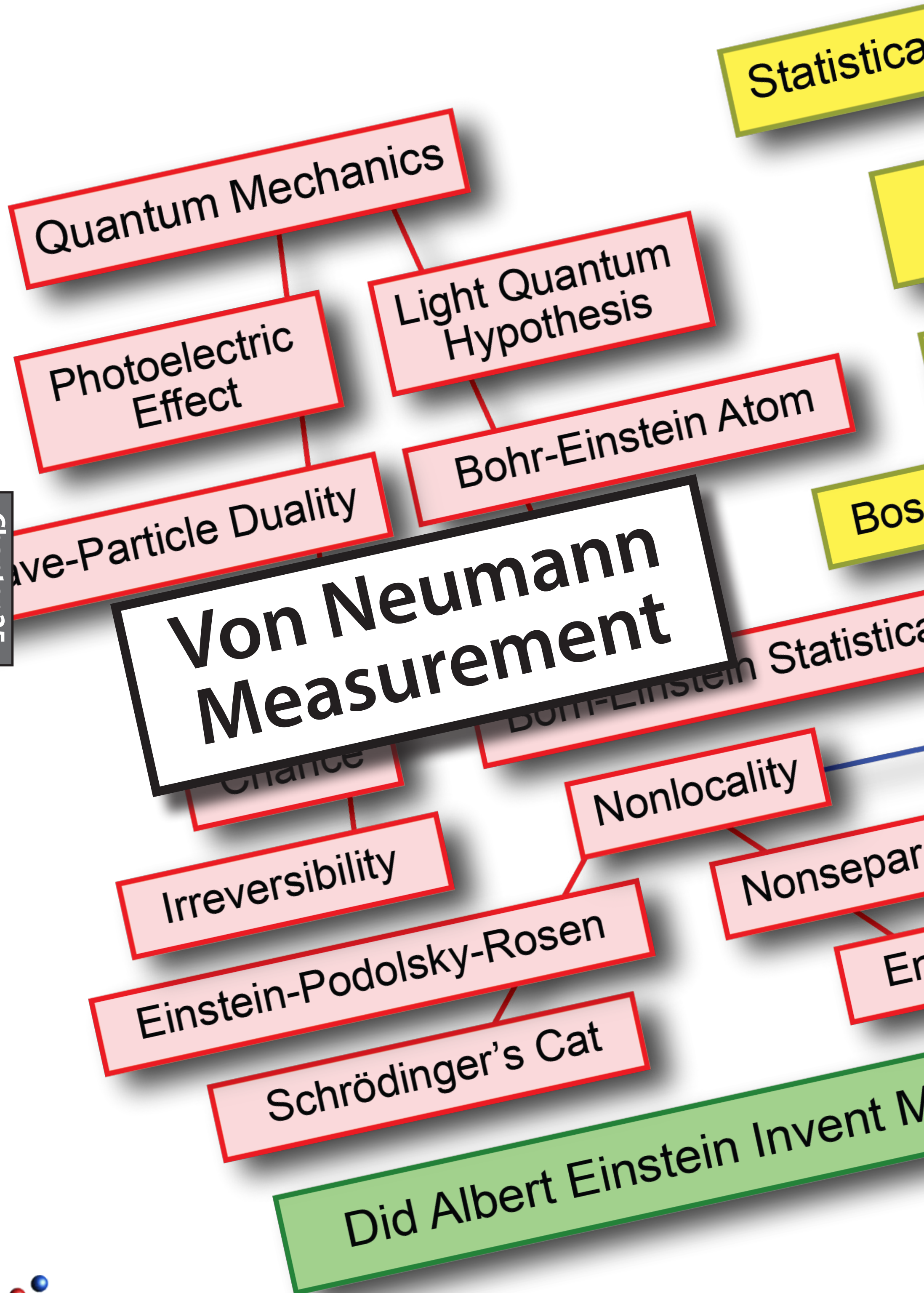
Chapter 25


Von Neumann Measurement
Quantum Mechanics
Photoelectric Effect
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# Von Neumann Measurement

In his 1932 *Mathematical Foundations of Quantum Mechanics* (in German, English edition 1955), John von Neumann explained that two fundamentally different processes are going on in quantum mechanics (in a temporal sequence for a given particle - not happening at the same time).

**Process 1.** A non-causal process, in which the measured electron jumps randomly into one of the possible physical states (eigenstates) of the measuring apparatus plus electron.

The probability for each eigenstate is given by the square of the coefficients $c_n$ of the expansion of the original system state (wave function $\psi$) in an infinite set of wave functions $\varphi$ that represent the eigenfunctions of the measuring apparatus plus electron.

The coefficients $c_n = < \varphi_n \mid \psi >$.

