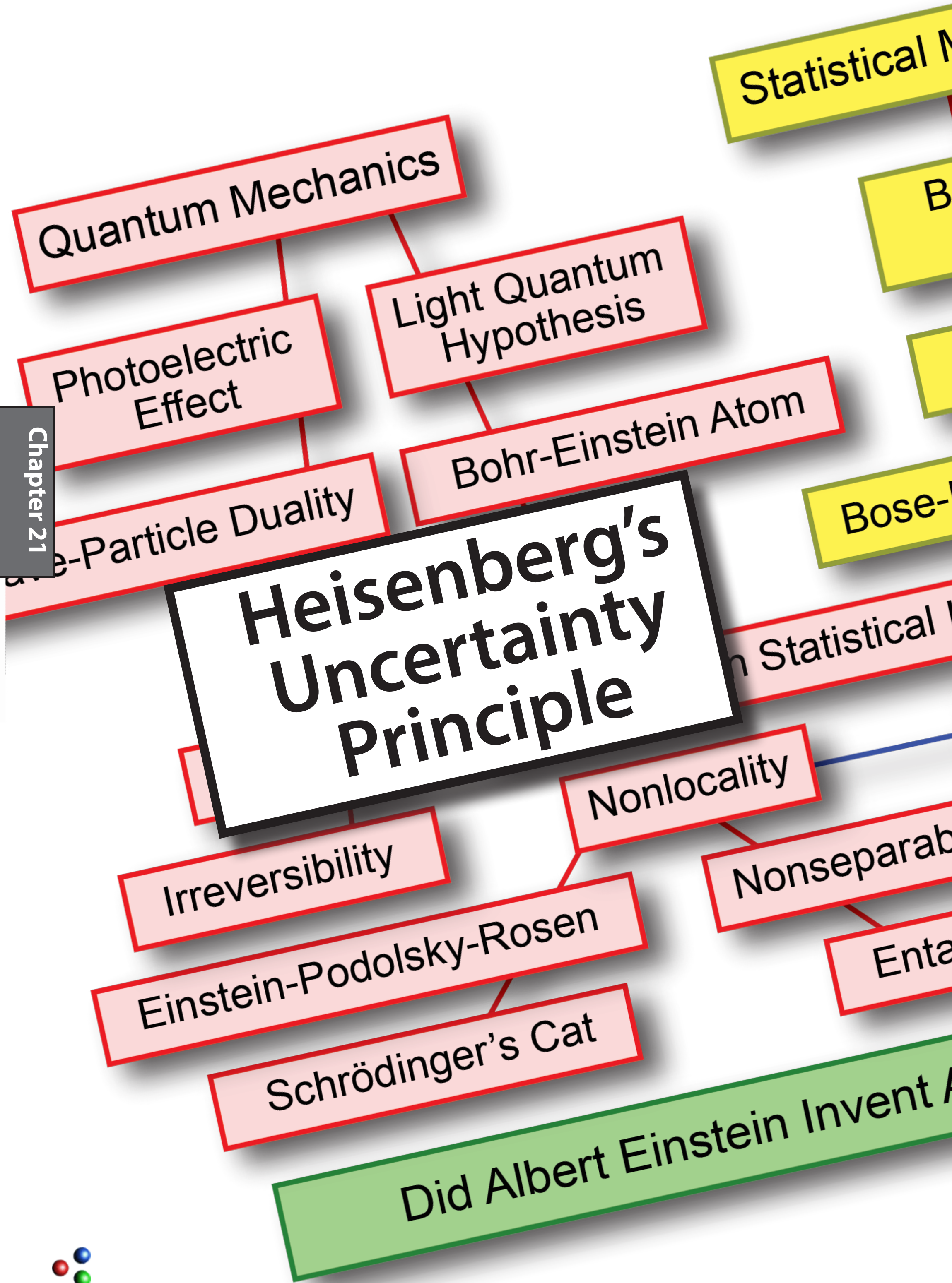
Quantum Mechanics
Light Quantum Hypothesis
Photoelectric Effect
Bohr-Einstein Atom
Particle Duality
Heisenberg's Uncertainty Principle
Statistical
Nonlocality
Irreversibility
Einstein-Podolsky-Rosen
Schrödinger's Cat
Did Albert Einstein Invent

# Heisenberg's Uncertainty Principle

From the time in the 1950's I first started work on the problem of how information structures formed in the universe and the related problems of free will and creativity, down to the publication of my first book in 2011, *Free Will: The Scandal in Philosophy*, my source for the random element needed to generate alternative possibilities, without which no new information is possible, was Werner Heisenberg's uncertainty principle of 1927.

