Copenhagen Interpretation

Quantum Foundations · Module 6 — Interpretations

Node 6.2

Position in Knowledge Graph

System: Quantum Foundations **Structural Domain:** Interpretations **Node:** 6.2

Copenhagen is the historical default interpretation of quantum mechanics — the view Niels Bohr, Werner Heisenberg, and their colleagues developed in the late 1920s and which appears, explicitly or implicitly, in nearly every introductory textbook. It resolves the measurement problem of Node 6.1 by *postulating* a cut between quantum and classical domains and refusing to formalize where the cut lies. The wavefunction is interpreted operationally or epistemically, not as a physical field. This node states the formal content of Copenhagen precisely, separates it from the various later "Copenhagen-ish" views it is sometimes conflated with, and evaluates it against the three criteria of Node 6.1: formal completeness, empirical equivalence, and ontological commitments.

Formal Statement

The two-domain structure

Copenhagen partitions physical situations into two domains, following Bohr's framing:

1. **Quantum domain.** Systems described by a state vector $|\psi\rangle \in \mathcal{H}$ evolving under the Schrödinger equation $i\hbar\partial_t|\psi\rangle = H|\psi\rangle$. All of Nodes 2.1–2.6 applies. The state is a complete description of the system's *predictive resources*, not necessarily a description of objective facts about the system.
2. **Classical domain.** Macroscopic apparatuses, observers, and measurement outcomes. These are described in the language of classical physics — definite positions, definite pointer readings, definite events. Classical concepts are *necessary* for the formulation of experiment: one cannot specify what is being measured without using classical language to describe the apparatus.

Between the two domains sits the **Heisenberg cut**: a (movable, methodological) boundary separating quantum from classical. The location of the cut is a choice made by the physicist for the purposes of a particular analysis — it is not a structural feature of nature.

The measurement rule

When a measurement is performed, the system's state collapses according to the projection postulate of Node 2.3:

$$|\psi\rangle \mapsto \frac{P_i|\psi\rangle}{\sqrt{\langle\psi|P_i|\psi\rangle}}, \qquad p(i) = \langle\psi|P_i|\psi\rangle.$$

The collapse is *physically ambiguous* in Copenhagen. It is a rule for updating the predictive state of the quantum system conditional on a macroscopically recorded outcome, not a physical process occurring at a precise moment. The question "exactly when did the wavefunction collapse?" is declared to be meaningless:

collapse is whatever is needed to make the quantum-domain description consistent with the classical-domain outcome.

Epistemic reading of the wavefunction

In Copenhagen, $|\psi\rangle$ is not a physical property of the system. It is a *calculational tool* that encodes the observer's knowledge (or the experimental setup's predictive resources) and allows the derivation of probabilities for future measurement outcomes. The question "what is the system actually doing between measurements?" is declared to be outside the scope of physics.

Different authors within the Copenhagen tradition vary on how strictly this epistemic reading is held. Bohr himself was careful not to commit to an ontological reading but emphasized the role of the classical apparatus. Heisenberg oscillated between epistemic and ontological readings. The "shut up and calculate" attitude associated with Mermin (who disavowed it) is a caricature but captures the operational spirit.

Intuition

Copenhagen is, in effect, the interpretation one arrives at by *refusing to ask* the questions that the measurement problem poses. The strategy is to draw a line at the outputs of measuring devices — classical pointer readings — and insist that physics makes predictions about these outputs via the Born rule, without committing to any story about what the wavefunction *is* or what happens *between* measurements. The epistemic reading is a natural fit: the wavefunction is whatever the physicist knows about the system, and "collapse" is just the update when new information arrives.

The appeal of Copenhagen is its operational minimalism. It requires no metaphysical commitments beyond the Born rule and the existence of classical apparatuses. It works for every actual calculation physicists do. It does not require you to believe in branching universes, hidden particles, or personal probabilities. For decades it was the interpretation physicists would give if pressed, and it is still the implicit framework of most laboratory practice.

The cost is precision: Copenhagen does not say *where* the cut lies or *what* counts as a measurement. A photomultiplier is a classical apparatus; what about a coherent superposition of photomultiplier readings? A single atom is a quantum system; what about an atom being measured by a single photon? Copenhagen's answer is that the cut can be placed anywhere that makes the analysis work — which is to say, the formalism does not determine where it should be placed. This is Bohr's **complementarity**: the placement of the cut is a feature of the observer's description, not of the physical situation.

