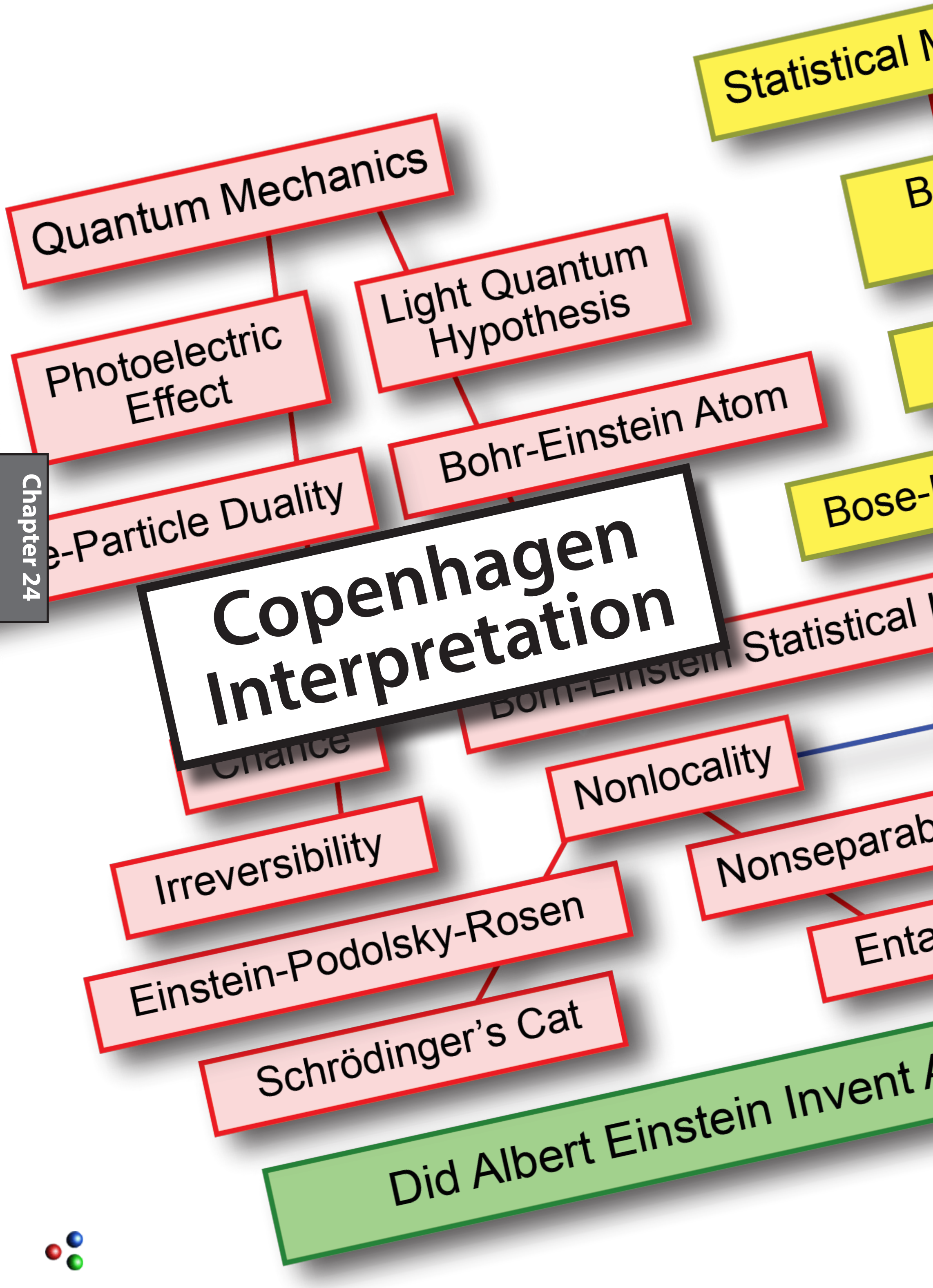
Quantum Mechanics
Light Quantum Hypothesis
Photoelectric Effect
Bohr-Einstein Atom
Copenhagen Interpretation
Nonlocality
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Schrödinger's Cat

Copenhagen Interpretation

The idea that there was a Copenhagen way of thinking was christened as the "*Kopenhagener Geist der Quantentheorie*" by Werner Heisenberg in his 1930 textbook *The Physical Principles of Quantum Theory*, based on his 1929 lectures in Chicago (given at the invitation of Arthur Holly Compton).

