimental accounts produced in the first stage.
- Unlike the first stage, neither everyday language nor its classical-mechanical precisifications directly constrain the second stage.[*]
- But they do indirectly constrain it insofar as the ultimate aim of the second stage is to obtain a comprehensive, quantitative, grasp of the overall experimental domain of an area of inquiry.[†]
- At least until new experiments are performed.[⸸] For despite the fact that an accepted master hypothesis will be implicit in any account of a given set of data, the first stage of the inductive process can in principle continue to operate effectively independently of the second stage,[‡]

---

[*] *From Data to Quanta*, pp. 39–41, 62.

[†] ibid., pp. 50–51.

[⸸] ibid., p. 60.

[‡] ibid., p. 15.

Second stage:

- Aims to unify the experimental accounts produced in the first stage.
- Unlike the first stage, neither everyday language nor its classical-mechanical precisifications directly constrain the second stage.[*]
- But they do indirectly constrain it insofar as the ultimate aim of the second stage is to obtain a comprehensive, quantitative, grasp of the overall experimental domain of an area of inquiry.[†]
- At least until new experiments are performed.[⸸] For despite the fact that an accepted master hypothesis will be implicit in any account of a given set of data, the first stage of the inductive process can in principle continue to operate effectively independently of the second stage,[‡] if the novel theoretical relations that are formulated in the second stage do not directly manifest themselves via controllable parameters in the lower-level experimental accounts.[§]

---

[*] *From Data to Quanta*, pp. 39–41, 62.

[†] ibid., pp. 50–51.

[⸸] ibid., p. 60.

[‡] ibid., p. 15.

[§] See also: MEC (2023), Review of Perović, *Philosophy of Science, 91(2)*, pp. 525-529.

Bohr, letter to Schrödinger, October 26, 1935:

"My emphasis of the point that the classical description of experiments is unavoidable amounts merely to the seemingly obvious fact that the description of any measuring arrangement must, in an essential manner, involve the arrangement of the instruments in space and their functioning in time, if we shall be able to state anything at all about the phenomena."*

* In Aaserud, F. (gen. ed.) and Kalckar, J. (ed.), *Niels Bohr, Collected Works, Volume 7*, North-Holland/Elsevier, 1996, pp. 511–512. Quoted in *On Theories*, p. 124.

Bohr, letter to Schrödinger, October 26, 1935:

"My emphasis of the point that the classical description of experiments is unavoidable amounts merely to the seemingly obvious fact that the description of any measuring arrangement must, in an essential manner, involve the arrangement of the instruments in space and their functioning in time, if we shall be able to state anything at all about the phenomena."*

Demopoulos:

"Bohr appears to be claiming that this is something any description of measuring instruments must include in order to play the epistemic role they do."†

---

* In Aaserud, F. (gen. ed.) and Kalckar, J. (ed.), *Niels Bohr, Collected Works, Volume 7*, North-Holland/Elsevier, 1996, pp. 511–512. Quoted in *On Theories*, p. 124.

† *On Theories*, p. 126.

Demopoulos on classicality

"On the explication of classicality that I believe is relevant to our understanding of quantum mechanics, the central characteristic of a framework or theory whose concepts are classical is the commutativity of the algebra of physical concepts—the parameters, physical magnitudes, and dynamical variables—with which it characterizes physical systems."*

* *On Theories*, p. 126.

Demopoulos on classicality

"On the explication of classicality that I believe is relevant to our understanding of quantum mechanics, the central characteristic of a framework or theory whose concepts are classical is the commutativity of the algebra of physical concepts—the parameters, physical magnitudes, and dynamical variables—with which it characterizes physical systems. Equivalently, classicality consists in the Boolean character of the algebra of all the properties or propositions that are associated with each physical system. On this view, classicality is a characteristic that attaches to the interrelations of the physical concepts of a theory, rather than to the concepts themselves."*

---

* *On Theories*, p. 126.

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.

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."

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

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 (Neo-)Bohrian View in a Nutshell

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 (Neo-)Bohrian View in a Nutshell

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*.

* 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."*

* George Boole, "On the Theory of Probabilities," *Philos. Trans. R. Soc. Lond. 152* (1862), p. 229. Cited in Pitowsky, I., "George Boole's 'Conditions of Possible Experience' and the Quantum Puzzle," *The British Journal for the Philosophy of Science 45*, 1994, p. 100.

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."*

- 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?

