The Heisenberg Interpretation of Quantum Mechanics

Armin Nikkhah Shirazi

University of Michigan, Ann Arbor
armin@umich.edu

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Physics and Philosophy by Werner Heisenberg

In lecture series and a book in the 1950's entitled *Physics and Philosophy*, Heisenberg drew a distinction, inspired by Aristotelian philosophy, which is encapsulated by this quote:

> *In the experiments about atomic events we have to do with things and facts, with phenomena that are just as real as any phenomena in daily life. But the atoms or the elementary particles themselves are not as real; they form a world of potentialities or possibilities rather than of things or facts.*
>
> *(Physics and Philosophy: The Revolution in Modern Science, p. 160)*

Turning the Philosophical Thesis into a Scientific Hypothesis

Heisenberg formulated his distinction merely as a philosophical thesis, not a scientific hypothesis. In this talk, I present an attempt to turn it into a scientific hypothesis.

As a warm-up, consider first classical probability theory

- Suppose I hold a fair die, not yet cast. Possible outcomes ‘exist’ as mutually incompatible potentialities
- Mathematically, this can be modeled in terms of an inverse projection: *A fiber of potentialities*
- Will use the term *actualizability* instead of potentiality to divest connotations of latter term unrelated to quantum mechanics and avoid confusion with the word ‘potential’ (actualizable=capable of becoming actual)

Actualizability in Axiomatic Probability Theory

Let $\Omega = \bigcup_{i=1}^{N} E_i$ be a set where N is either finite or countably infinite, $\mathcal{A} \subseteq \mathcal{P}(\Omega)$ a set of its mutually exclusive subsets E_i, and call the pair $(\Omega, \mathcal{A})$ a measurable space. Let $\Gamma = \{\gamma | \gamma = f(\omega)\}$ be a set where $f : \Omega \to \Gamma$ is a bijection and let $g : \Omega \to \Gamma$ be another map.

A real-valued function $P : \mathcal{A} \to \mathbb{R}$ satisfying

- Axiom 0: $P(g^{-1}(\gamma)) = P(\Omega)$
- Axiom 1: $P(\Omega) = 1$
- Axiom 2: $0 \leq P(E_i) \leq 1$
- Axiom 3: $P \bigcup_{i=1}^{N} E_i = \sum_{i=1}^{N} P(E_i)$

is called a *probability*.

Notice: To define a *non-probabilistic* unit measure, simply omit the red parts above; but then one obtains Kolmogorov's axioms! $\implies$ **Original axioms do not actually define a probability!**

The Equality of Inequivalents Problem

Consider the distinction between classes of “possibilities or potentialities” and “things or facts”:

- Mutually incompatible possibilities can coexist, mutually incompatible facts cannot $\Longrightarrow$ Facts and possibilities are mutually exclusive
- Facts and possibilities cover set of descriptions of all physical systems

$\Longrightarrow$ Facts and possibilities *partition* that set
$\Longrightarrow$ Facts and possibilities are equivalence classes

If Quantum-Classical distinction is based on this distinction, it inherits equivalence class structure.

Now consider quantum superposition:

$$|\psi\rangle = \sum_k c_k |\psi_k\rangle$$

Standard Quantum Formalism permits two distinct interpretations:

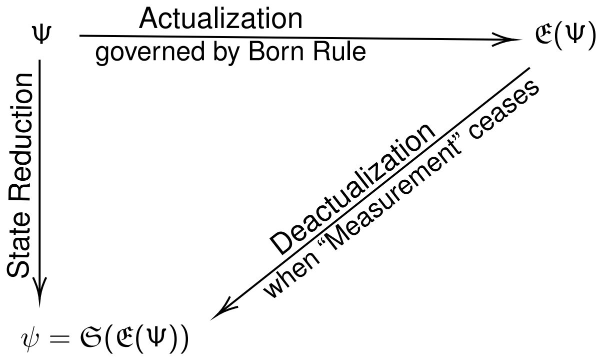
1. Right side always represent possibilities (=mutually incompatible coexisting states)
2. Interpretation 1: Left side represents unmeasured quantum state $\Longrightarrow$ Unproblematic
3. Interpretation 2: Left side represents an eigenstate under measurement $\Longrightarrow$ Problem: Members of distinct equivalence classes cannot be equal to each other!

This means, distinction cannot be introduced into standard formalism without making it incoherent!