The basic ideas of Copenhagen thinking were presented by Niels Bohr and Heisenberg at the 1927 Solvay conference on physics entitled "Electrons and Photons."

It is a sad fact that Albert Einstein, who had discovered more than any other scientist on the quantum interaction of electrons and photons, was largely ignored or misunderstood when he clearly described nonlocality at the 1927 conference. As we saw in the previous chapter, Bohr said he could not understand what Einstein was talking about.

At the Solvay conference, Bohr and Heisenberg consolidated their Copenhagen view as a "complete" picture of quantum physics, despite the fact that they could not, or would not, visualize or otherwise explain exactly what is going on in the microscopic world of "quantum reality." Electron paths (especially orbits) that cannot be observed, they said, simply do not exist!

Bohr and Heisenberg opposed Einstein's concept of an underlying "objective reality," but they clearly knew and said that the physical world is largely independent of human observations. In classical physics, the physical world is assumed to be completely independent of the act of observing the world.

In quantum physics however, Heisenberg said that the result of an experiment depends on the "free choice" of the experimenter as to what to measure. The quantum world of photons and electrons might look like waves or look like particles depending on what we look for, rather than what they "are" as "things in themselves."

Copenhageners were proud of their limited ability to know what is going on in the microscopic world.

According to his friend Aage Petersen, Bohr said:

> There is no quantum world. There is only an abstract quantum physical description. It is wrong to think that the task of physics is to find out how nature is. Physics concerns what we can say about nature.[1]

Bohr thus put severe *epistemological* limits on knowing the "things in themselves," just as Immanuel Kant had put limits on reason in the phenomenal world. The British empiricist philosophers John Locke and David Hume had put the "primary" objects beyond the reach of our "secondary" sensory perceptions. In this respect, Bohr shared the positivist views of many other empirical scientists and philosophers, Ernst Mach for example.

Twentieth-century analytic language philosophers like Bertrand Russell and Ludwig Wittgenstein thought that philosophy (and even physics) could not solve some basic problems, but only "dis-solve" them by showing them to be conceptual errors resulting from the misuse of language.

Neither Bohr nor Heisenberg thought that macroscopic objects actually *are* classical. They both saw them as composed of microscopic quantum objects. The information interpretation of quantum mechanics says there is only one world, the quantum world. Averaging over large numbers of microscopic quantum objects explains why macroscopic objects *appear* to be classical.

On the other hand, Bohr and Heisenberg insisted that the language of classical physics is essential as a tool for knowledge.

Heisenberg wrote:

> The Copenhagen interpretation of quantum theory starts from a paradox. Any experiment in physics, whether it refers to the phenomena of daily life or to atomic events, is to be described in the terms of classical physics. The concepts of classical physics form the language by which we describe the arrangement of our experiments and state the results. We cannot and should not replace these concepts by any others. Still the application of these concepts is limited by the relations of uncertainty. We must keep in mind this limited range of applicability of the classical concepts while using them, but we cannot and should not try to improve them.[2]

1 *Bulletin of the Atomic Scientists*. Sep 1963, Vol. 19 Issue 7, p.12

2 Heisenberg, 1955, p. 44

Einstein wanted us to get beyond questions of logic and language to get to an "objective reality" he saw as independent of the mind of man. Logic alone tells us nothing of the physical world, he said.