---

* George Boole, "On the Theory of Probabilities," *Philos. Trans. R. Soc. Lond. 152* (1862), p. 229. Cited in Pitowsky, I., "George Boole's 'Conditions of Possible Experience' and the Quantum Puzzle," *The British Journal for the Philosophy of Science 45*, 1994, p. 100.

General algorithm

- Given the logically connected events $E_1, \ldots, E_n$,

General algorithm

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

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

General algorithm

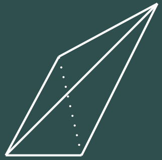
- Given the logically connected events $E_1, \ldots, E_n$,
- Write down the corresponding (propositional) truth table.
- Associate rows with vectors of (extremal) probabilities $(p_1, \ldots, p_n)$.
- Take the convex hull of these vectors to yield a polytope.

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 $E_1, \ldots, E_n$,
- Write down the corresponding (propositional) truth table.
- Associate rows with vectors of (extremal) probabilities $(p_1, \ldots, p_n)$.
- Take the convex hull of these vectors to yield a polytope.
- Determine the (linear) inequalities associated with its facets.

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

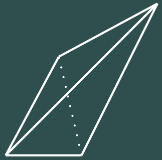


$$a_1 p_1 + a_2 p_2 + \cdots + a_n p_n + a \geq 0$$

General algorithm

- Given the logically connected events $E_1, \ldots, E_n$,
- Write down the corresponding (propositional) truth table.
- Associate rows with vectors of (extremal) probabilities $(p_1, \ldots, p_n)$.
- Take the convex hull of these vectors to yield a polytope.
- Determine the (linear) inequalities associated with its facets.

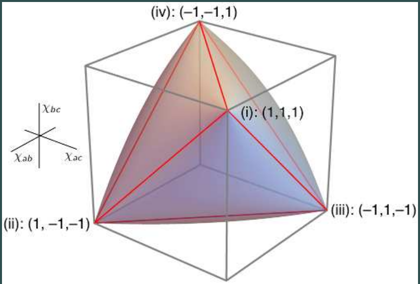
E_1	E_2	$\ldots$	E_n
0	0	$\ldots$	1
0	1	$\ldots$	0
$\vdots$	$\vdots$	$\vdots$	$\vdots$



$$a_1 p_1 + a_2 p_2 + \cdots + a_n p_n + a \geq 0$$

Special case: Bell inequalities*

* Pitowsky, I. (1994), George Boole's 'Conditions of Possible Experience' and the Quantum Puzzle. *British Journal for the Philosophy of Science 45*, pp. 99–125.



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

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

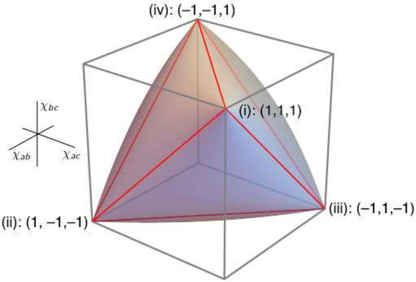
where $\rho_{XY} = \frac{\langle XY \rangle}{\sigma_X \sigma_Y}$ is the *Pearson correlation coefficient* for two balanced random variables X and Y and σ_X, σ_Y are the standard deviations of X and Y.

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

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 (Neo-)Bohrian View in a Nutshell

Outline



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

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

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.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

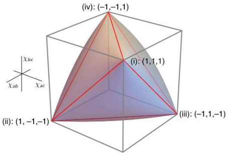
Derivation of Eq. (1) relies on the fact that:

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

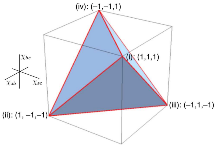
Modelling this relation in a local-hidden variables theory (LHVT):

- Requires a joint probability distribution over the values of X, Y, Z.
- Saturation of the elliptope only as # outcomes per variable $\rightarrow \infty$.

General elliptope:



Classical tetrahedron (2 values per ticket):



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

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

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

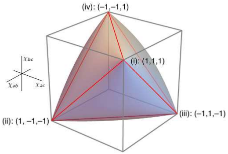
Derivation of Eq. (1) relies on the fact that:

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

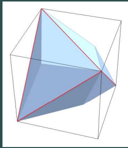
Modelling this relation in a local-hidden variables theory (LHVT):

- Requires a joint probability distribution over the values of X, Y, Z.
- Saturation of the elliptope only as # outcomes per variable $\to \infty$.