Structural Role

Copenhagen plays a specific role within the space of interpretations:

- **The operational floor.** Whatever else an interpretation claims, it must reproduce the Born-rule predictions that Copenhagen takes as axiomatic. Every subsequent interpretation of this module accepts Copenhagen's empirical content and then attempts to provide a structural *story* behind it.
- **Resistance to the measurement problem.** Copenhagen's strategy is to declare that the measurement problem is ill-posed: there is no need to reconcile unitary evolution with collapse, because they apply in different domains. This is a *refusal* rather than a resolution, but it is internally consistent as long as the cut can always be drawn somewhere sensible.
- **The interpretive zero point.** Because Copenhagen makes no claims beyond the operational minimum, it serves as the reference against which other interpretations can be measured. Many-Worlds (6.3) removes the collapse rule; Bohmian mechanics (6.4) adds hidden variables; QBism (6.5) makes the epistemic reading explicit and agent-centric. Each modifies Copenhagen along a specific axis.
- **Tension with structural realism.** Copenhagen is strongly anti-realist about the wavefunction (or at best agnostic). This makes it compatible with Bohrian philosophical views but incompatible with

any program that wants quantum mechanics to describe an observer-independent reality. Modern foundational work (Module 10) tends to treat Copenhagen as a *starting point* rather than a final resting place.

Mathematical Development

The Heisenberg cut as a boundary-condition choice

When analyzing an experiment involving a system S and an apparatus A, Copenhagen allows the Heisenberg cut to be placed anywhere along the chain from S to the final observer. Placing the cut between S and A means:

$$\rho_S = \sum_i p(i)|\phi_i\rangle\langle\phi_i|, \qquad p(i) = \text{Born rule for } S \text{ measurement.}$$

A is treated classically, with $p(i)$ as the probability of a classical pointer outcome.

Placing the cut after A means:

$$|\Psi_{SA}\rangle = \sum_i c_i|\phi_i\rangle_S|a_i\rangle_A,$$

a unitary-evolved entangled state of system and apparatus, with the cut deferred to a later stage (a second apparatus, the observer's eye, the observer's brain). Copenhagen asserts that both descriptions are operationally equivalent: they give the same predictions for whatever classical outcome is ultimately recorded.

The *mathematical* equivalence is straightforward (tracing out A in the second description gives the same statistics as the first). The *interpretive* content is that the precise location of the cut is undetermined by the formalism and must be chosen by the analyst.

Relation to decoherence

Decoherence (Module 5) provides a partial dynamical justification for the Heisenberg cut: macroscopic apparatuses decohere extremely rapidly, so their reduced density matrices become effectively diagonal in the pointer basis almost instantly. From a purely *operational* standpoint this means the apparatus's coherences cannot be detected, and so it may as well be classical.

Decoherence does *not*, however, solve the measurement problem within Copenhagen — the off-diagonal elements of the reduced density matrix become small but never actually zero, and the reduced state is still a mixed state encoding a superposition at the joint level. Copenhagen's response is that once the coherences are below detection thresholds, the pragmatic thing to do is to drop them and use a classical description. This makes the Heisenberg cut a *defensible approximation* rather than an arbitrary stipulation.

Nonetheless, from the point of view of Module 6.1's formal criterion, Copenhagen remains **formally incomplete**: it does not specify exactly when the cut should be drawn, only that it can always be drawn somewhere.

Contextuality and the observer

Bohr emphasized that the choice of experimental setup (including which classical apparatus is used) is part of the physical situation. Measuring Z and measuring X on the same qubit are not two readings of the same underlying reality — they are two *complementary* experimental contexts, each valid on its own but mutually exclusive. This view of **contextuality** anticipates the formal Kochen–Specker theorem (Node 10.2), which makes the impossibility of non-contextual hidden variable assignments rigorous. In Copenhagen, contextuality is not a bug but a feature: the classical apparatus is part of the description, and there is no observer-free quantum reality.

What Copenhagen *cannot* say

Copenhagen forbids certain questions as meaningless:

- "Which path did the particle take through the interferometer?" Meaningless, because no which-path detector was present.
- "What value did the observable have before it was measured?" Meaningless, because the question presupposes a pre-measurement value.
- "Where exactly did the wavefunction collapse?" Meaningless, because collapse is a methodological update, not a physical event.

This refusal to answer is the source of Copenhagen's critics' dissatisfaction. For operationalists, the refusal is appropriate — it marks the limits of what physics can say. For realists, it is evasive — the questions are about objective facts about nature and deserve answers.

Worked Example

Stern–Gerlach as the paradigm

The Stern–Gerlach experiment sends a beam of spin-1/2 atoms through an inhomogeneous magnetic field. Atoms with $S_z = +\hbar/2$ are deflected one way; atoms with $S_z = -\hbar/2$ are deflected the other way. A screen registers two spots.

In Copenhagen's framing:

- The **atom** (or rather, its spin) is a quantum system with state $|\psi\rangle_S$.
- The **magnet** is a classical apparatus. Its magnetic field is a classical field configuration — not a quantum field in a coherent state.
- The **detector screen** is another classical apparatus.

