Question: Explain the uncertainty principle.

In quantum mechanics, the uncertainty principle is any of a variety of mathematical inequalities asserting a fundamental limit to the precision with which certain pairs of physical properties of a particle known as complementary variables, such as position x and momentum p, can be known simultaneously. For instance, in 1927, Werner Heisenberg stated that the more precisely the position of some particle is determined, the less precisely its momentum can be known, and vice versa. The formal inequality relating the standard deviation of position σ_x and the standard deviation of momentum σ_p was derived by Earle Hesse Kennard later that year and by Hermann Weyl in 1928:

$$\sigma_x \sigma_p \geq \frac{\hbar}{2}$$

($\hbar$ is the reduced Planck constant).

The original heuristic argument that such a limit should exist was given by Heisenberg, after whom it is sometimes named the Heisenberg principle. This ascribes the uncertainty in the measurable quantities to the jolt-like disturbance triggered by the act of observation. Though widely repeated in textbooks, this physical argument is now known to be fundamentally misleading. While the act of measurement does lead to uncertainty, the loss of precision is less than that predicted by Heisenberg's argument; the formal mathematical result remains valid, however.

Historically, the uncertainty principle has been confused with a somewhat similar effect in physics, called the observer effect, which notes that measurements of certain systems cannot be made without affecting the systems. Heisenberg offered such an observer effect at the quantum level (see below) as a physical "explanation" of quantum uncertainty. It has since become clear, however, that the uncertainty principle is inherent in the properties of all wave-like systems, and that it arises in quantum mechanics simply due to the matter wave nature of all quantum objects. Thus, the uncertainty principle actually states a fundamental property of quantum systems, and is not a statement about the observational success of current technology. It must be emphasized that measurement does not mean only a process in which a physicist-observer takes part, but rather any interaction between classical and quantum objects regardless of any observer.

Since the uncertainty principle is such a basic result in quantum mechanics, typical experiments in quantum mechanics routinely observe aspects of it. Certain experiments, however, may deliberately test a particular form of the uncertainty principle as part of their main research program. These include, for example, tests of number-phase uncertainty relations in superconducting or quantum optics systems. Applications dependent on the uncertainty principle for their operation include extremely low noise technology such as that required in gravitational-wave interferometers.