General elliptope:



Classical polyhedron (3 values per ticket):



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

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

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

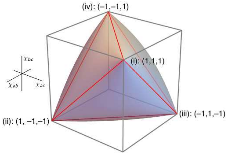
Derivation of Eq. (1) relies on the fact that:

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

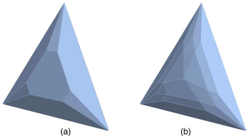
Modelling this relation in a local-hidden variables theory (LHVT):

- Requires a joint probability distribution over the values of X, Y, Z.
- Saturation of the elliptope only as # outcomes per variable $\rightarrow \infty$.

General elliptope:



Classical polyhedra (4 and 5 values):



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

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

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

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

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

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

- Requires a joint probability distribution over the values of X, Y, Z.
- Saturation of the elliptope only as # outcomes per variable $\to \infty$.

Modelling this relation in quantum mechanics (QM):

- Saturation of the elliptope for all values of spin.

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

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

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

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

$$\left\langle \left(\nu_1 \frac{X}{\sigma_X} + \nu_2 \frac{Y}{\sigma_Y} + \nu_3 \frac{Z}{\sigma_Z} \right)^2 \right\rangle \geq 0. \tag{2}$$

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

- Requires a joint probability distribution over the values of X, Y, Z.
- Saturation of the elliptope only as # outcomes per variable $\to \infty$.

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.

* Michael Janas, MEC, 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.
- Kinematical constraints (broad sense):[†] constraints imposed by a theoretical framework on our physical description of a system independently of the specifics of its dynamics.
- The kinematics of QM are less restrictive (consider the operator $\hat{S} \equiv \hat{S}_a + \hat{S}_b + \hat{S}_c$).[*]

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

[†] *Understanding Quantum Raffles*, ch. 1; see also Janssen, M., "Drawing the Line between Kinematics and Dynamics in Special Relativity," *Studies in History and Philosophy of Modern Physics 40*, pp. 26–52.

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

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

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

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

---

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

† *Understanding Quantum Raffles*, ch. 1; see also Janssen, M., "Drawing the Line between Kinematics and Dynamics in Special Relativity," *Studies in History and Philosophy of Modern Physics 40*, pp. 26–52.

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

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

- 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.

---

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

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

- 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.

---

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

† 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.

Understanding why QM, but not CM, allows us to saturate the elliptope for all values of spin is only one example of a problem that can be solved by appealing exclusively to QM's kinematical constraints.

Understanding why QM, but not CM, allows us to saturate the elliptope for all values of spin is only one example of a problem that can be solved by appealing exclusively to QM's kinematical constraints.

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.*

---

* *Understanding Quantum Raffles*, sec. 6.4.

Understanding why QM, but not CM, allows us to saturate the elliptope for all values of spin is only one example of a problem that can be solved by appealing exclusively to QM's kinematical constraints.

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.*

* *Understanding Quantum Raffles*, sec. 6.4.

Classical mechanics:

- Specifying a system's state yields an answer to every yes-or-no question that can be asked about a particular observable quantity (e.g., "Is the value of the observable A within the range Δ?").

Classical mechanics:

- Specifying a system's state yields an answer to every yes-or-no question that can be asked about a particular observable quantity (e.g., "Is the value of the observable A within the range Δ?").
- Classical state is a truthmaker (in a logical sense) for that observable;* i.e., it determines the answer to every yes-or-no question about the quantity irrespective of how we interact with the system.

---

* Bub, J., and Pitowsky, I., "Two Dogmas About Quantum Mechanics," in Saunders et al. (eds.), *Many Worlds? Everett, Quantum Theory, and Reality*, Oxford University Press, 2010, p. 433.

Classical mechanics:

- Specifying a system's state yields an answer to every yes-or-no question that can be asked about a particular observable quantity (e.g., "Is the value of the observable A within the range Δ?").
- Classical state is a truthmaker (in a logical sense) for that observable;* i.e., it determines the answer to every yes-or-no question about the quantity irrespective of how we interact with the system.
- 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. ...

* Bub, J., and Pitowsky, I., "Two Dogmas About Quantum Mechanics," in Saunders et al. (eds.), *Many Worlds? Everett, Quantum Theory, and Reality*, Oxford University Press, 2010, p. 433.

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

---

* *Understanding Quantum Raffles*, chs. 1 and 6; see also Pitowsky, I., "Quantum Mechanics as a Theory of Probability," in Demopoulos, W., and Pitowsky, I. (eds.), *Physical Theory and its Interpretation*, Dordrecht: Springer, 2006.