As we saw in chapter 19, this is Paul Dirac's *principle of superposition*. $c_n^2$ is the probability that the electron will be found in the *n*th eigenstate. This is Dirac's *projection postulate*. When measured it is found to have the eigenvalue corresponding to that eigenstate. This is Dirac's *axiom of measurement*.

This is as close as we get to a description of the motion of the particle aspect of a quantum system. According to von Neumann, the particle simply shows up somewhere as a result of a measurement. Exact predictions for an individual particle are not possible,. This is why Einstein called quantum mechanics *incomplete*.

Information physics says that for a particle to show up, a new stable information structure must be created, information that may be observed only *after* it has been created (recorded).

**Process 2.** A causal process, in which the electron wave function $\psi$ evolves deterministically according to Erwin Schrödinger's wave equation of motion,

$(ih/2\pi)\, \partial\psi/\partial t = H\psi.$

This evolution describes only the motion of the probability amplitude wave $\psi$ between measurements. The individual particle path itself can not be observed. It it were, new information from the measurement would require a new wave function.

Max Born had concisely described these two processes years earlier. “The motion of the particle follows the laws of probability, but the probability itself propagates in accord with causal laws.”[1]

Von Neumann claimed there is a major difference between these two processes. Process 1 is thermodynamically *irreversible*. Process 2 is reversible. But only when it describes a time during which the particle has no known interactions. Any interactions destroy the “coherence” of the wave functions.

Information physics establishes that *indeterministic* process 1 may create stable new information. An irreversible process 1 is always involved when new information is created. In chapter 12, we showed that the irreversibility of microscopic processes depends on the interaction between matter and radiation.



Process 2 is *deterministic* and information preserving or conserving. But process 2 is an idealization. It assumes that deterministic laws of motion exist. These are differential equations describing continuous quantities. As Born emphasized, continuous quantities evolving deterministically are only probabilities!

Process 1 has come to be called the “collapse of the wave function” or the “reduction of the wave packet.” It gave rise to the so-called “problem of measurement,” because its randomness prevents it from being a part of the deterministic mathematics of process 2. According to von Neumann, the particle simply shows up somewhere as a result of a measurement. Einstein described these very processes in his 1905 work on the photoelectric effect.

Information physics says that the particle “shows up” only when a new stable information structure is created, information that subsequently can be observed. We might then add an additional condition to process 1.

**Process 1b.** Note that the information created in Von Neumann’s Process 1 will only be stable if an amount of positive entropy greater than the negative entropy in the new information structure is transported away, in order to satisfy the second law of thermodynamics.

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1 “Quantum mechanics of collision processes,” *Zeit. f. Phys.* 1926, p.804

## The Measurement Problem

The original problem, said to be a consequence of Niels Bohr's "Copenhagen Interpretation" of quantum mechanics, was to explain how our measuring instruments, which are usually macroscopic objects and treatable with classical physics, can give us information about the microscopic world of atoms and subatomic particles like electrons and photons.

Bohr's idea of "complementarity" insisted that a specific experiment could reveal only partial information - for example, a particle's position. "Exhaustive" information requires complementary experiments, for example to also determine a particle's momentum (within the limits of Werner Heisenberg's indeterminacy principle).

Von Neumann's measurement problem is the logical contradiction between his two processes describing the time evolution of quantum systems; the unitary, continuous, deterministic, and information-conserving Schrödinger equation versus the non-unitary, discontinuous, indeterministic and information-creating collapse of the wave function.

The mathematical formalism of quantum mechanics provides no way to predict when the wave function stops evolving in a unitary fashion and collapses. Experimentally and practically, however, we can say that this occurs when the microscopic system interacts with a measuring apparatus. The Russian physicists Lev Landau and Evgeny Lifshitz described it in their 1958 textbook Quantum Mechanics"

> The possibility of a quantitative description of the motion of an electron requires the presence also of physical objects which obey classical mechanics to a sufficient degree of accuracy. If an electron interacts with such a "classical object", the state of the latter is, generally speaking, altered. The nature and magnitude of this change depend on the state of the electron, and therefore may serve to characterise it quantitatively...
>
> We have defined "apparatus" as a physical object which is governed, with sufficient accuracy, by classical mechanics.

> Such, for instance, is a body of large enough mass...
>
> Thus quantum mechanics occupies a very unusual place among physical theories: it contains classical mechanics as a limiting case [correspondence principle], yet at the same time it requires this limiting case for its own formulation. [2]

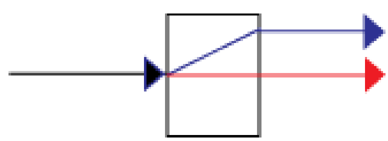
## The Measurement Apparatus

The apparatus must allow different components of the wave function to evolve along distinguishable paths into different regions of space, where the different regions correspond to (are correlated with) the physical properties we want to measure. We then can locate a detector in these different regions of space to catch particles travelling a particular path.

