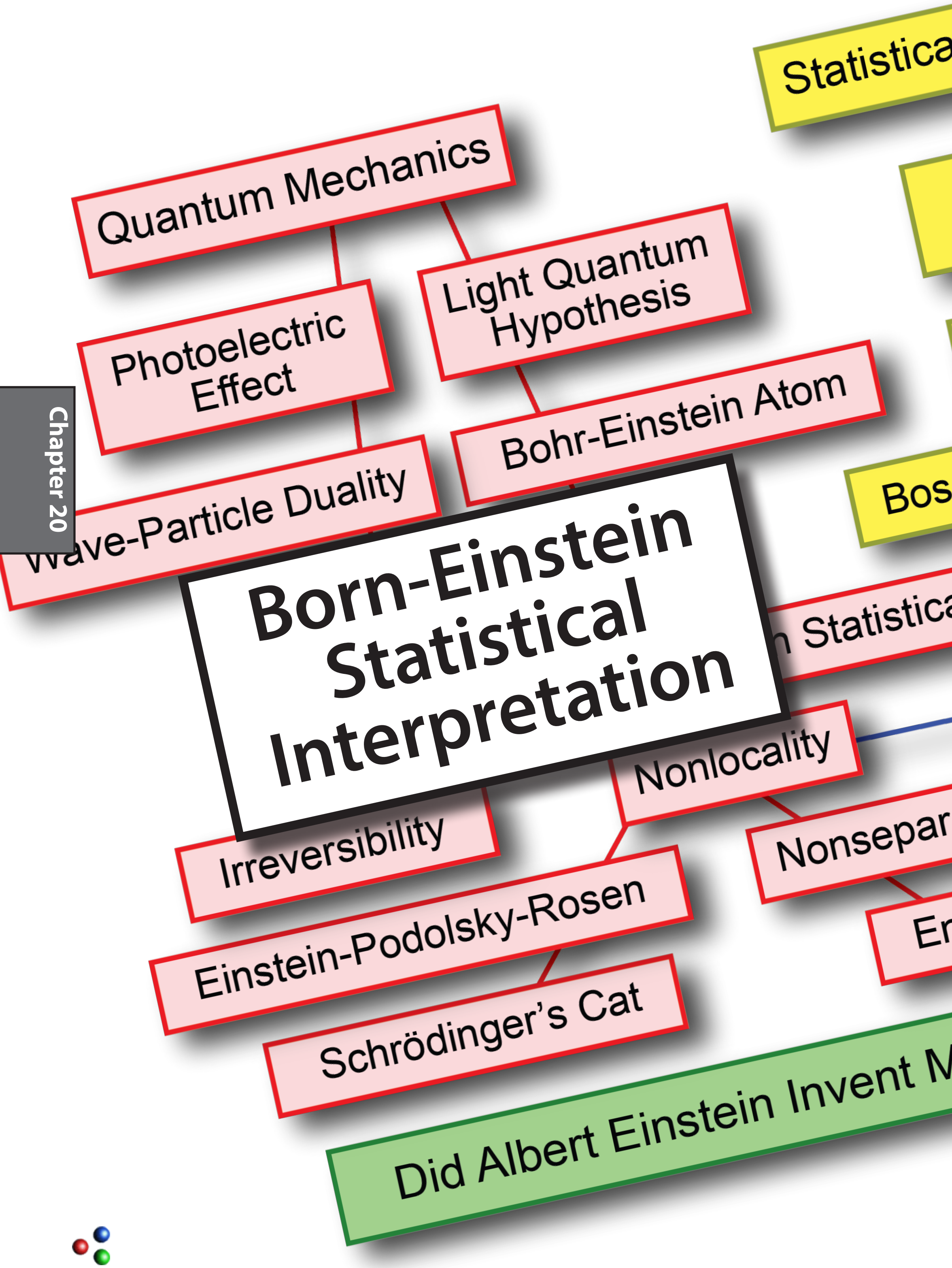
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Statistical Interpretation

It is often said that Max Born gave us the "statistical interpretation" of quantum mechanics that lies at the heart of Niels Bohr's and Werner Heisenberg's principle of complementarity and the "Copenhagen Interpretation" of quantum mechanics.