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

1. The "big" (aspect of the) 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.

* *Understanding Quantum Raffles*, chs. 1 and 6; see also Pitowsky, I., "Quantum Mechanics as a Theory of Probability," in Demopoulos, W., and Pitowsky, I. (eds.), *Physical Theory and its Interpretation*, Dordrecht: Springer, 2006.

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

1. The "big" (aspect of the) 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.

* *Understanding Quantum Raffles*, chs. 1 and 6; see also Pitowsky, I., "Quantum Mechanics as a Theory of Probability," in Demopoulos, W., and Pitowsky, I. (eds.), *Physical Theory and its Interpretation*, Dordrecht: Springer, 2006.

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

1. The "big" (aspect of the) 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" (aspect of the) measurement problem: The classical probability distributions associated with individual observables cannot be embedded into a global classical probability distribution over all observables.

* *Understanding Quantum Raffles*, chs. 1 and 6; see also Pitowsky, I., "Quantum Mechanics as a Theory of Probability," in Demopoulos, W., and Pitowsky, I. (eds.), *Physical Theory and its Interpretation*, Dordrecht: Springer, 2006.

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

1. The "big" (aspect of the) 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" (aspect of the) 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.

* *Understanding Quantum Raffles*, chs. 1 and 6; see also Pitowsky, I., "Quantum Mechanics as a Theory of Probability," in Demopoulos, W., and Pitowsky, I. (eds.), *Physical Theory and its Interpretation*, Dordrecht: Springer, 2006.

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

1. The "big" (aspect of the) 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" (aspect of the) 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).

* *Understanding Quantum Raffles*, chs. 1 and 6; see also Pitowsky, I., "Quantum Mechanics as a Theory of Probability," in Demopoulos, W., and Pitowsky, I. (eds.), *Physical Theory and its Interpretation*, Dordrecht: Springer, 2006.

(Slightly) more formally

Classical mechanics:

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

Quantum mechanics:

(Slightly) more formally

Classical mechanics:

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

Quantum mechanics:

- An observable A is represented by $\hat{A}$ acting on the Hilbert space of a system.

(Slightly) more formally

Classical mechanics:

- An observable A is represented by $f_A(\omega)$ acting on the phase space of a system.
- With f_A we can associate a Boolean algebra $\mathfrak{A}$ of yes-or-no questions concerning A.

Quantum mechanics:

- An observable A is represented by $\hat{A}$ acting on the Hilbert space of a system.

(Slightly) more formally

Classical mechanics:

- An observable A is represented by $f_A(\omega)$ acting on the phase space of a system.
- With f_A we can associate a Boolean algebra $\mathfrak{A}$ of yes-or-no questions concerning A.

Quantum mechanics:

- An observable A is represented by $\hat{A}$ acting on the Hilbert space of a system.
- With $\hat{A}$ we can associate a Boolean algebra $\mathfrak{A}$ of yes-or-no questions concerning A.

(Slightly) more formally

Classical mechanics:

- An observable A is represented by $f_A(\omega)$ acting on the phase space of a system.
- With f_A we can associate a Boolean algebra $\mathfrak{A}$ of yes-or-no questions concerning A.
- Points in phase space are "truthmakers"

Quantum mechanics:

- An observable A is represented by $\hat{A}$ acting on the Hilbert space of a system.
- With $\hat{A}$ we can associate a Boolean algebra $\mathfrak{A}$ of yes-or-no questions concerning A.

(Slightly) more formally

Classical mechanics:

- An observable A is represented by $f_A(\omega)$ acting on the phase space of a system.
- With f_A we can associate a Boolean algebra $\mathfrak{A}$ of yes-or-no questions concerning A.
- Points in phase space are "truthmakers" in the sense that
  - Fixing ω fixes the values for *every* observable.

Quantum mechanics:

- An observable A is represented by $\hat{A}$ acting on the Hilbert space of a system.
- With $\hat{A}$ we can associate a Boolean algebra $\mathfrak{A}$ of yes-or-no questions concerning A.

(Slightly) more formally

Classical mechanics:

- An observable A is represented by $f_A(\omega)$ acting on the phase space of a system.
- With f_A we can associate a Boolean algebra $\mathfrak{A}$ of yes-or-no questions concerning A.
- Points in phase space are "truthmakers" in the sense that
  - Fixing ω fixes the values for *every* observable.
  - $\mathfrak{A}, \mathfrak{B}, \ldots$ embeddable into a global Boolean algebra.