I wrote that "quantum physics in the twentieth century opened a crack in the wall of physical determinism."[1] My source was Arthur Stanley Eddington's great book, *The Nature of the Physical World*, the print version of his Gifford Lectures earlier in the year, with one great alteration.

In the delivered lectures, Eddington had described himself as unable "to form a satisfactory conception of any kind of law or causal sequence which shall be other than deterministic." A year later, in response to Heisenberg's uncertainty principle, Eddington revised his lectures for publication and dramatically announced "physics is no longer pledged to a scheme of deterministic law." He went even farther and enthusiastically identified indeterminism with freedom of the will. "We may note that science thereby withdraws its moral opposition to freewill."[2]

Eddington was the most prominent interpreter of the new physics to the English-speaking world. He confirmed Einstein's general theory of relativity with his eclipse observations in 1919, helping make Einstein a household word. And Eddington's praise of uncertainty contributed to making the young Heisenberg the symbolic head of the "founders" of the new quantum mechanics.

The Nobel Prizes of 1932/1933 for atomic physics were shared among Heisenberg, Erwin Schrödinger, and Paul Dirac. Heisenberg's key contribution in his 1925 matrix mechanics was the discovery that position $q$ and momentum $p$ are complex conjugate quantities that do not commute. $pq \neq qp$!

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1 Doyle, 2011, p.4.

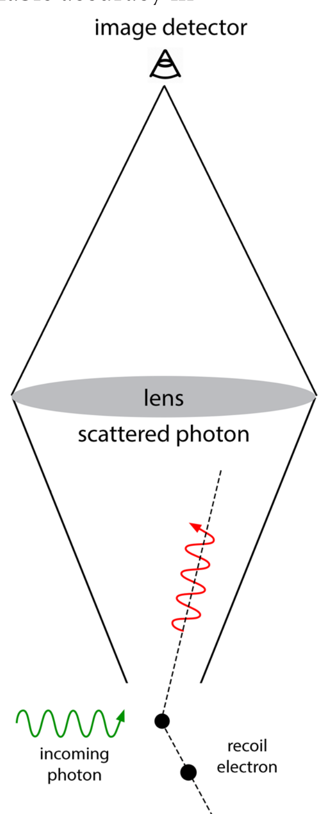
2 Eddington, 1927, p.294-295

Dirac made this non-commutativity the fundamental fact of his 1926 transformation theory, in the form $\boldsymbol{pq} - \boldsymbol{qp} = -ih/2\pi = -i\hbar$. In 1927, Heisenberg proposed the idea that there is a limit to the accuracy with which one can make simultaneous measurements of the position and momentum, which he called a straightforward consequence of the commutativity rule as expressed by Dirac.

## Heisenberg's Microscope

Heisenberg famously explained the joint uncertainty in position $\Delta q$ and in momentum $\Delta p$ in terms of measuring the properties of an electron under a microscope.

> For example, let one illuminate the electron and observe it under a microscope. Then the highest attainable accuracy in the measurement of position is governed by the wavelength of the light. However, in principle one can build, say, a γ-ray microscope and with it carry out the determination of position with as much accuracy as one wants. In this measurement there is an important feature, the Compton effect. Every observation of scattered light coming from the electron presupposes a photoelectric effect (in the eye, on the photographic plate, in the photocell) and can therefore also be so interpreted that a light quantum hits the electron, is reflected or scattered, and then, once again bent by the lens of the microscope, produces the photoeffect. At the instant when position is determined—therefore, at the moment when the photon is scattered by the electron—the electron undergoes a discontinuous change in momentum. This change is the greater the smaller the wavelength of the light employed—that is, the more exact the determination of the position. At the instant at which the position of the electron is known, its momentum therefore can be known up to magnitudes which correspond to that



Heisenberg's Microscope
Compare Compton Effect

discontinuous change. Thus, the more precisely the position is determined, the less precisely the momentum is known, and conversely. In this circumstance we see a direct physical interpretation of the equation $\boldsymbol{pq} - \boldsymbol{qp} = -i\hbar$. Let $q_1$ be the precision with which the value $q$ is known ($q_1$ is, say, the mean error of $q$) therefore here the wavelength of the light. Let $p_1$ be the precision with which the value $p$ is determinable; that is, here, the discontinuous change of $p$ in the Compton effect. Then, according to the elementary laws of the Compton effect $p_1$ and $q_1$ stand in the relation

$$p_1 q_1 \sim h. \qquad (1)$$

Here we can note that equation (1) is a precise expression for the facts which one earlier sought to describe by the division of phase space into cells of magnitude $h$.

