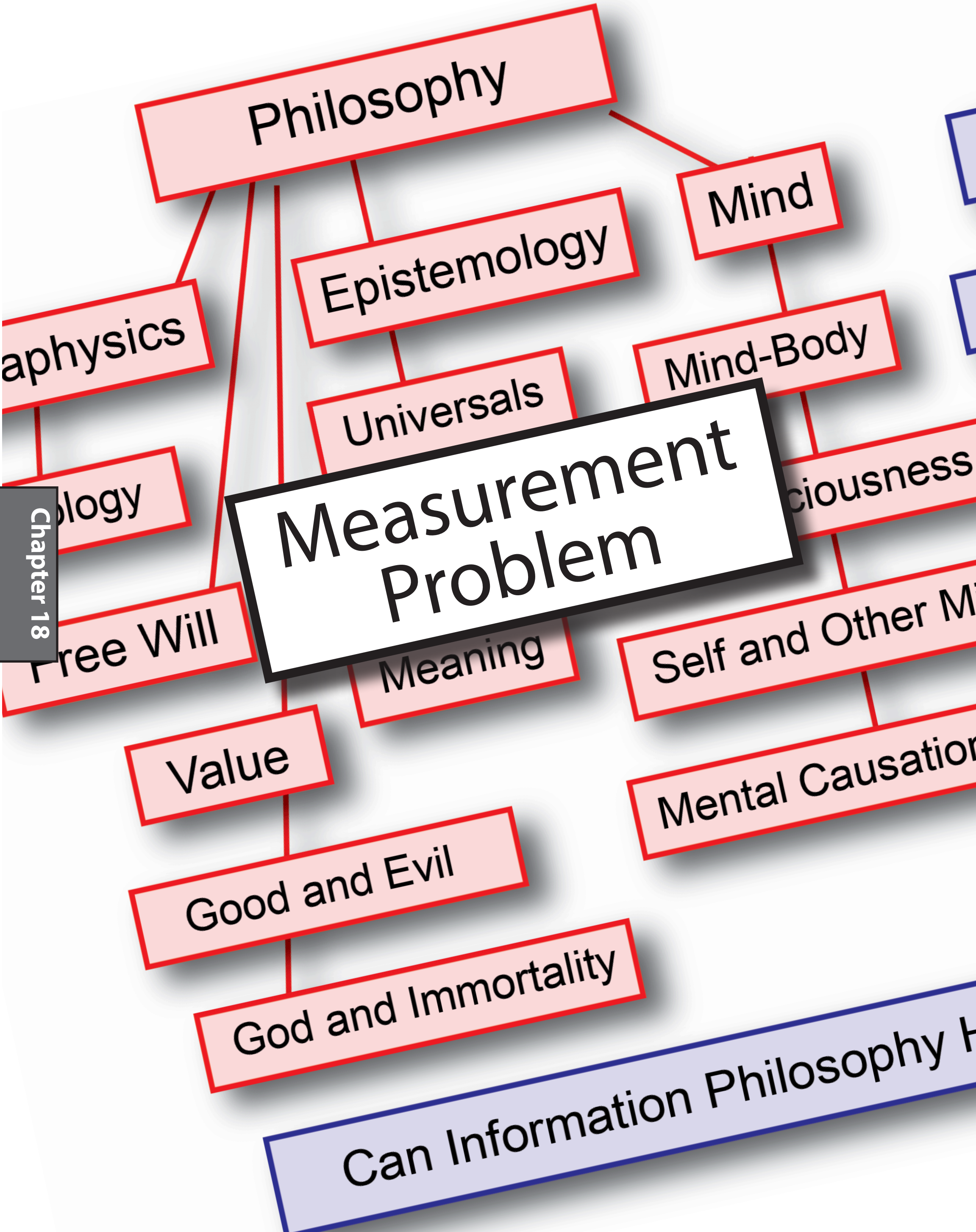

This chapter on the web
informationphilosopher.com/problems/measurement

The Measurement Problem

The "problem of measurement" in quantum mechanics has been defined in various ways, originally by scientists, and more recently by philosophers of science who question the "foundations" of quantum mechanics.