Quantum mechanics:

- An observable A is represented by $\hat{A}$ acting on the Hilbert space of a system.
- With $\hat{A}$ we can associate a Boolean algebra $\mathfrak{A}$ of yes-or-no questions concerning A.

(Slightly) more formally

Classical mechanics:

- An observable A is represented by $f_A(\omega)$ acting on the phase space of a system.
- With f_A we can associate a Boolean algebra $\mathfrak{A}$ of yes-or-no questions concerning A.
- Points in phase space are "truthmakers" in the sense that
  - Fixing ω fixes the values for *every* observable.
  - $\mathfrak{A}, \mathfrak{B}, \ldots$ embeddable into a global Boolean algebra.

Quantum mechanics:

- An observable A is represented by $\hat{A}$ acting on the Hilbert space of a system.
- With $\hat{A}$ we can associate a Boolean algebra $\mathfrak{A}$ of yes-or-no questions concerning A.
- Vectors in Hilbert space *not* "truthmakers"

(Slightly) more formally

Classical mechanics:

- An observable A is represented by $f_A(\omega)$ acting on the phase space of a system.
- With f_A we can associate a Boolean algebra $\mathfrak{A}$ of yes-or-no questions concerning A.
- Points in phase space are "truthmakers" in the sense that
  - Fixing ω fixes the values for *every* observable.
  - $\mathfrak{A}, \mathfrak{B}, \ldots$ embeddable into a global Boolean algebra.

Quantum mechanics:

- An observable A is represented by $\hat{A}$ acting on the Hilbert space of a system.
- With $\hat{A}$ we can associate a Boolean algebra $\mathfrak{A}$ of yes-or-no questions concerning A.
- Vectors in Hilbert space *not* "truthmakers" in the sense that
  - Fixing $|\psi\rangle$ only fixes $\Pr(\nu_A|A), \Pr(\nu_B|B), \ldots$

(Slightly) more formally

Classical mechanics:

- An observable A is represented by $f_A(\omega)$ acting on the phase space of a system.
- With f_A we can associate a Boolean algebra $\mathfrak{A}$ of yes-or-no questions concerning A.
- Points in phase space are "truthmakers" in the sense that
  - Fixing ω fixes the values for *every* observable.
  - $\mathfrak{A}, \mathfrak{B}, \ldots$ embeddable into a global Boolean algebra.

Quantum mechanics:

- An observable A is represented by $\hat{A}$ acting on the Hilbert space of a system.
- With $\hat{A}$ we can associate a Boolean algebra $\mathfrak{A}$ of yes-or-no questions concerning A.
- Vectors in Hilbert space *not* "truthmakers" in the sense that
  - Fixing $|\psi\rangle$ only fixes $\Pr(v_A|A),\ \Pr(v_B|B), \ldots$
  - $\mathfrak{A}, \mathfrak{B}, \ldots$ not embeddable into global Boolean algebra.

Demopoulos:

"The shift in the algebraic structure of observables and properties which marks the transition from classical to quantum mechanics is a radical departure, even by the standard set by the transition from Newtonian ideas that characterized the special and general theories of relativity."*

* *On Theories*, p. 129.

Demopoulos:

“The shift in the algebraic structure of observables and properties which marks the transition from classical to quantum mechanics is a radical departure, even by the standard set by the transition from Newtonian ideas that characterized the special and general theories of relativity. In the case of quantum mechanics, each observable is represented by a Boolean algebra of possible properties corresponding to the possible values of the observable, and this is reflected in the Boolean algebra of possible effects that are elicited by measurement interactions involving the determination of the value of the observable.*

* *On Theories*, p. 129.

Demopoulos:

"The radical disparity between the algebraic structure of the classical and quantum-mechanical frameworks is not a problem that must be overcome, but is rather the true basis for the uniqueness of quantum mechanics in the evolution of physical theories that Bohr sought to highlight by his insistence on the methodological primacy of classical concepts."*

* *On Theories*, p. 134.

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 (Neo-)Bohrian 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."*

* Bell, J. S., "Subject and Object," in *Speakable and Unspeakable in Quantum Mechanics*, Cambridge University Press, 1987, p. 41, emphasis in original.

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."*
- Since, in QM, the values of observable (dynamical) quantities cannot in general be consistently interpreted (because of the big and small measurement problems) as representing the antecedently given properties of a physical system (i.e., since there is no Boolean algebra of properties that we can assign to all of the system's observables), there are two options:

* Bell, J. S., "Subject and Object," in *Speakable and Unspeakable in Quantum Mechanics*, Cambridge University Press, 1987, p. 41, emphasis in original.