But Born himself said many times he had only applied an idea of Albert Einstein that had circulated privately for many years. To be sure, Born and Einstein quarreled for years over determinism and causality, but as we saw in chapter 11, it was Einstein who discovered "chance" in the interaction of matter and radiation, even if he considered it a "weakness in the theory."

As we showed in chapters 2 to 4, probability and statistics were very important in the two centuries before Born's work, but most physicists and philosophers saw the implied randomness to be "epistemic," the consequence of human ignorance. Random distributions of all kinds were thought to be completely deterministic at the particle level, with collisions between atoms following Newton's dynamical laws. Ludwig Boltzmann's transport equation and H-Theorem showed that the increase of entropy is statistically irreversible at the macroscopic level, even if the motions of individual particles were time reversible.

Boltzmann did speculate that there might be some kind of molecular "chaos" or "disorder" that could cause particles traveling between collisions to lose the "correlations" or information about their past paths that would be needed for the paths to be time reversible and deterministic, but nothing came of this idea.

In his early career, Erwin Schrödinger was a great exponent of fundamental chance in the universe. He followed his mentor Franz S. Exner, who as a colleague of Boltzmann at the University of Vienna was a great promoter of statistical thinking.

In his inaugural lecture at Zurich in 1922, Schrödinger argued that available evidence can not justify our assumptions that physical laws are deterministic and strictly causal. His inaugural lecture was modeled on that of Exner in 1908.

> Exner's assertion amounts to this: It is quite possible that Nature's laws are of thoroughly statistical character. The demand for an absolute law in the background of the statistical law — a demand which at the present day almost everybody considers imperative — goes beyond the reach of experience. Such a dual foundation for the orderly course of events in Nature is in itself improbable. The burden of proof falls on those who champion absolute causality, and not on those who question it. For a doubtful attitude in this respect is to-day by far the more natural.[1]

Several years later, Schrödinger presented a paper on "Indeterminism in Physics" to the June, 1931 *Congress of A Society for Philosophical Instruction* in Berlin. He supported the idea of Boltzmann that "an actual continuum must consist of an infinite number of parts; but an infinite number is undefinable.."

> If nature is more complicated than a game of chess, a belief to which one tends to incline, then a physical system cannot be determined by a finite number of observations. But in practice a finite number of observations is all that we can make. All that is left to determinism is to believe that an infinite accumulation of observations would in principle enable it completely to determine the system. Such was the standpoint and view of classical physics, which latter certainly had a right to see what it could make of it. But the opposite standpoint has an equal justification: we are not compelled to assume that an infinite number of observations, which cannot in any case be carried out in practice, would suffice to give us a complete determination.

In the history of science it is hard to find ears more likely to be sympathetic to a new idea than Schrödinger should have been to Max Born's suggestion that the square of the amplitude of Schrödinger's wave function $|\psi^2|$ should be interpreted statistically as the likelihood of finding a particle. And Schrödinger should have known Einstein thought quantum mechanics is statistical.

Yet Schrödinger objected strenuously, not so much to the probability and statistics as to the conviction of Born and his brilliant student Heisenberg that quantum phenomena, like

1 'What Is a Law of Nature?,' *Science and the Human Temperament*, p.142.

quantum jumps between atomic energy levels, were only predictable *statistically*, and that there is a fundamental *indeterminacy* in the classical idea that particles have simultaneously knowable exact positions and velocities (momenta). Born, Heisenberg, and Bohr had declared classical determinism and causality untrue of the physical world.

It is likely that Schrödinger was ecstatic that his wave equation implied a deterministic physical theory. His wave function ψ evolves in time to give exact values for itself for all times and places. Perhaps Schrödinger thought that the waves themselves could provide a field theory of physics, much as fields in Newton's gravitational theory and in Maxwell's electromagnetic theory provide complete descriptions of nature. Schrödinger wondered whether nature might be only waves, no particles?

In July of 1926, Born used Louis de Broglie's matter waves for electrons, as described by Schrödinger's wave equation, but he interpreted the wave as the *probability* of finding an electron going off in a specific collision direction, proportional to the square of the wave function ψ, now seen as a "probability amplitude."