But since language has evolved to describe the familiar world of "classical" objects in space and time, Bohr and Heisenberg insisted that somewhere between the quantum world and the classical world there must come a point where our observations and measurements can be expressible in classical concepts. They argued that a measurement apparatus and a particular observation must be describable classically in order for it to be understood and become knowledge in the mind of the observer.

The exact location of that transition from the quantum to the classically describable world was arbitrary, said Heisenberg. He called it a "cut" (*Schnitt*). Heisenberg's and especially John von Neumann's and Eugene Wigner's insistence on a critical role for a "conscious observer" has led to a great deal of nonsense being associated with the Copenhagen Interpretation and in the philosophy of quantum physics. Heisenberg may only have been trying to explain how knowledge reaches the observer's mind. But for von Neumann and Wigner, the mind was actually considered a *causal factor* in the behavior of the quantum system. It is not.

Today, a large number of panpsychists, some philosophers, some scientists, still believe that the mind of a conscious observer is needed to cause the "collapse of the wave function." We explore von Neumann's "psycho-physical parallelism" in the next chapter.

In the mid-1950's, Heisenberg reacted to David Bohm's 1952 "pilot-wave" interpretation of quantum mechanics by calling his work with Bohr the "Copenhagen Interpretation" and indeed insisted it is the only correct interpretation of quantum mechanics. A significant fraction of working quantum physicists today say they agree with Heisenberg, though few have ever looked carefully into the fundamental assumptions of the Copenhagen Interpretation.

We'll see that much of the Copenhagen interpretation is standard quantum physics and correct. But it also contains a lot of nonsense that has made understanding quantum physics difficult and spawned several quantum mysteries that we hope to resolve.

What Exactly Is in the Copenhagen Interpretation?

There are several major components to the Copenhagen Interpretation, which most historians and philosophers of science agree on:

No Observer-Independent Quantum Reality. The most radical concept of the Copenhagen school is that because the wave function gives us only probabilities about quantum properties, that these properties do not exist in the sense of Einstein's "objective reality."

No Path? Bohr, Heisenberg, and others said we cannot describe a particle as having a path, or a definite position before a measurement. Indeed, it is said a particle can be in two places at once, like going through the two slits in the two-slit experiment.

But just because we cannot know the path does not mean it cannot exist. Einstein's "objective reality" hoped for a deeper level of physics in which particles do have paths (even if we cannot know them) and, in particular, the paths obey conservation principles.

Conscious Observer. This is the claim that quantum systems cannot change their states without an observation being made by a conscious observer. Does the collapse only occur when an observer "looks at" the system? How exactly does the mind of the observer have causal power over the physical world? (the mind-body problem). John Bell asked sarcastically, "does the observer need a Ph.D.?"

Einstein objected to the absurd idea that his bed had diffused throughout the room and only gathered itself back together when he opened the bedroom door and looked in. Does the moon only exist when somoone is looking at it?, he asked.

John von Neumann and Eugene Wigner seemed to believe that the mind of the observer was essential, but it is not found in the original work of Bohr and Heisenberg, so should perhaps not be a part of the Copenhagen Interpretation? It has no place in standard quantum physics today.

Wave-particle duality. Einstein's 1909 insight into this dual aspect of quantum mechanics led to Bohr's deep philosophical notion of *complementarity*, though Bohr did not mention Einstein.

Bohr wanted a synthesis of the particle-matrix mechanics theory of Heisenberg, Max Born, and Pascual Jordan, with the wave mechanical theory of Louis de Broglie and Erwin Schrödinger,. Wave theory became critical to Bohr's concept of complementarity, which we sw in chapter 22.

Heisenberg had to have his arm twisted by Bohr in 1927 to accept the equal importance of the wave description.

Copenhagen says quantum objects *are both* waves and particles, that what you see depends on how you look at them. In Einstein's "objective reality," physical objects are particles. Waves are mathematical theories about their behavior, giving us the *probabilities* of where they will be found, and with what properties.