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."*
- Since, in QM, the values of observable (dynamical) quantities cannot in general be consistently interpreted (because of the big and small measurement problems) as representing the antecedently given properties of a physical system (i.e., since there is no Boolean algebra of properties that we can assign to all of the system's observables), there are two options:
  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 ((neo-)Everett).

---

* Bell, J. S., "Subject and Object," in *Speakable and Unspeakable in Quantum Mechanics*, Cambridge University Press, 1987, p. 41, emphasis in original.

On a (neo-)Bohrian approach:

- Isn't opposed to the traditional metaphysical picture *per se.*

On a (neo-)Bohrian approach:

- Isn't opposed to the traditional metaphysical picture *per se.*
  - This picture would (arguably) be apt, for instance, if (textbook) classical mechanics were fundamental.

On a (neo-)Bohrian approach:

- Isn't opposed to the traditional metaphysical picture *per se.*
  - This picture would (arguably) be apt, for instance, if (textbook) classical mechanics were fundamental.
  - But we are also open to the possibility that it is not apt.

On a (neo-)Bohrian approach:

- Isn't opposed to the traditional metaphysical picture *per se.*
  - This picture would (arguably) be apt, for instance, if (textbook) classical mechanics were fundamental.
  - But we are also open to the possibility that it is not apt.
  - How we carve nature at the joints is something that should be motivated by physical theory (rather than *a priori*).

On a (neo-)Bohrian approach:

- Isn't opposed to the traditional metaphysical picture *per se.*
    - This picture would (arguably) be apt, for instance, if (textbook) classical mechanics were fundamental.
    - But we are also open to the possibility that it is not apt.
    - How we carve nature at the joints is something that should be motivated by physical theory (rather than *a priori*).

- 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.
    - However instrumentalism, in that sense, is compatible with realism on a more reasonable, methodological, construal of what it means to be a realist.

On a (neo-)Bohrian approach:

- Isn't opposed to the traditional metaphysical picture *per se.*
    - This picture would (arguably) be apt, for instance, if (textbook) classical mechanics were fundamental.
    - But we are also open to the possibility that it is not apt.
    - How we carve nature at the joints is something that should be motivated by physical theory (rather than *a priori*).

- 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.
    - 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.*

* Bohr, N. Quantum Physics and Philosophy. In R. Klibansky (ed.), *Philosophy in the Mid-Century: A Survey*, La Nuova Italia Editrice (1958): p. 310.

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.*
- This, we take it, is the methodology characteristic of what Bohr called the "ordinary causal description" of phenomena that a framework like classical mechanics makes precise, and for which quantum mechanics provides a generalisation.

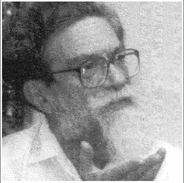
* Bohr, N. Quantum Physics and Philosophy. In R. Klibansky (ed.), *Philosophy in the Mid-Century: A Survey*, La Nuova Italia Editrice (1958): p. 310.

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.*
- This, we take it, is the methodology characteristic of what Bohr called the "ordinary causal description" of phenomena that a framework like classical mechanics makes precise, and for which quantum mechanics provides a generalisation.
- Providing an "ordinary causal description" of phenomena functions as a fundamental constraint in this sense.

* Bohr, N. Quantum Physics and Philosophy. In R. Klibansky (ed.), *Philosophy in the Mid-Century: A Survey*, La Nuova Italia Editrice (1958): p. 310.

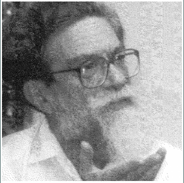
Howard Stein on the connection between observation and theory:



- 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.

* Stein, H., Some Reflections on the Structure of our Knowledge in Physics, in Prawitz et al. (eds.), *Logic, Metholodogy and Philosophy of Science IX*, Elsevier (1994): p. 638.

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.
- “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).”†

* Stein, H., Some Reflections on the Structure of our Knowledge in Physics, in Prawitz et al. (eds.), *Logic, Methology and Philosophy of Science IX*, Elsevier (1994): p. 638.

† Ibid., p. 639.

Howard Stein (continued)

- 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."*

* *Some Reflections*, p. 638.

Howard Stein (continued)

- 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 suggests that the only way to connect theory and observation is by "schematizing the observer within the theory".

