Back-Action from the World

The classical mechanics of Newton was initially found to be consistent with the fundamental characteristic of a successful measurement: from the results of an experiment, it could derive conclusions regarding the results of subsequent experiments. This is due to the property that the states of the observed system before and after the measurement can be regarded as identical. This continued to be the case when classical mechanics was extended to Albert Einstein's (1879-1955) view of space-time coordination of events from his theory of relativity in 1905 to account for the finite speed of light and its invariance for inertial observers. Although the implications were not immediately realized, all of this had already changed in 1900 with the discovery by Max Planck (1858-1947) that the existence of a new elementary quantity called the *quantum of action* designated by *h*, now called Planck's constant, was needed to understand atomic radiation (*action* is a quantity with dimensions of energy-time). The introduction of the fundamental quantum of action by Planck was the beginning of the end for determinism. It took several decades for this to be generally accepted by the scientific community but eventually led in 1925 to a new corresponding theory, *quantum mechanics*. For Niels Bohr (1885-1962), who was one of the major figures in quantum measurement as well as atomic and nuclear physics, the essence of quantum theory could be expressed in terms of a *quantum postulate*, which [310]

> *attributes to any atomic process an essential discontinuity, or rather individuality, completely foreign to the classical theories and symbolized by Planck's quantum of action*.
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This postulate implies a renunciation of the causal space-time coordination of atomic processes. Classically, quantifiable properties exist as an objective reality and measurement determines the value of these pre-existing quantities with in principle arbitrary accuracy. For quantum mechanics, with intrinsically non-deterministic physics, the situation is very different since the measurement generally causes a change in the state of the system (except for special cases such as *non-demolition measurements* discussed further in Chapter 7), and this change is in principle impossible to predict. Bohr wrote in 1935 [311]:

> *The procedure of measurement has an essential influence on the conditions on which the very definition of the physical quantities in question rests.*
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This property of quantum measurement reflects the *back-action* occurring between measurement device and measured system. In *Measure for Measure*, Shakespeare

(1564-1616) took the meaning of his title from Mathew 7:2, “with what measure ye mete, it shall be measured to you again,” the title then being aptly suggestive of the back-action between measurement device and system characteristic of quantum measurement.

Individual quantum systems need not have well-defined states but instead may be in correlated arrangements with other quantum systems, “entanglement”, where only the entire superposition carries information about the whole. The term *entanglement* was introduced by Erwin Schrödinger (1887-1961) in 1935 [156], though aspects of it had been seen by Einstein and Bohr over the previous twenty years [111]. As will be discussed, Bohr and Einstein in many ways pioneered the deepest inquiries into quantum measurement during the first half of the 20th century. Entanglement can occur between different particles or between two or more properties of the same particle. In particular, according to Schrödinger’s equation, a measurement device interacting with a quantum system may become entangled with its observable properties before measurement occurs. Other signatures of the quantum had also been identified in the quest to understand the essential differences between classical and quantum. As demonstrated in Chapter 4, the quantum measurement problem is related to the unitary prediction of *entanglement,* as given by the mantra:

To the extent there is entanglement, there is no measurement.

In 1927, Werner Heisenberg (1901-1976), working at Bohr’s institute in Copenhagen, obtained his indeterminacy or “uncertainty” relations when he realized that quantum mechanics must allow for approximate values of position and momentum with trajectories that are not sharply defined [7]. In relation to this, Heisenberg and Bohr also examined the possibility of “disturbances” occurring during quantum measurements, such as Heisenberg’s famous example of the γ-ray microscope [9], in which the act of observing would impart uncontrollable momentum kicks to any quantum objects showing the futility of determining its trajectory. However, Bohr later considered this description as misleading and instead emphasized the role of the interaction between measurement device and system, because the interaction required during measurement is uncontrollable. This necessarily affects the state of the closed system, and the results have an apparent random or non-deterministic appearance.