Complementarity in the World

Theories of physics are built up using elementary physical quantities such as space, time, energy, and momentum. Measurement devices utilize the properties of these physical quantities to extract information about the observed system. For example, rigid rulers extended in space might be used to determine the position of an object. However, the same object could be allowed to collide with a movable piece of the measurement device with known mass in order to determine its momentum. An important difference between classical and quantum mechanics is that in classical physics, various measurement tools may be used in combination to supplement one another in the measurement of a state of the same system. Combining the disparate information from separate measurements is what allows a deterministic causal description of a system to be possible in classical physics. However, in quantum physics, the results from different types of measurements cannot always be combined and a quantum physical phenomenon found by observing the same system with different experimental arrangements can be mutually exclusive. The separation between the observer and observed system in realizing measurements of events may be arranged in many ways corresponding to different conditions of observations and type of apparatus determining the particular aspect of the phenomenon we wish to observe. At the quantum level, the deterministic chain of events in classical physics instead becomes lines of similar possibilities, each weighed by an amplitude for probability of occurrence and closed by the irreversible click of a detector [312, p. 124].

In his 1927 lecture at the Volta Congress in Como, Italy [310], Bohr called this logical exclusion of phenomena from different experimental arrangements *complementarity*, a view that generalizes the concept of wave-particle duality:

> *The very nature of the quantum theory thus forces us to regard space-time coordination and the claim of causality, the union of which characterized the classical theories, as complementary but exclusive features of the description, symbolizing the idealization of observation and definition respectively.*
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> https://doi.org/10.1038/121580a0

Bohr’s initial attempts at justifying the complementarity picture used the uncertainty relations and arguments in terms of disturbances to the system occurring during measurement; see Plotnitsky [313] for a detailed account. However, depending on the particulars of the experiment, complementarity has more generally appeared to be enforced by a variety of other signatures for quantum behavior that have since been identified within quantum mechanics: entanglement, uncertainty, measurement disturbance, which-way information, visibility, and distinguishability, among others. The role of these various signatures in quantum interference experiments have turned out to be neither completely logically independent nor logical consequences of one another, recently leading to arguments in the literature [314] [315] and showing that there are numerous ways of dissecting complementarity. Bohr's concept of complementarity continues to play a role today with studies of interference involving the most current experimental measurement techniques [316].

The logic of quantum physics can also appear similar to that of introspection. The concept of observation occurs in both physics and psychology with a long history of repercussions. When we describe our thinking activity, it can also be made part of the content of consciousness when attempting self-perception, Figure 5.4. In this case, the

Figure 5.4: Ernst Mach's 1886 self-portrait presenting a "view from the left eye," illustrates issues occurring when attempting self-perception; with the right eye closed, the accompanying cut is presented to the left eye in a frame formed by the ridge of the eyebrow, nose and mustache.

subject and object can even appear to alternate in an infinite regression [317, p. 302]. Bohr's favorite presentation of this situation was Paul Møller's humorous *Tale of a Danish Student*, in which the student becomes dismayed when contemplating his own consciousness [318, p. 48]:

> *"And then I come to think of my thinking about it; again, I think that I think of my thinking about it, and divide myself into an infinitely retreating succession of egos observing each other. I don't know which ego is the real one to stop at, for as soon as I stop at any one of them, it is another ego again that stops at it. My head gets all in a whirl with dizziness, as if I were peering down a bottomless chasm, and the end of my thinking is a horrible headache."*

Bohr compared this arbitrariness of the separation between object and subject in psychology with the arbitrariness in the distinction between system and measurement device in quantum physics [319, p. 24]:

> *The unavoidable influencing by introspection of all psychical experience, that is characterized by the feeling of volition, shows a striking similarity to the conditions responsible for the failure of causality in the analysis of atomic phenomena.*
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> http://doi.org/10.1038/116845a0

As will be discussed further in the section *Free will, Consciousness, and Soul*, for much of Bohr's life he considered not only the analogies of the complementarity of psychological perception with observation of quantum processes but also seriously considered the possible role of consciousness and volition in relation to the quantum of action.

Bohr's complementarity principle was an important historic step in quantum measurement, but only one of several lines of approach to understand measurement after the initial development of quantum mechanics. Within this initial overview of the historical perspective of the measurement problem, complementarity was the natural starting point for this "measure for measure" aspect of observation. More details of complementarity will be discussed in later sections; however. a myriad of other historical details not yet mentioned underlie the array of physical concepts required to arrive at even this level of understanding in the early 1930s. As will be seen, subsequent interest in the deeper aspects of measurement waned with the necessity of understanding nuclear physics, the onset of World War II and the subsequent focus on a range of new developments and applications of quantum theory, from quantum electrodynamics to condensed matter. However, beginning in the 1950s there was a low-level resurgence of interest both in *interpretations* of quantum theory and in new approaches to the question of quantum measurement. These efforts continued to grow in the following decades, particularly after John Bell's (1928-1990) theorems in the 1960s allowing tests to discriminate the underlying workings of quantum theory, of Einstein's unholy choice between *hidden variables* and *spooky action at a distance*. However, the subject of measurement was also transformed in the last twenty years due to advances in experimental techniques, which make it possible to perform repeated measurements, feedback, and partial measurements on single continuously measured quantum systems. An idea of this surge in interest in measurement in the last decades, both theoretical and experimental, can be seen from a sampling of the cast of characters involved [320, p. 339]. Nevertheless, the quantum measurement problem has remained unresolved.

Developments in measurement followed many intertwined paths of concepts and experiments extending from the ancient Greeks and the later development of science as we view it today, up to the present state of the quantum measurement problem. These details of our theory of nature developed over centuries and have involved many diverse concepts. The history of the quantum measurement problem can be viewed broadly as *The Rise and Fall of Classicality* followed by *The Rise of the Measurement Problem*. As will be seen in the following, these developments were fought on several different fronts across overlapping historical times, each battle a dichotomy of conflicting and complementary notions described in sections of this chapter, such as: *Space-Time versus Quanta, Deductive versus Inductive Thought, Atomism versus Continuum, Clockwork versus Free Will,* and *Irreversibility versus Demon*.