Alone in a Dark Wood

In his 1927 indeterminacy paper [7], Heisenberg describes the collapse of an electron wave function by repeated interaction with light of wavelength λ, so that "Each determination of position reduces therefore the wave packet back to its original size λ." In a letter to Bohr regarding the role played by wave function reduction in Heisenberg's 1927 indeterminacy paper, Pauli explains [4, p. 162],

> *This is precisely a point that was not quite satisfactory in Heisenberg; there the "reduction of the packets" seemed a bit mystical. Now however, it is to be stressed that at first such reductions are not necessary if one includes in the system all means of measurement. But in order to describe observational results theoretically at all, one has to ask what one can say about just a part of the whole system.*
>
> G. Bacciagaluppi and A. Valentini, Quantum Theory at the Crossroads: Reconsidering the 1927 Solvay Conference, Cambridge University Press, 2013.

Pauli's view is that an overall unitary evolution of the system coupled to the measurement device will lead to measurement. A statement by Heisenberg later in the 1950's from his book *Physics and Philosophy* suggests a similar viewpoint [620]:

See the print edition of The Quantum Measurement Problem for quotation.

This is a point of view that has become almost commonplace in recent years as revealed in the survey of the different approaches to measurement presented in Chapter 4. This had begun to become prevalent in the decades following World War II after most research efforts became redirected and younger physicists lost touch with the views of the founders of quantum theory and the subtleties of the measurement problem. As additional examples of such views, consider Richard Feynman and Julian Schwinger, two of the most prominent theoretical physicists in the mid-20th century who, along with Shin'ichirō Tomonaga, had shared the Nobel Prize for their work in quantum electrodynamics [621]. Both viewed measurement as being a unitary phenomenon and therefore not an area of fundamental importance.

Feynman's colleague R.W. Hellwarth had said [622, p. 437],

> *Feynman thought that there was little of practical consequence left to be done in the theory of measurement. He certainly impressed upon his students that the so-called "collapse" of the wave function, said to occur upon measurement, follows the Schrödinger equation precisely. The subtlety in the process is the same as that in any irreversible process.*
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> The Beat of a Different Drum, The Life and Science of Richard Feynman by J. Mehra (2000), from p.437, By permission of Oxford University Press. http://www.oup.com

While a graduate student at Princeton, Feynman discussed these problems with von

Neumann who was nearby at the Institute for Advanced Study but he was dissatisfied with von Neumann's approach. Attempting to formulate an objective statement, he had argued at the time [621, pp. 394-395],

> *If you could correlate the position of a piece of the world with other pieces, then if the other pieces (or their action or energy or something) would go to infinity and the correlation approaches a finite value, then that thing is measurable.*

However, all of this could be addressed as an unexceptional unitary process.

Schwinger's views on measurement were presented at a Snowbird Conference, now in a record of the University of California Los Angeles archives, and he indicated that quantum measurement was a non-existent problem [623, pp. 368-369],

> *To me, the formalism of quantum mechanics is not just mathematics; rather it is a symbolic account of the realities of atomic measurement. That being so, no independent quantum theory of measurement is required—it is part and parcel of the formalism. This is not a universally held opinion, however. I quote from one recent paper: "Ordinary quantum mechanics is based on two distinct principles of evolution of the wave function. The first principle, to be applied in ordinary situations, is expressed by the Schrödinger equation, which provides a deterministic evolution of the wave function. The second principle, to be applied when a measurement takes place, is the reduction postulate, according to which the wave function undergoes a sudden stochastic evolution"... In my opinion, this is a desperate attempt to solve a non-existent problem, one that flows from a false premise, namely that of the von Neumann dichotomization of quantum mechanics. Surely physicists can agree that a microscopic measurement is a physical process, to be described as would any physical process, that is distinguished only by the effective irreversibility produced by amplification to the macroscopic level. Perhaps what has been lacking is a detailed analysis of the dynamics involved in some realistic measurements.*

