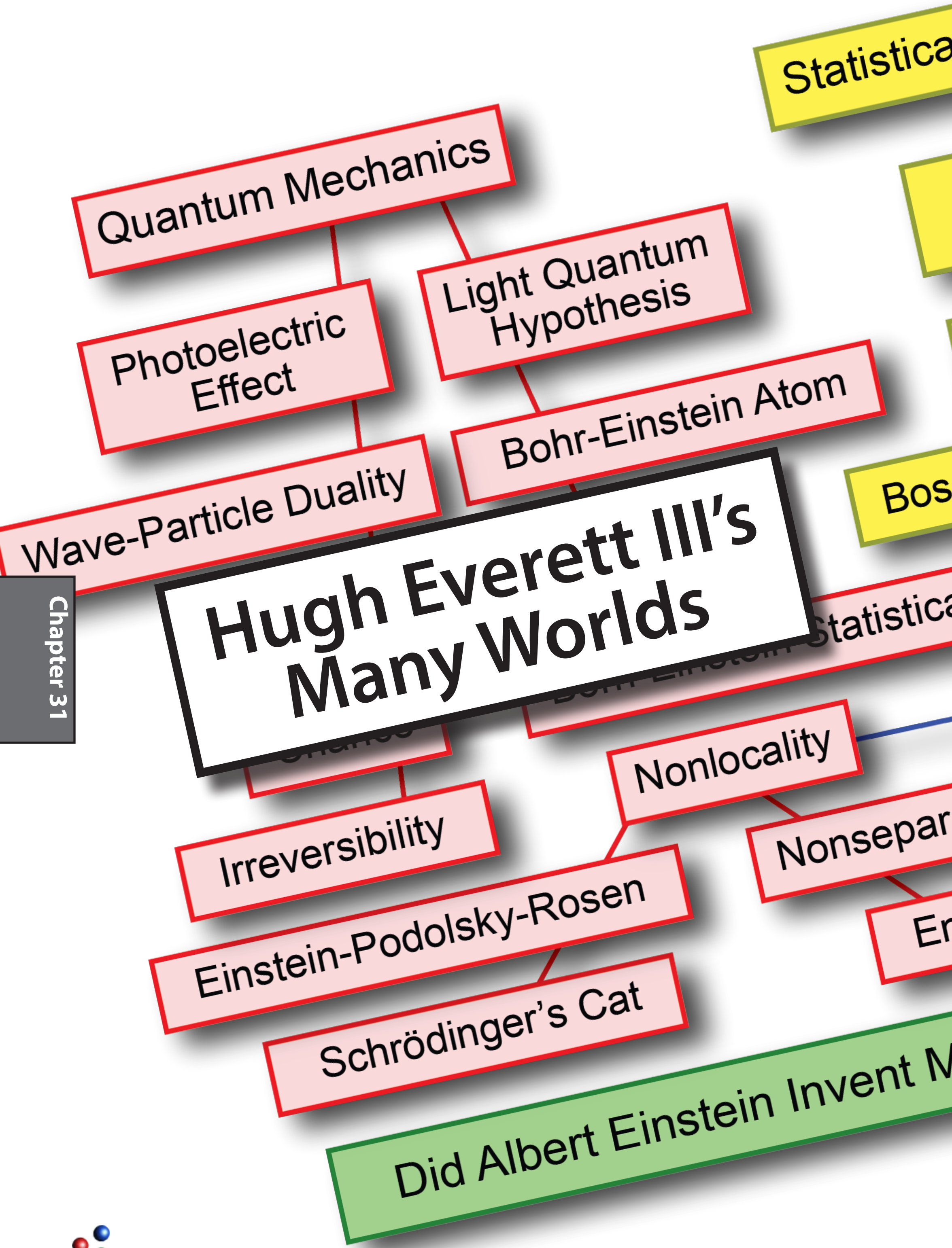
Chapter 31

Hugh Everett III's Many Worlds



Hugh Everett III's Many Worlds

Hugh Everett III was one of John Wheeler's most famous graduate students. Others included Richard Feynman. Wheeler supervised more Ph.D. theses than any Princeton physics professor.

Everett took mathematical physics classes with Eugene Wigner, who argued that human consciousness (and perhaps some form of cosmic consciousness) was essential to the "collapse" of the wave function.

Everett was the inventor of the "universal wave function" and the "relative state" formulation of quantum mechanics, later known as the "many-worlds interpretation."

