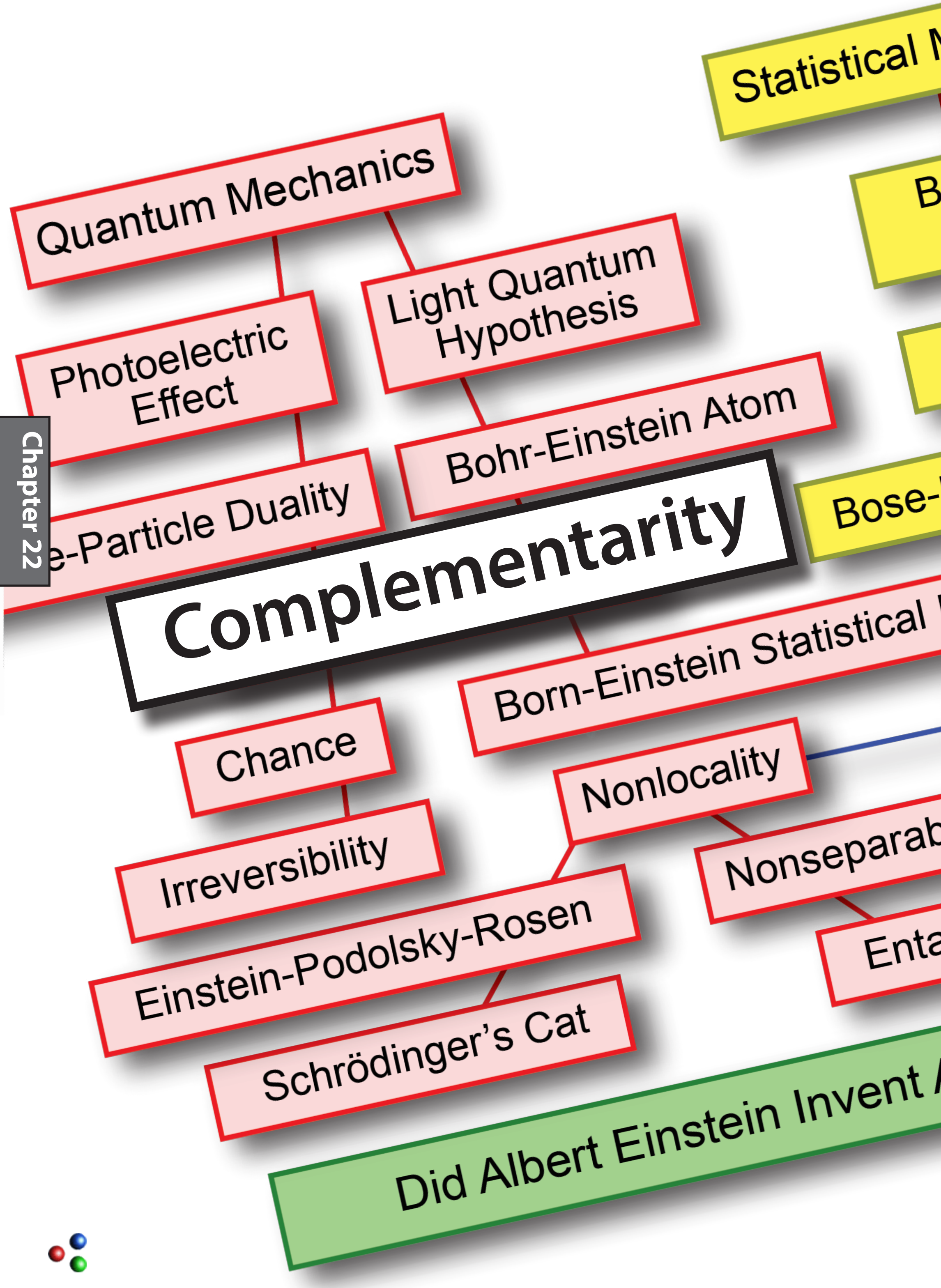

Statistical
Quantum Mechanics
Light Quantum Hypothesis
Photoelectric Effect
Bohr-Einstein Atom
Particle Duality
Complementarity
Born-Einstein Statistical
Chance
Nonlocality
Irreversibility
Einstein-Podolsky-Rosen
Schrödinger's Cat
Did Albert Einstein Invent

Bohr Complementarity

Among all the major scientists of the twentieth century, Niels Bohr may have most wanted to be considered a philosopher. Bohr introduced his concept of *complementarity* in a lecture at Lake Como in Italy in 1927, shortly before the fifth Solvay conference. It was developed in the same weeks as WERNER HEISENBERG was formulating his uncertainty principle. Complementarity, based largely on the wave-particle duality proposed by Einstein in 1909, lies at the core of the Copenhagen Interpretation of quantum mechanics.