...in all cases in which relations exist in classical theory between quantities which are really all exactly measurable, the corresponding exact relations also hold in quantum theory (laws of conservation of momentum and energy). Even in classical mechanics we could never practically know the present exactly, vitiating Laplace's demon. But what is wrong in the sharp formulation of the law of causality, "When we know the present precisely, we can predict the future," it is not the conclusion but the assumption that is false. Even in principle we cannot know the present in all detail. For that reason everything observed is a selection from a plenitude of possibilities and a limitation on what is possible in the future. As the statistical character of quantum theory is so closely linked to the inexactness of all perceptions, one might be led to the presumption that behind the perceived statistical world there still hides a "real" world in which causality holds. But such speculations seem to us, to say it explicitly, fruitless and senseless. Physics ought to describe only the correlation of observations. One can express the true state of affairs better in this way: Because all experiments are subject to the laws of quantum mechanics, and therefore to equation (1), it follows that quantum mechanics establishes the final failure of causality...one can say, if one will, with Dirac, that the statistics are brought in by our experiments.[3]

3 Heisenberg, 1927, p.64

Chapter 21

Now this idea that it is our experiments that makes quantum mechanics statistical is very subtle. Bohr suggested Heisenberg use the word uncertainty (*Unsicherheit* in German) because it connotes an *epistemological* problem, knowledge of the world in our minds. A reluctant Heisenberg went along, but even the words he preferred, *Unbestimmtheit* or *Ungenauigkeit*, connote vagueness or indeterminacy as a property of our interaction with the world and not necessarily an *ontological* property of nature itself.

Einstein's objective reality agrees that the statistical nature of quantum mechanics lies in the results from many experiments, which only give us statistical data. But for Einstein there is an underlying reality of objects following continuous paths, conserving their fundamental properties when they are not acted upon.



Heisenberg had submitted his uncertainty paper for publication without first showing it to Bohr for his approval. When he did read it, Bohr demanded that Heisenberg withdraw the paper, so that it could be corrected. Heisenberg, quite upset, refused, but he did agree to add this paragraph in proof, admitting several errors.

> After the conclusion of the foregoing paper, more recent investigations of Bohr have led to a point of view which permits an essential deepening and sharpening of the analysis of quantum-mechanical correlations attempted in this work. In this connection Bohr has brought to my attention that I have overlooked essential points in the course of several discussions in this paper. Above all, the uncertainty in our observation does not arise exclusively from the occurrence of discontinuities, but is tied directly to the demand that we ascribe equal validity to the quite different experiments which show up in the corpuscular theory on one hand, and in the wave theory on the other hand. In the use of an idealized gamma-ray microscope, for example, the necessary divergence of the bundle of rays must be taken into account. This has as one consequence that in the observation of the position of the electron the direction of the Compton recoil is only known with a spread which then leads to relation (1). Furthermore, it is not sufficiently stressed that the simple theory of the Compton effect, strictly speaking, only applies to free electrons. The consequent care needed in employing the uncertainty relation is, as Professor Bohr has explained, essential, among other things, for a comprehensive discussion

> of the transition from micro- to macromechanics. Finally, the discussion of resonance fluorescence is not entirely correct because the connection between the phase of the light and that of the electronic motion is not so simple as was assumed. I owe great thanks to Professor Bohr for sharing with me at an early stage the results of these more recent investigations of his—to appear soon in a paper on the conceptual structure of quantum theory—and for discussing them with me. [4]

As we shall see in chapter 24, a core tenet of the Copenhagen Interpretation is Heisenberg's idea that experiments bring particle properties into existence. Heisenberg described this as "the 'path' only comes into being because we observe it" (*Die "Bahn" entsteht erst dadurch, dass wir sie beobachten*).



Einstein, while disliking the statistical nature of quantum mechanics (which he himself discovered), nevertheless defended what he called the "objective" nature of reality, independent of the human mind or our experimental methods. He wanted to know whether a particle has a path *before* it is measured. He sarcastically asked (his biographer, Abraham Pais), is the moon only there when we are looking at it? Einstein (and we) use conservation principles to visualize the Compton Effect and Heisenberg's Microscope!

In the next chapter. we shall see that in his Como lecture later in 1927, Bohr further embarrassed and upset Heisenberg by publishing how position and momentum uncertainty can be explained completely using only properties of light waves, as in Schrödinger's wave mechanics. Bohr said that it actually has nothing to do with collisions disturbing the state of a particle! [5]

Perhaps as a consequence, from then on Heisenberg became quite deferential to Bohr. He traveled the world lecturing on the greatness of Bohr's "Copenhagen Interpretation." Despite this, Heisenberg continued to describe his uncertainty principle as a result of the Compton Effect. As a result, Heisenberg's microscope is still mistakenly taught as the reason for quantum uncertainty in many physics textbooks and popular science treatments.

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4 *ibid.*, p.83
5 See chapter 22