No Visualizability? Bohr and Heisenberg both thought we could not produce models of what is going on at the quantum level. Bohr thought that since the wave function cannot be observed we can't say anything about it. Heisenberg said it was a probability and the basis for the statistical nature of quantum mechanics.

Whenever we draw a diagram of waves impinging on the two-slits, we are in fact visualizing the wave function as possible locations for a particle, with calculable probabilities for each possible location.

The Quantum Postulates. Bohr postulated that quantum systems (beginning with his "Bohr atom" in 1913) have "stationary states" which make discontinuous "quantum jumps" between the states with the emission or absorption of radiation. Until at least 1925 Bohr insisted the radiation itself is *continuous*. Einstein had said radiation is a *discrete* localized "light quantum" (later called a photon) as early as 1905.

Ironically, ignorant of the history (dominated by Bohr's account), most of today's physics textbooks teach the "Bohr atom" as emitting or absorbing photons - Einstein's light quanta!

Indeterminacy principle. Heisenberg sometimes called it his "uncertainty" principle, which implies human ignorance, making it an epistemological (knowledge) problem rather than an ontological (reality) problem. Indeterminacy is another example of complementarity, between the non-commuting conjugate variables momentum and position, for example, $\Delta p\ \Delta x \geq h$. Energy and time, as well as action and the angle variables, are also complementary.

Completeness. Copenhageners claim that Schrödinger's wave function ψ provides a "complete" description of a quantum system, despite the fact that conjugate variables like position and momentum cannot both be known with arbitrary accuracy, as they can in classical systems. There is less information in the quantum world than classical physics requires. The wave function ψ evolves according to the unitary deterministic Schrödinger equation of motion, conserving that information. When one possibility discontinuously becomes actual, new information may be irreversibly created and recorded by a measurement apparatus.

Einstein, however, maintained that quantum mechanics is *incomplete*, because it provides only statistical information derived from ensembles of quantum systems.

Correspondence principle. Bohr maintained that in the limit of large quantum numbers, the atomic structure of quantum systems approaches the behavior of classical systems. Bohr and Heisenberg both described this case as when Planck's quantum of action h can be neglected. They mistakenly described this as $h \rightarrow 0$.

Planck's h is a constant of nature, like the velocity of light. The quantum-to-classical transition is when the action of a macroscopic object is large compared to h. Bohr compared it to non-relativistic physics when the velocity v is small compared to the velocity of light. It is not an apt comparison because h never becomes small. It is when the number of quantum particles increases (as mass increases) that large macroscopic objects behave like classical objects. Position and velocity become arbitrarily accurate as $h / m \rightarrow 0$.

$\Delta v\ \Delta x \geq h / m.$

The correspondence between classical and quantum physics occurs for large numbers of particles that can be averaged over and for large quantum numbers. This is known as the quantum-to-classical transition.

Standard Quantum Physics. Paul Dirac formalized quantum mechanics with three fundamental concepts, all very familiar and accepted by Bohr, Heisenberg, and the other Copenhageners:

Axiom of measurement. Bohr's stationary quantum states have eigenvalues with corresponding eigenfunctions (the eigenvalue-eigenstate link).

Superposition principle. According to Dirac's transformation theory, ψ can be represented as a linear combination of vectors that are a proper basis for the combined target quantum system and the measurement apparatus.

Projection postulate. The collapse of the wave function ψ, which is irreversible, upon interacting with the measurement apparatus and creating new information.

Irreversibility. Without irreversible recording of information in the measuring apparatus (a pointer reading, blackened photographic plate, Geiger counter firing, etc.), there would be nothing for observers to see and to know.

All the founders of quantum mechanics mention the need for irreversibility. The need for entropy transfer to stabilize irreversibly recorded information so it could be observed was first shown by Leo Szilard in 1929, later by Leon Brillouin and Rolf Landauer.

Classical apparatus. Bohr's requirement that the macroscopic measurement apparatus be described in ordinary "classical" language is a third kind of "complementarity," between the microscopic quantum system and the macroscopic "classical apparatus."