* *Some Reflections*, p. 638.
† 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).

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).
- "[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).

This was well-understood by Bohr.

This was well-understood by Bohr.

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"*

---

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

Upshot: 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.

Upshot: 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. Bohr was explicit about this:

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

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

- An "observer"—or rather, an observational context—is represented as a 'Boolean frame'—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:
    - questions of the form "Is the value of A within the range Δ?"

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

- An "observer"—or rather, an observational context—is represented as a 'Boolean frame'—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:
  - 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.

* Otherwise we can move back the 'Heisenberg cut' (*Understanding Quantum Raffles pp. 202–214.*).

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.*

---

* Hughes, R. I. G. (1989), *The Structure and Interpretation of Quantum Mechanics*, Cambridge, MA: Harvard University Press, p. 61.

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.

---

* Hughes, R. I. G. (1989), *The Structure and Interpretation of Quantum Mechanics*, Cambridge, MA: Harvard University Press, p. 61.

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 (Neo-)Bohrian 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.

- 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.

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

* Curiel, E., "Classical Mechanics is Lagrangian; It is Not Hamiltonian," *The British Journal for Philosophy of Science 65*, 2014, sec. 3.

- 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.
- 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.

---

* Curiel, E., "Classical Mechanics is Lagrangian; It is Not Hamiltonian," *The British Journal for Philosophy of Science 65*, 2014, sec. 3.

- 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.
- 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.
- 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.

* Curiel, E., "Classical Mechanics is Lagrangian; It is Not Hamiltonian," *The British Journal for Philosophy of Science 65*, 2014, sec. 3.

- That said, in a given measurement context, which we can by assumption effectively describe in Boolean terms, one can give a dynamical model of the system, for that context, also in such terms.

- That said, in a given measurement context, which we can by assumption effectively describe in Boolean terms, one can give a dynamical model of the system, for that context, also in such terms.
- Such a model does not suffer—in a given measurement context—from the "small" measurement problem (since the observables associated with that context commute).

- That said, in a given measurement context, which we can by assumption effectively describe in Boolean terms, one can give a dynamical model of the system, for that context, also in such terms.
- 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.

- That said, in a given measurement context, which we can by assumption effectively describe in Boolean terms, one can give a dynamical model of the system, for that context, also in such terms.
- 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.
- 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?

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

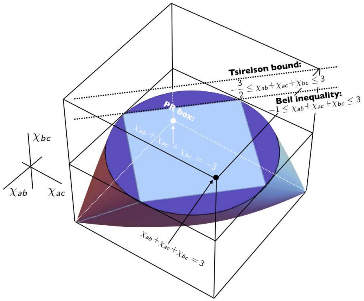
- But can nothing really be said, on the (neo-)Bohrian view, about what the world is like independently of the observational context?
- On the contrary:
  (a) Non-dynamical quantities (mass, spin, charge, etc.): valid regardless of experimental context.
  (b) Dynamical quantities: The world is such that all of the effectively classical (i.e., effectively 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!
- Does (b) depend, physically or metaphysically, on the existence of conscious observers?

- But can nothing really be said, on the (neo-)Bohrian view, about what the world is like independently of the observational context?
- 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., effectively 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!
- Does (b) depend, physically or metaphysically, on the existence of conscious observers?
  - No (or anyway this isn't the point).

- But can nothing really be said, on the (neo-)Bohrian view, about what the world is like independently of the observational context?
- 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., effectively 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!
- Does (b) depend, physically or metaphysically, on the existence of conscious observers?
  - No (or anyway this isn't the point). The point, rather, is that 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 implicit in the physical world are necessarily related to one another.

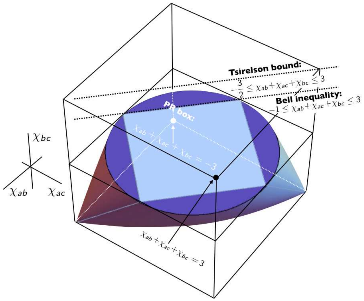
For a (neo-)Bohrian:

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



For a (neo-)Bohrian:

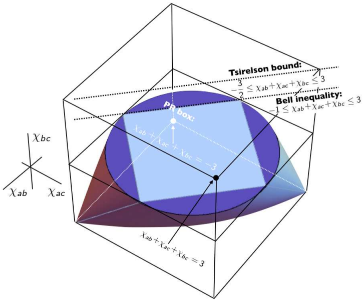
- Physics is in the business of describing the true empirical relations that obtain in the world.
- Of course, that doesn't amount to the description of a substance existing in itself in the traditional metaphysical sense.*



* Cf. Janssen, *Drawing the line*, sec. 1.2.