The first draft of Everett's thesis was called "Wave Mechanics Without Probability." Like the younger Albert Einstein and later Erwin Schrödinger, Everett was appalled at the idea of indeterministic events. For him, it was much more logical that the world was entirely deterministic.

Everett began his thesis by describing John von Neumann's "two processes."

> Process 1: The discontinuous change brought about by the observation of a quantity with eigenstates $\varphi_1, \varphi_2, \ldots$, in which the state ψ will be changed to the state φ_j with probability $|\psi, \varphi_j|^2$
>
> Process 2: The continuous, deterministic change of state of the (isolated) system with time according to a wave equation $\delta\psi/\delta t = U\psi$, where U is a linear operator. [1]

Everett then presents the internal contradictions of observer-dependent collapses of wave functions with examples of "Wigner's Friend," an observer who observes another observer. For whom does the wave function collapse?

Everett considers several alternative explanations for Wigner's paradox, the fourth of which is the standard statistical interpretation of quantum mechanics, which was criticized (correctly) by Einstein as not being a *complete* description.

Alternative 4: To abandon the position that the state function

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1 The Many-Worlds Interpretation of Quantum Mechanics, p.3

> is a complete description of a system. The state function is to be regarded not as a description of a single system, but of an ensemble of systems, so that the probabilistic assertions arise naturally from the incompleteness of the description.
>
> It is assumed that the correct complete description, which would presumably involve further (hidden) parameters beyond the state function alone, would lead to a deterministic theory, from which the probabilistic aspects arise as a result of our ignorance of these extra parameters in the same manner as in classical statistical mechanics. [2]

For the most part, Everett seems to represent Einstein's "ensemble" or statistical interpretation, but he also is following David Bohm. In order to be "complete," "hidden variables" would be necessary.

Everett's "theory of the universal wave function" is the last alternative, in which he rejects process 1, wave function collapse:

> Alternative 5: To assume the universal validity of the quantum description, by the complete abandonment of Process 1. The general validity of pure wave mechanics, without any statistical assertions, is assumed for all physical systems, including observers and measuring apparata. Observation processes are to be described completely by the state function of the composite system which includes the observer and his object-system, and which at all times obeys the wave equation (Process 2). [3]

Everett says this alternative has many advantages.

> It has logical simplicity and it is complete in the sense that it is applicable to the entire universe. All processes are considered equally (there are no "measurement processes" which play any preferred role), and the principle of psycho-physical parallelism is fully maintained. Since the universal validity of the state function description is asserted, one can regard the state functions themselves as the fundamental entities, and one can even consider the state function of the whole universe. In this sense this theory can be called the theory of the "universal wave function," since all of physics is presumed to follow from this function. [4]

2 The Many-Worlds Interpretation of Quantum Mechanics, p.8
3 ibid.
4 ibid.

Information and Entropy

In a lengthy chapter, Everett develops the concept of information - despite the fact that his deterministic view of physics allows no alternative possibilities. For Claude Shannon, the developer of the theory of communication of information, there can be no information created ad transmitted without possibilities. Everett correctly observes that in classical mechanics information is a conserved property, a constant of the motion. No new information can be created in such a deterministic universe.

> As a second illustrative example we consider briefly the classical mechanics of a group of particles. The system at any instant is represented by a point...in the phase space of all position and momentum coordinates. The natural motion of the system then carries each point into another, defining a continuous transformation of the phase space into itself. According to Liouville's theorem the measure of a set of points of the phase space is invariant under this transformation. This invariance of measure implies that if we begin with a probability distribution over the phase space, rather than a single point, the total information,... which is the information of the joint distribution for all positions and momenta, remains constant in time. [5]

Everett correctly notes that if total information is constant, the total entropy is also constant.

> if one were to define the total entropy to be the negative of the total information, one could replace the usual second law of thermodynamics by a law of conservation of total entropy, where the increase in the standard (marginal) entropy is exactly compensated by a (negative) correlation entropy. The usual second law then results simply from our renunciation of all correlation knowledge (*stosszahlansatz*), and not from any intrinsic behavior of classical systems. The situation for classical mechanics is thus in sharp contrast to that of stochastic processes, which are intrinsically irreversible.