But Born and Heisenberg never actually said the measuring apparatus is "classical." They knew that everything is fundamentally a quantum system.

Statistical Interpretation (probability and acausality). Born interpreted the squared modulus of Schrödinger's complex wave function as the probability of finding a particle. Einstein's "ghost field" or "guiding field," de Broglie's pilot or guide wave, and Schrödinger's wave function as the distribution of the electric charge density were similar views in earlier years.

All the predicted properties of physical systems and the "laws of nature" are only probabilistic (acausal). All the results of physical experiments are purely statistical information.

Theories give us probabilities. Experiments give us statistics.

Large numbers of identical experiments provide the statistical evidence for the theoretical probabilities predicted by quantum mechanics. We know nothing about paths of individual particles.

Bohr's emphasis on epistemological questions suggests he thought that the statistical uncertainty may only be in our knowledge. It may not describe nature itself. Or at least Bohr thought that we can not describe a "reality" for quantum objects, certainly not with classical concepts and language. But we shall see that the concept of an abstract and immaterial wave function (ψ as pure information moving through space, determined by boundary conditions) makes quantum phenomena "visualizable."

Ontological acausality, chance, and a probabilistic or statistical nature were first seen by Einstein in 1916, as Born acknowledged. He knew that "his statistical interpretation" was based entirely on the work of Einstein, who generously gave Born credit, partly because of his doubts about any theory in which "God plays dice!"

Two-slit experiment. A "gedanken" experiment in the 1920's, but a real experiment today, exhibits the combination of wave and particle properties.

Note that what the two-slit experiment really shows is

- first, the wave function deterministically and *continuously* exploring all the possibilities for interaction, its values determined by the boundary conditions of the experiment.
- second, the particle randomly and *discontinuously* chooses one of those possibilities to become actual. In Einstein's "objective reality" view, the particle goes through one slit, and the wave function, being different when two slits are open, guides the particle to display the two-slit interference pattern.

Measurement problem. There are actually at least three definitions of the measurement problem not normally associated with the Copenhagen Interpretation..

1) The claim that the two dynamical laws, unitary deterministic time evolution according to the Schrödinger equation and indeterministic collapse according to Dirac's projection postulate are logically inconsistent. They cannot both be true, it's claimed.

The proper interpretation is simply that the two laws apply at different times in the evolution of a quantum object, one for possibilities, the other for an actuality (as Heisenberg knew):

- first, the unitary deterministic evolution moves through space exploring all the possibilities for interaction, or may simply be defined at all positions by the boundary conditions of an experiment.
- second, the indeterministic collapse randomly (acausally) selects one of those possibilities to become actual.

2) The original concern that the "collapse dynamics" (von Neumann Process 1) is not part of the formalism (von Neumann Process 2) but an *ad hoc* element, with no rules for when to apply it.

If there was a deterministic law that predicted a collapse, or the decay of a radioactive nucleus, it would not be quantum mechanics!

3) Decoherence theorists (chapter 34) define the measurement problem as the failure to observe macroscopic superpositions, for example, Schrödinger's Cat (chapter 28).

Opposition to the Copenhagen Interpretation

Einstein, de Broglie, and especially Schrödinger insisted on a more "complete" picture, not merely what can be said, but what we can "see," a visualization (*Anschaulichkeit*) of the microscopic world. But de Broglie and Schrödinger's emphasis on the wave picture made it difficult to understand material particles and their "quantum jumps." Indeed, Schrödinger and more recent physicists like John Bell and the decoherence theorists H. D. Zeh and Wojciech Zurek deny the existence of particles and the collapse of the wave function.

Perhaps the main claim of those today denying the Copenhagen Interpretation (as well as standard quantum mechanics) is that "there are no quantum jumps." Decoherence theorists and others favoring Hugh Everett's Many-Worlds Interpretation reject Dirac's projection postulate, a cornerstone of quantum theory.