We do not say that the system is on a particular path in this first step. That would cause the probability amplitude wave function to collapse. This first step is reversible, at least in principle. It is deterministic and an example of von Neumann process 2.



Let's consider the separation of a beam of photons into horizontally and vertically polarized photons by a birefringent crystal.



We need a beam of photons (and the ability to reduce the intensity to a single photon at a time). Vertically polarized photons pass straight through the crystal. They are called the ordinary ray.

Horizontally polarized photons, however, are deflected at an angle up through the crystal, then exit the crystal back at the original angle. They are called the extraordinary ray.

Note that this first part of our apparatus accomplishes the separation of our two states into distinct physical regions.

We have not actually measured yet, so a single photon passing through our measurement apparatus is described as in a linear combination (a superposition) of horizontal and vertical polarization states,

$$|\psi> = ( 1/\sqrt{2})\,|h> + ( 1/\sqrt{2})\,|v> \qquad (1)$$

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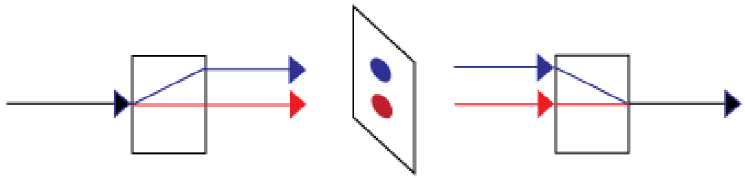
2 Quantum Mechanics, Lev Landau and Evgeny Lifshitz, pp.2-3

To show that von Neumann's process 2 is reversible, we can add a second birefringent crystal upside down from the first, but inline with the superposition of physically separated states,

Since we have not made a measurement and do not know the path of the photon, the phase information in the (generally complex) coefficients of equation (1) has been preserved, so when they combine in the second crystal, they emerge in a state identical to that before entering the first crystal (final arrow).

We can now create an information-creating, irreversible example of process 1. Suppose we insert something between the two crystals that is capable of a measurement to produce observable information. We need detectors, for example two charge-coupled devices that locate the photon in one of the two rays.

We can write a quantum description of the CCDs, one measuring horizontal photons, $|A_h>$ (the upper extraordinary ray), and the other measuring vertical photons, $|A_v>$ (passing straight through).



We treat the detection systems quantum mechanically, and say that each detector has two eigenstates, e.g., $|A_{h0}>$, corresponding to its initial state and correlated with no photons, and the final state $|A_{h1}>$, in which it has detected a horizontal photon.

When we actually detect the photon, say in a horizontal polarization state with statistical probability 1/2, there are two "collapses" or "quantum jumps" that occur.

The first is the jump of the probability amplitude wave function $|\psi>$ of the photon in equation (1) into the horizontal state $|h>$.

The second is the quantum jump of the horizontal detector from $|A_{h0}>$ to $|A_{h1}>$. These two happen together, as the quantum states have become correlated with the states of the sensitive detectors in the classical apparatus.

One can say that the photon has become entangled with the sensitive horizontal detector area, so that the wave function describing their interaction is a superposition of photon and apparatus states that cannot be observed independently.

$|\psi> + |A_{h0}> \quad => \quad |\psi, A_{h0}> \quad => \quad |h, A_{h1}>$

These jumps destroy (unobservable) phase information, raise the (Boltzmann) entropy of the apparatus, and increase visible information (Shannon entropy) in the form of the visible spot. The entropy increase takes the form of a large chemical energy release when the photographic spot is developed (or a cascade of electrons in a CCD).

Note that the birefringent crystal and the parts of the macroscopic apparatus other than the sensitive detectors are treated classically.

We see that our example agrees with von Neumann. A measurement which finds the photon in a specific polarization state is thermodynamically irreversible, whereas the deterministic evolution described by Schrödinger's equation is time reversible and can be reversed experimentally, provided no decohering interaction occurs.

We thus establish a clear connection between a measurement, which increases the information by some number of bits (negative Shannon entropy), and the compensating increase in the (positive Boltzmann) entropy of the macroscopic apparatus, needed to satisfy the second law of thermodynamics.

Note that the Boltzmann entropy can be radiated away (ultimately into the night sky to the cosmic microwave background) only because the expansion of the universe, discovered by Einstein, provides a sink for the positive entropy.

## The *Schnitt* and Conscious Observer

Von Neumann developed WERNER HEISENBERG's idea that the collapse of the wave function requires a "cut" (*Schnitt* in German) between the microscopic quantum system and the observer. He said it did not matter where this cut was placed, because the mathematics would produce the same experimental results.

There has been a lot of controversy and confusion about this cut. Eugene Wigner placed it outside a room which includes the measuring apparatus and an observer A, and just before observer B makes a measurement of the physical state of the room, which is imagined to evolve deterministically according to process 2 and the Schrödinger equation.