Over the years, Bohr suggested somewhat extravagantly that complementarity could explain many great philosophical issues: it can illuminate the mind/body problem, it might provide for the difference between organic and inorganic matter, and it could underlie other great dualisms like subject/object, reason versus passion, and even free will versus causality and determinism.

Information philosophy identifies the wave function as pure abstract information, providing a theoretical prediction of the probability of finding particles, of matter or energy, at different positions in space and time. As such, it is similar in some sense to the idea of an *immaterial* mind in the material body. In this respect, Bohr was correct.

Like most educated persons of his time, Bohr knew of IMMANUEL KANT's noumenal/phenomemal dualism. He often spoke as if the goal of his complementarity was to reconcile opposites. He likened it to the eastern yin and yang, and his grave is marked with the yin/yang symbol.

Bohr was often criticized for suggesting that both A and Not-A could be the case. This was a characteristic of GEORG W. F. HEGEL's dialectical materialism. Had Bohr absorbed some Hegelian thinking? Another Hegelian trait was to speak indirectly and obscurely of the most important matters, and sadly this was Bohr's way, to the chagrin of many of his disciples. They sarcastically called his writing "obscure clarity." They hoped for clarity but got mostly fuzzy thinking when Bohr stepped outside of quantum mechanics.

Bohr might very much have liked the current two-stage model for free will incorporating both randomness and an adequate statistical determinism. He might have seen it as a shining example of his complementarity.

As a philosopher, Bohr was a logical positivist, greatly influenced by Ernst Mach. Mach put severe epistemological limits on knowing the Kantian "things in themselves," just as Kant had put limits on reason. The British empiricist philosophers John Locke and David Hume had put the "primary" objects beyond the reach of our "secondary" sensory perceptions.

Bohr was an avid follower of the analytic philosophy of Bertrand Russell. He admired the *Principia Mathematica* of Russell and Alfred North Whitehead.

Bohr seemed to deny the existence of Einstein's "objective reality," but clearly knew and said often 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. Copenhageners were proud of their limited ability to know. 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]

Agreeing with Russell, Ludwig Wittgenstein, and other twentieth-century analytic language philosophers, Bohr emphasized the importance of conventional language as a tool for knowledge. Since language 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 when our observations and measurements will 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 for it to become knowledge in the mind of the observer. And controversially, they maintained that a measurement is not "complete" until it is knowledge in the mind

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

of a "conscious observer." This is a step too far. The physical change in an information structure undergoing a measurement is complete when the new information is recorded physically, well before it is understood in any observer's mind.

Bohr was convinced that his complementarity implies that quantum mechanics is "complete." This was vigorously challenged by Einstein in his EPR paper of 1935.

Heisenberg's Microscope Revisited

As we saw in the last chapter,"Heisenberg's Microscope" showed that low-energy long-wavelength photons would not disturb an electron's momentum, but their long waves provided a blurry picture at best, so they lacked the resolving power to measure the position accurately. Conversely, if a high-energy, short wavelength photon is used (e.g., a gamma-ray), it might measure momentum, but the recoil of the electron ("Compton Effect") would be so large that its position becomes uncertain.

But in his Como Lecture, Bohr showed Heisenberg's disturbance of a *particle* is not the fundamental cause. He said that one can correct for the disturbance (the recoil) but can not eliminate the limits on resolving power of the measuring instrument, a consequence of the *wave* picture, not the particle picture.

Bohr cleverly derived Heisenberg's indeterminacy principle solely from space-time considerations about waves, greatly upsetting Heisenberg.

Adding to his embarassment, Max Born tells a story that Heisenberg could not answer his thesis examiner Willy Wien's question on resolving power and nearly failed the oral exam for his doctorate. [2]

Born says Heisenberg looked up the answers to all the questions he could not answer, and the optical formula for resolution became the basis for his famous example of the microscope a few years later.