5 ibid., p.31

The *Appearance* of Irreversibility in a Measurement

> There is another way of looking at this apparent irreversibility within our theory which recognizes only Process 2. When an observer performs an observation the result is a superposition, each element of which describes an observer who has perceived a particular value. From this time forward there is no interaction between the separate elements of the superposition (which describe the observer as having perceived different results), since each element separately continues to obey the wave equation. Each observer described by a particular element of the superposition behaves in the future completely independently of any events in the remaining elements, and he can no longer obtain any information whatsoever concerning these other elements (they are completely unobservable to him).
>
> The irreversibility of the measuring process is therefore, within our framework, simply a subjective manifestation reflecting the fact that in observation processes the state of the observer is transformed into a superposition of observer states, each element of which describes an observer who is irrevocably cut off from the remaining elements. While it is conceivable that some outside agency could reverse the total wave function, such a change cannot be brought about by any observer which is represented by a single element of a superposition, since he is entirely powerless to have any influence on any other elements.
>
> There are, therefore, fundamental restrictions to the knowledge that an observer can obtain about the state of the universe. It is impossible for any observer to discover the total state function of any physical system, since the process of observation itself leaves no independent state for the system or the observer, but only a composite system state in which the object-system states are inextricably bound up with the observer states. [6]

This is Everett's radical thesis that the observation "splits" the single observer into a "superposition" of multiple observers, each one of which has knowledge only of the new object-system state or "relative state" (interpreted later by Bryce DeWitt as different "universes") As soon as the observation is performed, the composite state is split into a superposition for which each element describes

6 ibid., p.98

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a different object-system state and an observer with (different) knowledge of it. Only the totality of these observer states, with their diverse knowledge, contains complete information about the original object-system state - but there is no possible communication between the observers described by these separate states. Any single observer can therefore possess knowledge only of the relative state function (relative to his state) of any systems, which is in any case all that is of any importance to him.

In the final chapter of his thesis, Everett reviews five possible "interpretations, the "popular", the "Copenhagen", the "hidden variables", the "stochastic process", and the "wave" interpretations.

> a. The "popular" interpretation. This is the scheme alluded to in the introduction, where ψ is regarded as objectively characterizing the single system, obeying a deterministic wave equation when the system is isolated but changing probabilistically and discontinuously under observation.[7]

> b. The Copenhagen interpretation. This is the interpretation developed by Bohr. The ψ function is not regarded as an objective description of a physical system (i.e., it is in no sense a conceptual model), but is regarded as merely a mathematical artifice which enables one to make statistical predictions, albeit the best predictions which it is possible to make. This interpretation in fact denies the very possibility of a single conceptual model applicable to the quantum realm, and asserts that the totality of phenomena can only be understood by the use of different, mutually exclusive (i.e., "complementary") models in different situations. All statements about microscopic phenomena are regarded as meaningless unless accompanied by a complete description (classical) of an experimental arrangement.[8]

> c. The "hidden variables" interpretation. This is the position (Alternative 4 of the Introduction) that ψ is not a complete description of a single system. It is assumed that the correct complete description, which would involve further (hidden) parameters, would lead to a deterministic theory, from which the probabilistic aspects arise as a result of our ignorance of these extra parameters in the same manner as in classical statistical mechanics.[9]

7 ibid., p.110
8 ibid.
9 ibid., p.111.

Everett says that here the ψ-function is regarded as a description of an ensemble of systems rather than a single system. Proponents of this interpretation include Einstein and Bohm.

> d. The stochastic process interpretation. This is the point of view which holds that the fundamental processes of nature are stochastic (i.e., probabilistic) processes. According to this picture physical systems are supposed to exist at all times in definite states, but the states are continually undergoing probabilistic changes. The discontinuous probabilistic "quantum-jumps" are not associated with acts of observation, but are fundamental to the systems themselves. [10]

This is very close to our information interpretation of quantum mechanics, which claims that collapses of the wave function result from interactions between quantum systems, independent of any observers or measurement processes.

> e. The wave interpretation. This is the position proposed in the present thesis, in which the wave function itself is held to be the fundamental entity, obeying at all times a deterministic wave equation. [11]

Everett says that his thesis follows most closely the view held by Erwin Schrödinger, who denied the existence of "quantum jumps" and collapses of the wave function. See Schrödinger's *Are There Quantum Jumps?*, Part I and Part II (and, years after Everett, John Bell (1987) and H. Dieter Zeh (1993) who wrote articles with similar themes.