Measurements are described with diverse concepts in quantum physics such as:

- wave functions (probability amplitudes) evolving unitarily and deterministically (preserving information) according to the linear Schrödinger equation,
- superposition of states, i.e., linear combinations of wave functions with complex coefficients that carry phase information and produce interference effects (the *principle of superposition*),
- quantum jumps between states accompanied by the "collapse of the wave function" that can destroy or create information (Paul Dirac's *projection postulate*, John von Neumann's Process 1),
- probabilities of collapses and jumps given by the square of the absolute value of the wave function for a given state,
- values for possible measurements given by the eigenvalues associated with the eigenstates of the combined measuring apparatus and measured system (the *axiom of measurement*),
- the indeterminacy or uncertainty principle.

The original measurement 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 or its momentum. "Exhaustive" or "complete" information requires two complementary experiments. Measurement of both a particle's momentum and its position can only be within the limits of Werner Heisenberg's uncertainty principle. This demands that the product of the indeterminacy in the position Δx multiplied by the indeterminacy in the momentum Δp be equal to or greater than Planck's quantum of action h.

Some define the problem of measurement simply as the logical contradiction between two laws describing the motion of quantum systems; the unitary, information preserving, continuous, and deterministic time evolution of the Schrödinger equation versus the non-unitary, discontinuous, and indeterministic collapse of the wave function. John von Neumann saw a problem with these two distinct (indeed, logically opposing) processes.

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 measurement apparatus. or indeed just with another quantum system.

Others define the measurement problem as the failure to observe macroscopic superpositions.

Decoherence theorists[1] (e.g., H. Dieter Zeh and Wojciech Zurek, who use various non-standard interpretations of quantum mechanics, denying the projection postulate, quantum jumps, and even the existence of particles), define the measurement problem as the failure to observe superpositions such as Schrödinger's Cat. Unitary time evolution of the wave function according to the Schrödinger wave equation should produce such macroscopic superpositions, they claim.

Information physics treats a measuring apparatus quantum mechanically by describing parts of it as in a metastable state like the excited states of an atom, the critically poised electrical potential energy in the discharge tube of a Geiger counter, or the supersaturated water and alcohol molecules of a Wilson cloud chamber. (The pi-bond orbital rotation from cis- to trans- in the light-sensitive retinal molecule is an example of a critically poised apparatus).

1 See chapter 22.

Excited (metastable) states are poised to collapse when an electron (or photon) collides with the sensitive detector elements in the apparatus. This collapse is macroscopic and *irreversible*[2], generally a cascade of quantum events that release large amounts of energy, increasing the (Boltzmann) entropy. But in a "measurement" there is also a local decrease in the entropy. This negative entropy corresponds to the information gained in the measurement. The global entropy increase is normally orders of magnitude more than the small local decrease in entropy (an increase in stable information or Shannon entropy) that constitutes the "measured" experimental data available to human observers.

The creation of new information in a measurement thus follows the same two core processes of all information creation - quantum cooperative phenomena and thermodynamics. These two are involved in the formation of microscopic objects like atoms and molecules, as well as macroscopic objects like galaxies, stars, and planets.

According to the correspondence principle, all the laws of quantum physics asymptotically approach the laws of classical physics in the limit of large quantum numbers and large numbers of particles. Quantum mechanics can be used to describe even the largest macroscopic systems.

Does this mean that the positions and momenta of macroscopic objects are uncertain? Yes, it does. Although the uncertainty becomes vanishingly small for large objects, it is not zero.

Noting that the momentum p is the product of mass and velocity mv, Heisenberg's indeterminacy principle, $\Delta p\ \Delta x > h$, can be rewritten as $\Delta v\ \Delta x > h / m$. It is thus not when h is small, but when the mass m is large enough and h / m is small enough, that errors in the position and momentum of macroscopic objects become smaller that can be measured.