The most significant development for the measurement problem following the period of the EPR discussions after 1935 were the *Bell inequalities* in 1964 and their experimental verification beginning with Aspect in 1982 [83]. Interest in the measurement problem waned with the disruption of World War II, and the subsequent focus was on new developments and applications of quantum theory including nuclear physics, elementary particles and relativistic quantum field theory, condensed matter, and low temperature physics, much of it beginning to be carried out in larger scale laboratories. The war also spurred developments of radar, missile technology, jet aircraft, computation, and nuclear technology. Governments invested in scientific research as they recovered economically from the war and support for research increased at universities and in systems of national laboratories. This affected the direction of research projects both due to the pressures of funding and due to the administrative organization of the new research institutions. The displacements of many researchers due to the war, including the founders of quantum theory, also necessarily affected research and collaborations [624, p. 1246]. Bohr escaped in 1943 from German-occupied Denmark and worked on the Manhattan Project in the United States, returning to Denmark in 1945 to continue work on quantum-theoretical problems. Schrödinger left Berlin in 1933 to Oxford and continued to migrate via Graz, Rome, Oxford, Belgium, and finally Ireland where Eamon de Valera installed him at the Dublin Institute for Advanced Studies. The pattern continued with scores of other scientists and collaborations inevitably were interrupted.

Interest in the foundations of quantum physics and the measurement problem faded with the rise of these new directions in research. Einstein and Bohr, the two deductive thinkers who had been at the focus of the measurement problem in the first half of the 20th century, had enormous stature, but young scientists coming into research were not motivated by their professors to study the foundations of quantum mechanics. Einstein died in 1955 and Bohr just seven years later in 1962, just before the Bell inequality developments. By the 1980s, the Copenhagen interpretation was summarized as [625]:

> *If I were forced to sum up in one sentence what the Copenhagen interpretation says to me, it would be "Shut up and calculate!"*
>
>

This is largely the opposite of a rallying cry for students to investigate the measurement problem. The fundamental nondeterminism, discontinuities, and causal renunciation of Bohr, Born, and others continued to diminish in importance. New faces appeared who began to largely calculate and explain finer and finer effects, e.g., the theory of the Lamb shift for the measured shift due to the electromagnetic field interaction. Very few modern researchers appeared to fully grasp the measurement problem and often believed that the universe was described completely by Schrödinger's equation.

> *Midway in our life's journey, I went astray…*
> *and woke to find myself alone in a dark wood.*
> [Dante c.1320]

Midway in the 20th century, the state of the Quantum Measurement Problem indeed found itself alone in a dark wood. 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. The history of the period between 1950 and 1990 is well-described in Freire Junior's book, *The Quantum Dissidents* [320], giving the background of the theories of Bohm, Everett, Wigner, and others and the era of the development of Bell's theorem to the renewal of interest in quantum foundations. These efforts into measurement continued to heat up in the following decades, particularly after John Bell's (1928-1990) theorem in the 1960s allowing a test 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, interaction-free measurements, quantum non-demolition, feedback and partial measurements on single continuously measured quantum systems. Implementation of these in physical systems has been made possible by the unprecedented level of control allowed by lasers, computers, and superconducting devices. The result is the ability to directly control and manipulate individual quantum systems and minimize undesired influences from the environment. In the process, thought-experiments are often now able to be realized involving single particle interferometers and cavities.

Starting with the resurgence of interest in measurement in the 1950s up to today, the collection of theories of quantum measurement have by now proliferated in great numbers. These include Bohmian mechanics, Relative-state or Many-worlds, GRW and Stochastic collapse theories, Consistent histories, Information-based, and Bayesian theories, among many others. These theories have been reviewed in detail in Chapter 4 along with a discussion of their capabilities for discerning the quantum measurement problem.

Are we now coming into the *Age of Quantum Measurement*? New developments devoted to measurement in both experiment and theory are constantly appearing in the journals, arXiv.org, and the proliferation of online organizations and social media platforms. Nevertheless, at this point in history, the *Quantum Measurement Problem* remains unresolved.