So when Bohr pointed out the mistake in Heisenberg's first uncertainty paper draft suggesting that a "disturbance" was the source of the uncertainty. Heisenberg says he was "brought to tears."

2 Born, 1978, p.213

Bohr's Uncertainty Derivation

A "wave packet" with significant values in a spatially limited volume can be made from a superposition of plane waves with a range of frequencies.

Let Δt be the time it takes a wave packet to pass a certain point. $\Delta \nu$ is the range of frequencies of the superposed waves.

In space instead of time, the wave packet is length Δx and the range of waves per centimeter is $\Delta \sigma$.

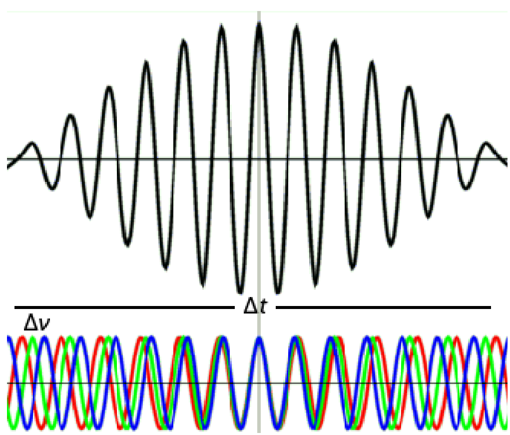
Bohr showed that the range of frequencies $\Delta\nu$ needed so the wave packet is kept inside length of time Δt is related as

$\Delta \nu \, \Delta t = 1$.

A similar argument in space relates the physical size of a wave packet Δx to the variation in the number of waves per centimeter $\Delta \sigma$. σ is the so-called wave number = $1/\lambda$ (λ *is* the wavelength):

$\Delta \sigma \, \Delta x = 1$.

If we multiply both sides of the above equations by Planck's constant h, and use the relation between energy and frequency $E = h\nu$ (and the similar relation between momentum and wavelength $p = h\sigma = h / \lambda$), the above become the Heisenberg indeterminacy relations:



$\Delta E \, \Delta t = h, \quad \Delta p \, \Delta x = h$.

This must surely have dazzled and perhaps deeply upset Heisenberg. Bohr had used only the space and time properties of waves to derive the physical limits of Heisenberg's uncertainty principle!

Bohr was obviously impressed by the new de Broglie - Schrödinger wave mechanics. His powerful use of Schrödinger's new wave mechanics frustrated Heisenberg, whose matrix mechanics was the first derivation of the new quantum principles, especially the non-commutativity of position and momentum operators.

The equal embrace of particle and wave pictures was the core idea of Bohr's new complementarity, a position that Heisenberg defended vigorously in coming years, though without abandoning his microscope!

Bohr was pleased that Schrödinger's wave function provides a "natural" explanation for the "quantum numbers" of the "stationary states" in his quantum postulate. They are just the nodes in the wave function. On the other hand, Schrödinger himself hoped to replace particles and "unnatural" quantum jumps of Bohr's quantum postulate by resonances in his wave field. This led to many years of bitter disagreement between Bohr and Schrödinger.

Free Choice in Quantum Mechanics

Complementarity led Bohr and Heisenberg to a very important idea. Because there are always two complementary ways to approach any problem in quantum physics. They 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." This is partly true.

In classical physics, simultaneous values exist for the position and momentum of elementary particles like electrons. In quantum physics, measuring one of these with high accuracy reduces the accuracy of the other, because of the uncertainty principle.

Indeed, in quantum mechanics, Bohr and Heisenberg claimed that neither of these properties could be said to exist until an experimenter freely decides to make a measurement.

Heisenberg says the property comes into existence as a result of the experiment. This is true, but only in a limited sense. If the experimenter decides to measure position, the result is a position. If momentum is measured, then the result is a momentum.

Einstein asked whether the particle has a position (and a path) before a particle is measured (his "objective reality"). He thought the idea that fundamental physical properties like momentum do not exist before a measurement is simply absurd.

Conservation laws allow us to *retrodict* those properties between successive measurements, as we shall see.