Niels Bohr used the uncertainty of macroscopic objects to defeat Albert Einstein's several objections to quantum mechanics at the 1927 Solvay conference.

2 See chapter 25.

But Bohr and Heisenberg also insisted that a measuring apparatus must be a regarded as a purely classical system. They can't have it both ways. Can the macroscopic apparatus also be treated by quantum physics or not? Can it be described by the Schrödinger equation? Can it be regarded as in a superposition of states?

The most famous example of macroscopic superposition is no doubt Schrödinger's Cat[3], which is claimed to be in a superposition of live and dead cats, and the Einstein-Podolsky-Rosen experiment, in which entangled electrons or photons are in a superposition of two-particle states that collapse over macroscopic distances to exhibit properties "nonlocally" at speeds faster than the speed of light.

The radical treatments of macroscopic systems, by Schrödinger and Einstein and his colleagues, were intended to expose inconsistencies and incompleteness in quantum theory. The critics hoped to restore determinism and "local reality" to physics. They resulted in some strange and extremely popular "mysteries" about "quantum reality," such as the "many-worlds" interpretation, "hidden variables," and signaling faster than the speed of light.

We develop a quantum-mechanical treatment of macroscopic systems, especially a measuring apparatus, to show how it can create new information. If the apparatus were describable only by classical deterministic laws, no new information could come into existence. The apparatus need only be adequately determined, that is to say, "classical" to a sufficient degree of accuracy.

As Landau and Lifshitz described it in their 1958 textbook,

> "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. However, it must not be supposed that

3 See chapter 23

> apparatus is necessarily macroscopic. Under certain conditions, the part of apparatus may also be taken by an object which is microscopic, since the idea of "with sufficient accuracy" depends on the actual problem proposed.
>
> "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."[4]

Von Neumann's Two Processes

The measurement problem was analyzed mathematically in 1932 by John von Neumann. Following the work of Bohr and Heisenberg, he divided the world into a microscopic (atomic-level) quantum system and a macroscopic (classical) measuring apparatus.

Von Neumann explained that two fundamentally different processes are going on in quantum mechanics.

First, a non-causal **Process 1**, in which the measured electron winds up randomly in one of the possible physical states (eigenstates) of the measuring apparatus plus electron.

This process came to be called the "collapse of the wave function" or the "reduction of the wave packet."

The probability for finding the electron in a specific eigenstate is given by the square of the coefficients c_n of the expansion of the original system state (wave function ψ) in an infinite set of wave functions φ_n that represent the eigenfunctions of the measuring apparatus plus electron.

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.

Information physics says that the particle "shows up" only when a new stable information structure is created, information that subsequently can be observed.

So we can also add a **Process 1b**. 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

4 *Quantum Mechanics, non-relativistic theory*, pp.1-2

structure is transported away, in order to satisfy the second law of thermodynamics.

Next, von Neumann's causal **Process 2**, in which the electron wave function ψ evolves deterministically according to Schrödinger's equation of motion for the wavelike aspect.

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

This evolution describes the motion of the probability amplitude wave ψ between measurements. The wave function exhibits interference effects. But the particle path itself can not be observed. Interference is destroyed if the particle has a definite position or momentum. *The particle does not have a definite position between measurements.*

Von Neumann claimed there is another major difference between his two processes. **Process 1** is thermodynamically irreversible. **Process 2** is reversible. This confirms the fundamental connection between quantum mechanics and thermodynamics that information physics finds at the heart of all information creation.

Information physics can show quantum mechanically how **Process 1** creates information. Something like **Process 1** is always involved when any information is created, whether or not the new information is ever "observed" by a human being.

Process 2 is deterministic and information conserving.

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.

Process 3 is a conscious observer recording new information in a mind. For this we need two local reductions in the entropy (new information in the measurement apparatus, new information 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.

Designing a Quantum Measurement Apparatus

The first step is to build an apparatus that allows 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. Knowing the position 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 a birefringent crystal separating a beam of photons into horizontally and vertically polarized photons.[5]

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 though the crystal, then exit the crystal back at the original angle. This is the extraordinary ray.