Born's interpretation of the quantum mechanical wave function of a material particle as the probability (amplitude) of finding the material particle was a direct extension of Einstein's interpretation of light waves giving probability of finding photons.

To be sure, Einstein's interpretation may be considered only qualitative, where Born's was quantitative, since the new quantum mechanics now allowed exact calculations.

Nevertheless, Born initially gave full credit for the statistical interpretation to Einstein for the "ghost field" idea. Although the original idea is pure Einstein, it is widely referred to today as "Born's statistical interpretation," another example of others getting credit for a concept first seen by Einstein.

Born described his insights in 1926,

> Collision processes not only yield the most convincing experimental proof of the basic assumptions of quantum theory, but also seem suitable for explaining the physical meaning of the formal laws of the so-called "quantum

mechanics.”... The matrix form of quantum mechanics that was founded by Heisenberg and developed by him and the author of this article starts from the thought that an exact representation of processes in space and time is quite impossible and that one must then content oneself with presenting the relations between the observed quantities, which can only be interpreted as properties of the motions in the limiting classical cases. On the other hand, Schrödinger (3) seems to have ascribed a reality of the same kind that light waves possessed to the waves that he regards as the carriers of atomic processes by using the de Broglie procedure; he attempts “to construct wave packets that have relatively small dimensions in all directions,” and which can obviously represent the moving corpuscle directly.

Neither of these viewpoints seems satisfactory to me. Here, I would like to try to give a third interpretation and probe its utility in collision processes. I shall recall a remark that Einstein made about the behavior of the wave field and light quanta. He said that perhaps the waves only have to be wherever one needs to know the path of the corpuscular light quanta, and in that sense, he spoke of a “ghost field.” It determines the probability that a light quantum - viz., the carrier of energy and impulse – follows a certain path; however, the field itself is ascribed no energy and no impulse.

One would do better to postpone these thoughts, when coupled directly to quantum mechanics, until the place of the electromagnetic field in the formalism has been established. However, from the complete analogy between light quanta and electrons, one might consider formulating the laws of electron motion in a similar manner. This is closely related to regarding the de Broglie-Schrödinger waves as “ghost fields,” or better yet, “guiding fields.”

I would then like to pursue the following idea heuristically: The guiding field, which is represented by a scalar function ψ of the coordinates of all particles that are involved and time, propagates according to Schrödinger’s differential equation. However, impulse and energy will be carried along as when corpuscles (i.e., electrons) are actually flying around. The paths of these corpuscles are determined only to the extent that they are constrained by the law of energy and impulse; moreover, only a probability that a certain path will be followed will be

> determined by the function ψ. One can perhaps summarize this, somewhat paradoxically, as: The motion of the particle follows the laws of probability, but the probability itself propagates in accord with causal laws. [2]

This last sentence is a remarkably concise description of the dualism in quantum mechanics, a strange mixture of indeterminism and determinism, of chance and necessity.

In his 1948 Waynflete lectures, Born elaborated on his understanding of chance,

> There is no doubt that the formalism of quantum mechanics and its statistical interpretation are extremely successful in ordering and predicting physical experiences. But can our desire of understanding, our wish to explain things, be satisfied by a theory which is frankly and shamelessly statistical and indeterministic? Can we be content with accepting chance, not cause, as the supreme law of the physical world?
>
> To this last question I answer that not causality, properly understood, is eliminated, but only a traditional interpretation of it, consisting in its identification with determinism. I have taken pains to show that these two concepts are not identical. Causality in my definition is the postulate that one physical situation depends on the other, and causal research means the discovery of such dependence. This is still true in quantum physics, though the objects of observation for which a dependence is claimed are different: they are the probabilities of elementary events, not those single events themselves. [3]

Ever since 1930, when Born's young graduate student Heisenberg had been selected for the Nobel Prize in physics although much of the theory was his own work, Born felt he had been treated unfairly.

He finally received recognition, with the Nobel Prize for physics in 1954, for his "statistical interpretation." But Born's voluminous correspondence with Einstein reveals that he had perhaps come to think that Einstein's supposed determinism meant Einstein did not believe in the statistical nature of quantum physics, so this idea may now rightfully belong to Born. He called it "his own" in the 1950's.

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2 Born. 1926, p. 803.

3 Born, 1964, p.102