For a (neo-)Bohrian:

- Physics is in the business of describing the true empirical relations that obtain in the world.
- Of course, that doesn't amount to the description of a substance existing in itself in the traditional metaphysical sense.*
- But on the empiricist perspective embraced by the (neo-)Bohrian interpreter we were never committed to this.



* Cf. Janssen, *Drawing the line*, sec. 1.2.

Analogy: Helmholtz on our knowledge of physical geometry

- Helmholtz showed how Euclid's postulates I–IV presuppose the principle of the free mobility of rigid bodies.*

*DiSalle, R. (2006), *Understanding Space-time*, Cambridge: Cambridge University Press, pp. 128–129.

Analogy: Helmholtz on our knowledge of physical geometry

- Helmholtz showed how Euclid's postulates I–IV presuppose the principle of the free mobility of rigid bodies.* But Postulate V, which describes a global feature of space, does not likewise follow.

---

* DiSalle, R. (2006), *Understanding Space-time*, Cambridge: Cambridge University Press, pp. 128–129.

Analogy: Helmholtz on our knowledge of physical geometry

- Helmholtz showed how Euclid's postulates I–IV presuppose the principle of the free mobility of rigid bodies.* But Postulate V, which describes a global feature of space, does not likewise follow.
- He then showed how iterating a number of basic local constructions will result in a series of sense impressions through which one can become acquainted with the global structure of a space.

* DiSalle, R. (2006), *Understanding Space-time*, Cambridge: Cambridge University Press, pp. 128–129.

Analogy: Helmholtz on our knowledge of physical geometry

- Helmholtz showed how Euclid's postulates I–IV presuppose the principle of the free mobility of rigid bodies.* But Postulate V, which describes a global feature of space, does not likewise follow.
- He then showed how iterating a number of basic local constructions will result in a series of sense impressions through which one can become acquainted with the global structure of a space.
- His analysis of how this is done highlights the role played by the conditions for the possibility of measurement,† made precise through the concept of a rigid body, as the basis for the pre-relativistic belief that the global geometry of space is Euclidean in the first place‡

* DiSalle, R. (2006), *Understanding Space-time*, Cambridge: Cambridge University Press, pp. 128–129.

† Lenoir, T. (2006), Operationalizing Kant: Manifolds, Models, and Mathematics in Helmholtz's Theories of Perception. In Friedman, M. & Nordmann, A., *The Kantian Legacy in 19th Century Science*, pp. 180, 201.

‡ DiSalle, *Understanding Space-time*, 134–136.

Analogy: Helmholtz on our knowledge of physical geometry

- Helmholtz showed how Euclid's postulates I–IV presuppose the principle of the free mobility of rigid bodies.* But Postulate V, which describes a global feature of space, does not likewise follow.
- He then showed how iterating a number of basic local constructions will result in a series of sense impressions through which one can become acquainted with the global structure of a space.
- His analysis of how this is done highlights the role played by the conditions for the possibility of measurement,† made precise through the concept of a rigid body, as the basis for the pre-relativistic belief that the global geometry of space is Euclidean in the first place‡

QM similarly allows the "piecing together" of the Boolean algebras characterizing individual observables associated with a system, so that the resulting global structure of the system's abstract state space is non-Boolean.

---

* DiSalle, R. (2006), *Understanding Space-time*, Cambridge: Cambridge University Press, pp. 128–129.

† Lenoir, T. (2006), Operationalizing Kant: Manifolds, Models, and Mathematics in Helmholtz's Theories of Perception. In Friedman, M. & Nordmann, A., *The Kantian Legacy in 19th Century Science*, pp. 180, 201.

‡ DiSalle, *Understanding Space-time*, 134–136.

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 (Neo-)Bohrian View in a Nutshell

The (neo-)Bohrian 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",*
  - i.e., as objectively (i.e., non-contextually) associated with a given concrete measurement context (cf. Myrvold's concept of 'epistemic chance')

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

The (neo-)Bohrian 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",*
  - i.e., as objectively (i.e., non-contextually) associated with a given concrete measurement context (cf. Myrvold's concept of 'epistemic chance')
- 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.

* 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.

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.
- In other words, QM allows us to do physics in much the same way as we always have.

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.
- 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.*

* Cf. Pitowsky, 1994, p. 118.