Von Neumann contributed a lot to this confusion in his discussion of subjective perceptions and "psycho-physical parallelism." He wrote:

> [I]t is a fundamental requirement of the scientific viewpoint -- the so-called principle of the psycho-physical parallelism -- that it must be possible so to describe the extra-physical process of the subjective perception as if it were in reality in the physical world -- i.e., to assign to its parts equivalent physical processes in the objective environment, in ordinary space.
>
> In a simple example, these concepts might be applied about as follows: We wish to measure a temperature. If we want, we can pursue this process numerically until we have the temperature of the environment of the mercury container of the thermometer, and then say: this temperature is measured by the thermometer. But we can carry the calculation further, and from the properties of the mercury, which can be explained in kinetic and molecular terms, we can calculate its heating, expansion, and the resultant length of the mercury column, and then say: this length is seen by the observer.
>
> Going still further, and taking the light source into consideration, we could find out the reflection of the light quanta on the opaque mercury column, and the path of the remaining light quanta into the eye of the observer, their refraction in the eye lens, and the formation of an image on the retina, and then we would say: this image is registered by the retina of the observer.
>
> And were our physiological knowledge more precise than it is today, we could go still further, tracing the chemical reactions which produce the impression of this image on the retina, in the optic nerve tract and in the brain, and then in the end say: these chemical changes of his brain cells are perceived by the observer. But in any case, no matter how far we calculate -- to the mercury vessel, to the scale of the thermometer, to the retina, or into the

> brain, at some time we must say: and this is perceived by the observer. That is, we must always divide the world into two parts, the one being the observed system, the other the observer...
>
> The boundary between the two is arbitrary to a very large extent... That this boundary can be pushed arbitrarily deeply into the interior of the body of the actual observer is the content of the principle of the psycho-physical parallelism -- but this does not change the fact that in each method of description the boundary must be put somewhere, if the method is not to proceed vacuously, i.e., if a comparison with experiment is to be possible. Indeed experience only makes statements of this type: an observer has made a certain (subjective) observation; and never any like this: a physical quantity has a certain value.
>
> Now quantum mechanics describes the events which occur in the observed portions of the world, so long as they do not interact with the observing portion, with the aid of the process 2, but as soon as such an interaction occurs, i.e., a measurement, it requires the application of process 1. The dual form is therefore justified. However, the danger lies in the fact that the principle of the psycho-physical parallelism is violated, so long as it is not shown that the boundary between the observed system and the observer can be displaced arbitrarily in the sense given above. [3]



Information physics places the von Neumann/Heisenberg cut or boundary at the place and time of information creation. It is only *after* information is created that an observer could make an observation. Beforehand, there is no information to be observed.

Just as the new information recorded in the measurement apparatus cannot subsist unless a compensating amount of entropy is transferred away from the new information, something similar to Process 1b must happen in the mind of an observer if the new information is to constitute an "observation."

It is only in cases where information persists long enough for a human being to observe it that we can properly describe the observation as a "measurement" and the human being as an "observer." So, following von Neumann's "process" terminology, we can complete his theory of the measuring process by adding an anthropomorphic third process...

3 *The Mathematical Foundations of Quantum Mechanics*, pp. 418-21

**Process 3** - a conscious observer recording new information in a mind. This is only possible if there are two local reductions in the entropy (the first in the measurement apparatus, the second in the mind), both balanced by even greater increases in positive entropy that must be transported away from the apparatus and the mind, so the overall increase in entropy can satisfy the second law of thermodynamics.

For some physicists, it is the wave-function collapse that gives rise to the "problem" of measurement because its randomness prevents us from including it in the mathematical formalism of the deterministic Schrödinger equation in process 2.

Information creation occurs as a result of the interaction between the indeterministic microscopic system and the adequately deterministic measuring apparatus. It is a severe case of anthropomorphism to think it requires the consciousness of an observer for the wave function itself to collapse.

The collapse of a wave function and information creation has been going on in the universe for billions of years before human consciousness emerged. The cosmic information-creating process requires no conscious observer. *The universe is its own observer*.

It is enough that the new information created is observable and stable, so that a human observer can look at it in the future. Information physics is thus subtly involved in the question of what humans can know (epistemology).

Many scientists and philosophers deny von Neumann's process 1, the collapse of the wave function (also Paul Dirac's projection postulate), claiming that the Schrödinger equation is all that is needed to describe a "unitary," information-conserving evolution of the "wave function of the universe." But in such a universe, nothing ever happens.

Information physics solves the problem of measurement by identifying the moment and place of the collapse of the wave function with the creation of a potentially observable information structure. Some interactions between matter and radiation create irreversible collapses but do not produce information structures that last long enough to be observed. These can never be the basis of measurements of "observables" by physicists.