Heisenberg had initially insisted on his own "matrix mechanics" of particles and their discrete, discontinuous, indeterministic behavior, the "quantum postulate" of unpredictable events that undermine the classical physics of causality. But Bohr told Heisenberg that his matrix mechanics was too narrow a view of the problem. The "complementary" wave picture must be included, Bohr insisted. This greatly disappointed Heisenberg and almost ruptured their relationship. But Heisenberg came to accept the criticism and he eventually endorsed all of Bohr's deeply philosophical view that quantum reality is unvisualizable.

In his September Como Lecture, a month before the 1927 Solvay conference, Bohr introduced his theory of "complementarity" as a "complete" theory. It combines the contradictory notions of wave and particle. Since both are required, they complement (and "complete") one another, he thought.

Although Bohr is often credited with integrating the dualism of waves and particles, it was Einstein who predicted a "fusion" of these would be necessary as early as 1909. But in doing so, Bohr obfuscated further what was already a mysterious picture. How could something possibly be both a discrete particle and a continuous wave? Did Bohr endorse the continuous deterministic wave-mechanical views of Schrödinger? Not exactly, but that Bohr accepted Schrödinger's wave mechanics as equal to and complementing his matrix mechanics was most upsetting to Heisenberg.

Bohr had astonished Heisenberg by deriving (in Bohr's Como Lecture) the uncertainty principle from the space-time wave picture alone, with no reference to the causal dynamics of Heisenberg's picture! After this, Heisenberg did the same derivation in his 1930 text and subsequently completely accepted complementarity. Heisenberg spent the next several years widely promoting Bohr's views to scientists and philosophers around the world.

Bohr said these contradictory pictures were "complementary" and that both were needed for a "complete" picture. He vigorously denied Einstein's claim that quantum mechanics is "incomplete," despite Bohr's acceptance of the fact that simultaneous knowledge of exact position and momentum is impossible. Classical physics has twice the number of precisely knowable variables (and thus twice the information) as quantum physics. In this sense, classical physics seems more "complete," quantum physics "incomplete."

Many critics of Copenhagen thought that Bohr deliberately embraced logically contradictory notions - of *continuous* deterministic waves and *discrete* indeterministic particles - perhaps as evidence of the Kantian "antinomies" that put limits on reason and human knowledge. These "contradictions" only strengthened Bohr's epistemological resolve and his insistence that physics requires a subjective view unable to reach Einstein's "objective reality" - the Kantian "things in themselves."

Subject and object were prominent examples of Bohr's complementarity. As Heisenberg described it in his 1955 explanation of the Copenhagen Interpretation

> This again emphasizes a subjective element in the description of atomic events, since the measuring device has been constructed by the observer, and we have to remember that what we observe is not nature in itself but nature exposed to our method of questioning. [3]

Some critics object to the idea that the "free choice" of the experimenter determines what properties appear, but this is correct. If we measure the z-component of spin, we get a definite answer for z, and know nothing about x- or y-components.

Key objections to the Copenhagen Interpretation include:

- The many unreasonable philosophical claims for "complementarity," e.g., that it solves the mind-body problem?
- The basic "subjectivity" of the Copenhagen interpretation. It deals with epistemological knowledge of things, rather than the objectively real "things themselves."
- Bohr's strong claim that there is no quantum world, or at least that we can know nothing about it.
- The idea that nothing exists until an observer measures it.

There is in fact only one world. It is a quantum world. Ontologically it is *indeterministic*, but epistemically, common sense and everyday experience inclines us to see it as only *adequately deterministic*.

Bohr and Heisenberg's Copenhagen Interpretation insists we use classical (deterministic?) concepts and everyday language to communicate our knowledge about quantum processes.

This may be a desirable goal when we begin to teach lay persons about the mysteries of quantum mechanics, but there comes a time when our deeper goal is for them to learn about the nature of the "objective reality" that Einstein wanted us to see.

3 Heisenberg, 1955, p. 58