A single atom prepared in state $|\psi\rangle = \alpha|+\rangle + \beta|-\rangle$ passes through the apparatus. The classical description of the outcome is: with probability $|\alpha|^2$ the atom hits the upper spot, with probability $|\beta|^2$ the lower. The quantum-to-classical collapse is what happens at the detector.

The Heisenberg cut can be placed at different positions:

- **At the magnet:** The atom's spin is measured by the classical magnetic field. Outcome probabilities are computed by Born rule.
- **At the screen:** The atom+magnet system evolves unitarily into an entangled state $\alpha|+\rangle|\text{upper path}\rangle + \beta|-\rangle|\text{lower path}\rangle$, and the screen measures which path by classical detection.

Both analyses give the same predictions. Copenhagen is silent about "which one is correct" — either is acceptable as long as the computed probabilities match.

The contextual role of the magnet is essential: if instead of the z-field magnet a horizontal one were used, the apparatus would measure S_x and give different outcome probabilities. Copenhagen refuses to say that the spin "had" either an S_z or S_x value before the measurement — the apparatus choice is part of the specification of the observable.

Double-slit

A particle passes through a double-slit screen and hits a detector. Copenhagen's analysis:

- Without a which-path detector: the particle's state is in superposition across the two slits; interference pattern emerges at the detector; one cannot speak of the particle having taken a definite path.
- With a which-path detector: the particle's state is effectively measured at the slit; interference is destroyed; one of the two paths is recorded.

The classical-domain description of the experimental setup (which detectors are present) determines what can be said about the quantum-domain state. Questions like "which slit did the particle actually pass through in the interference case?" are declared meaningless by Copenhagen.

Contrast with a hidden-variable analysis

A Bohmian analysis (Node 6.4) of the same experiment would assign a definite trajectory to the particle, moving through one specific slit. Copenhagen would reject this as unnecessary metaphysical commitment: all predictions are reproduced by the standard analysis, so why commit to trajectories that are in principle unobservable?

The structural disagreement is not empirical — Copenhagen and Bohmian mechanics make the same predictions — but about what counts as a *satisfying* theory. Copenhagen says: if the predictions are right, there is nothing more to ask. Bohmian mechanics says: if predictions are all we care about, physics has abandoned its claim to describe reality.

Cross-Links

- **Module 6.1 (Measurement problem):** Copenhagen's strategy is to deny the problem is well-posed. This is internally consistent but formally incomplete.
- **Module 5.5 (Pointer basis / einselection):** Decoherence provides a dynamical story for *why* macroscopic apparatuses can be described classically, without solving the measurement problem.
- **Module 2.3 (Born rule):** Copenhagen takes the Born rule as axiomatic; other interpretations attempt to derive it.
- **Module 10.2 (Kochen–Specker):** Formalizes contextuality — Copenhagen's insistence on apparatus-dependent observables turns out to be forced, not a choice.
- **Statistics:** Frequentist statistics has a similar operational orientation — refuses to assign probabilities to hypotheses, only to observed outcomes under fixed experimental setups.

Structural Compression

Invariant: Copenhagen posits a methodological (not ontological) cut between a quantum domain of unitary dynamics and a classical domain of definite outcomes. The wavefunction is epistemic, not physical. The measurement rule is a calculational prescription, not a physical process.

Mechanism: Heisenberg cut, deliberately not formalized. Unitary evolution in the quantum domain, Born-rule probability updating at the cut, classical description of apparatuses.

Cross-System Echo: Frequentist statistics refuses to formalize the prior; Copenhagen refuses to formalize the cut. Both are operational frameworks that gain precision by restricting what questions can be asked.

Exercises

1. State precisely the criteria under which the Heisenberg cut may be placed in a Copenhagen analysis. What formal requirement must hold for the two sides of the cut to be "equivalent"?
2. Argue why decoherence makes the Heisenberg cut a defensible approximation but does not eliminate its arbitrariness.
3. For the Stern–Gerlach experiment, construct the joint state of atom + magnet before the detector screen measures the position. Verify that tracing out the magnet gives the same outcome probabilities as treating the magnet as a classical measuring device.
4. Explain why Copenhagen is formally incomplete (in the sense of Node 6.1) despite being empirically adequate.

5. In what sense is Copenhagen "realist" about the classical domain but not about the quantum domain? Is this combination internally consistent?
6. Compare the Copenhagen treatment of the measurement problem with its treatment of Bell nonlocality (Module 10.1). Is Copenhagen's refusal to assign pre-measurement values consistent with Bell's theorem?
7. Argue, structurally, why Copenhagen's operational minimalism has kept it the default interpretation of working physicists even as foundational work has moved beyond it.

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Concepts: born-rule
Prerequisites: 6.1
Enables: 6.6

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