On the "Conscious Observer"

Everett proposed that the complicated problem of "conscious observers" can be greatly simplified by noting that the most important element in an observation is the recorded information about the measurement outcome in the memory of the observer. He proposed that human observers could be replaced by automatic measurement equipment that would achieve the same result. A measurement would occur when information is recorded by the measuring instrument.

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10 ibid., p.114

11 ibid., p.115.

> It will suffice for our purposes to consider the observers to possess memories (i.e., parts of a relatively permanent nature whose states are in correspondence with past experience of the observers). In order to make deductions about the past experience of an observer it is sufficient to deduce the present contents of the memory as it appears within the mathematical model.
>
> As models for observers we can, if we wish, consider automatically functioning machines, possessing sensory apparatus and coupled to recording devices capable of registering past sensory data and machine configurations.[12]

Everett's observer model is a classic example of artificial intelligence.

> We can further suppose that the machine is so constructed that its present actions shall be determined not only by its present sensory data, but by the contents of its memory as well. Such a machine will then be capable of performing a sequence of observations (measurements), and furthermore of deciding upon its future experiments on the basis of past results. If we consider that current sensory data, as well as machine configuration, is immediately recorded in the memory, then the actions of the machine at a given instant can be regarded as a function of the memory contents only, and all relevant experience of the machine is contained in the memory.[13]

Everett's observer model has what might be called artificial consciousness.

> For such machines we are justified in using such phrases as "the machine has perceived A" or "the machine is aware of A" if the occurrence of A is represented in the memory, since the future behavior of the machine will be based upon the occurrence of A. In fact, all of the customary language of subjective experience is quite applicable to such machines, and forms the most natural and useful mode of expression when dealing with their behavior, as is well known to individuals who work with complex automata.[14]

12 ibid., p.64.
13 ibid.
14 ibid.

Everett's model of machine memory completely solves the problem of "Wigner's Friend." As in the information interpretation of quantum mechanics, it is the recording of information in a "measurement" that makes a subsequent "observation" by a human observer possible.

Bryce De Witt

Everett stepped away from theoretical physics almost entirely even before his thesis was finally accepted under John Wheeler and published in the July 1957 issue of *Reviews of Modern Physics*. along with an accompanying article by Wheeler.

Without the strong interest in the many-worlds interpretation of quantum mechanics by Bryce DeWitt, it might have much less interest and influence today.

In 1970, DeWitt wrote an article on Everett's "relative-state" theory for *Physics Today*. A few years later he compiled a collection of Everett's work, including the 1957 paper and the much longer "The Theory of the Universal Wave Function,"along with interpretive articles, by DeWitt, Wheeler, and others.

Summary of Everett's Ideas

Everett's idea for the "universal validity of the quantum description" can be read as saying that quantum mechanics applies to all physical systems, not merely microscopic systems. This is correct. Then the transition to "classical" mechanics emerges in the limit of the Planck quantum of action $h \rightarrow 0$, or more importantly, $h/m \rightarrow 0$ (since h never changes), so that classical physics appears in large massive objects (like human beings) because the indeterminacy is too small to measure.

Like Einstein, Everett says that the ψ-function is a description of an ensemble of systems rather than a single system. It is true that the phenomenon of wave interference is only inferred from the results of many single particle experiments. We never "see" interference in single particles directly. Probabilistic assertions arise naturally from the incompleteness of the description.

Everett correctly observes that in classical mechanics information is a conserved property, a constant of the motion. No new information can be created in a classical universe. But the observed universe has clearly been gaining new information structures since the origin. Indeed, both information and entropy have been increasing and continue to increase today. This cannot be explained by Everett.

Everett's automatic measuring equipment that stores information about measurements in its "memory" nicely solves von Neumann's problem of "psycho-physical parallelism" in "conscious-observer"-dependent quantum mechanics, like the Bohr-Heisenberg "Copenhagen Interpretation."

The Everett theory preserves the "appearance" of possibilities as well as all the results of standard quantum mechanics. It is an "interpretation" after all. So even wave functions "appear" to collapse. Note that if there are many possibilities, whenever one becomes actual, the others disappear instantly. In Everett's theory, they become other possible worlds

Unfortunately, as DeWitt and most modern followers of Everett see it, alternative possibilities are in different, inaccessible universes. In each deterministic universe, there is only one possible future.

Many of Everett's original ideas become central in later deterministic interpretations of quantum mechanics, such as the decoherence program of H.Dieter Zeh and Wojciech Zurek.

Some of Everett's important new ideas show up also in the work of John Bell, to which we now turn.