The Heisenberg Interpretation of Quantum Mechanics

- *Postulate* 0*:* The L^2 complex Hilbert space $\mathcal{H}$ is an actualizability space.
- *Postulate* 1*:* The physical states of a quantum systems are completely represented by elements of $\mathcal{H}$, denoted by $|\Psi(t)\rangle$.
- *Postulate* 2*:* Observables are represented by linear Hermitian operators acting on the elements of $\mathcal{H}$.
- *Postulate* 3*:* The time evolution of an element $|\Psi(t)\rangle$ of $\mathcal{H}$ is given by the Hamiltonian operator $\hat{H}$: $i\hbar\frac{d}{dt}|\Psi(t)\rangle = \hat{H}|\Psi(t)\rangle$
- *Postulate* 4*:* A "Measurement" of the property of a state is represented by a map $\mathfrak{E} : \mathcal{H} \to \mathcal{C}$, where $\mathcal{C}$ is the unstructured collection of all basis states of $\mathcal{H}$ in all bases as actualities, which will be called *'classical states'*, and $\mathfrak{E}$ will be called the *actualization map*. The image of the map domain is denoted $\mathcal{B} \subset \mathcal{C}$, the collection of all basis states as actualities in the measurement basis.
- *Postulate* 5*:* The Probability of obtaining the property of the classical state $\mathfrak{E}(|\Psi\rangle)$ corresponding to the eigenvalue λ of an eigenstate $|\psi\rangle$ upon a measurement of $|\Psi\rangle$ is given by the integral of $|\langle\psi|\Psi\rangle|^2$.
- *Postulate* 6*:* The Completion of a measurement is represented by a map $\mathfrak{S} : \mathcal{B} \to \mathcal{H}$ such that $\mathfrak{S}(\mathcal{E}(|\Psi\rangle)) = |\psi\rangle$, an eigenstate of $|\Psi\rangle$, where $\mathfrak{S}$ will be called the *deactualization map.*

State Reduction as the composition of two maps



- Note that $\mathcal{E}(\Psi)$ is the counterpart as an actuality of the eigenstate ψ.

Advantages over Standard Formalism

1. The HI resolves the Equality of Inequivalents problem
2. The HI circumvents the violation of unitary time evolution
3. The HI grounds the Heisenberg cut in the formalism
4. The HI supplies a partial ontology for the Born Rule
5. The HI focuses attention on deactualization
6. The HI reframes quantum non-locality as correlated actualization
7. The HI clarifies the role of configuration space as a home for the wave function
8. The HI may render the spacetime picture of quantum mechanics more intuitive
9. The HI brings attention to novel kinds of symmetry
10. The HI may indicate a refinement for the scope of quantum decoherence
11. The HI may set the stage for novel predictions
12. The HI suggests a more fundamental successor to Quantum Mechanics

The HI resolves the Equality of Inequivalents Problem

- Under the Heisenberg interpretation, in the equation

$$|\psi\rangle = \sum_k c_k |\psi_k\rangle$$

  the left side *cannot* represent a state under measurement
- A state under measurement is represented by $\mathcal{E}(|\psi\rangle)$, which is never equal to a quantum superposition because it is not an element of a Hilbert Space.

HI circumvents Violation of Unitary Time Evolution

- Incompatibility between Schrödinger evolution and state collapse has been there since von Neumann's formalization of Quantum Mechanics in 1932.
- Incompatibility is only a problem if they share a common domain of applicability.
- The Heisenberg Interpretation separates the domains:
  - $|\Psi\rangle$ obeys Schrödinger evolution
  - $\mathcal{E}(|\Psi\rangle)$ does not obey Schrödinger evolution, but since it is not an element of a Hilbert space, Schrödinger evolution does not apply
  - $\mathfrak{S}(\mathfrak{E}(|\Psi\rangle)) = |\psi\rangle$ obeys Schrödinger evolution once more
- $\implies$ The Heisenberg Interpretation "steps around the problem" of non-conservation of probability.

Classical probability can be interpreted to undergo a similar process:

- Before a die throw, possible outcomes are elements of an actualizability fiber=sample space
- Result of throw is not an element of the sample space $\implies$ Probability does not apply to it
- Preparing for new throw is represented by sample space once again.

HI Brings Attention to Novel Symmetries

- Ontic Status Symmetry: Invariance of ontic status under interchange of system (Standard Formalism)
- Actualization Symmetry: Invariance of Actualizer/Actualizee under interchange of system (Heisenberg Interpretation)

Actualization Symmetry	**Ontic Status Symmetry**
Pertains to quantum system and microscopic constituent of measurement apparatus	Pertains to quantum system and whole apparatus
Requires ontic distinction	Precludes ontic distinction
"Measurement" must be an ontic transformation	"Measurement" cannot be an ontic transformation
Compatible with deactualization	Incompatible with deactualization
Incompatible with a wave function for the universe	Compatible with a wave function for the universe

- Awareness of different symmetries may prevent "talking past each other".

HI sets stage for new experimental predictions

- “Setting the Stage for a prediction” vs. “Making a prediction” $\Longrightarrow$ Need some external assumption on how Gravity relates to HI
- Simplest and most natural: “Classical” means “subject to General Relativity”
- Introduces a sharp boundary between GR and the Standard Model. Predictions:
  - Each “Measurement” creates a (tiny) gravitational field
  - Light, falling on the quantum side of the boundary, is not a gravitational field source
    - Note: Argument from conservation of momentum in gravitational bending of light does not apply to potentialities
- A feasible test (but not cheap): Measure the gravity field of an ultra high-energy density laser beam.
  - If a field is found in accordance with current paradigm, then HI is false, but it gives first definite experimental evidence for quantum gravity.
  - If a null-result is obtained, will upset current paradigm
  - Either result will make experiment a success!

Conclusion: A Work in Progress

- In this talk, I introduced The Heisenberg interpretation of quantum mechanics.
- It offers a number of advantages over the standard formalism, but commits one to a sharp quantum-classical distinction
- If it captures distinctions in reality correctly, it hints at a successor theory to quantum mechanics in which the mathematical structures are modal.
- More work needs to be done to work out details of actualization/deactualization
- The Heisenberg interpretation suggests that a gravity of light experiment has the potential to revolutionize physics.

Thank you!