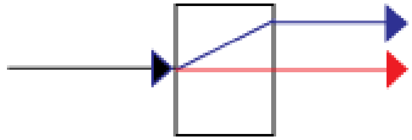

Figure 18-11. Separating horizontal and vertical polarized photons

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

5 See http://www.informationphilosopher.com/problems/measurement/#design for an animation of the birefringent crystal experiment

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,

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

A Reversible Example of Process 2

To show that 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,

Figure 18-12. If we don't measure, we can recombine the beams

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 the state they had before entering the first crystal.

An Irreversible Example of Process 1

But now suppose we insert something between the two crystals that is capable of a measurement to produce observable information. We need detectors that may locate the photon in one of the two rays.

Let's consider an ideal photographic plate capable of precipitating visible silver grains upon the receipt of a single photon (and subsequent development). Today photography cannot detect single photons, but detectors using charge coupled devices (CCDs) are approaching this sensitivity.

We can write a quantum description of the plate as containing two sensitive collection areas, the part of the apparatus measuring horizontally polarized photons, $| \, A_h >$ (shown as the upper spot), and the part of the apparatus measuring vertically polarized photons, | A_v > (shown as the lower spot).

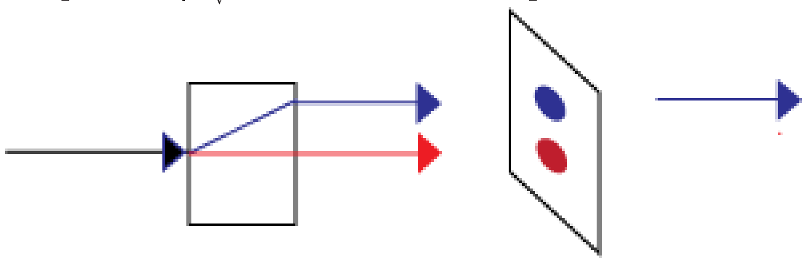

Figure 18-13. Two possible paths become one actual when detected.

We treat the detection systems quantum mechanically, and say that each detector has two eigenstates, e.g., | A_{h0} >, corresponding to

• the jump of the probability amplitude wave function | ψ > of the photon in equation (1) into the horizontally polarized state | h >.

• the quantum jump of the horizontal detector from | A_{h0} > to | A_{h1} >.

These two happen together, as the initial states of the detectors are correlated with no photons, and the final state | A_{h1} >, in which the upper detector has registered a horizontal photon.

When we actually detect the photon, say in a horizontal polarization state with statistical probability 1/2, two "collapses" or "jumps" occur. They are 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 animate these irreversible and reversible processes on our website.[6]

We see that our example agrees with Von Neumann **Process 1**. A measurement which finds the photon in a specific state n is thermodynamically irreversible, whereas the deterministic evolution described by Schrödinger's equation is reversible.

We thus establish a clear connection between a measurement, which increases the information by some number of bits (Shannon entropy), and the necessary compensating increase in the (Boltzmann) entropy of the macroscopic apparatus, and the cosmic creation process, where new particles form, reducing the entropy locally, and the energy of formation is radiated or conducted away as Boltzmann entropy.[7]

Note that the Boltzmann entropy can only be radiated away (ultimately into the night sky to the cosmic microwave background) because the expansion of the universe provides a sink for the entropy, as pointed out by DAVID LAYZER. Note also that this cosmic information-creating process requires no conscious observer. The universe is its own observer.

The Boundary between the Classical and Quantum Worlds

Some scientists, von Neumann and Heisenberg for example, have argued that in the absence of a conscious observer, or some "cut" between the microscopic and macroscopic world, the evolution of the quantum system and the macroscopic measuring apparatus would be described deterministically by Schrödinger's equation of motion for the wave function $| \psi + A >$ with the Hamiltonian H energy operator,

$$(ih/2\pi)\, \partial/\partial t \,| \psi + A > = H \,| \psi + A >.$$

Our quantum mechanical analysis of the measurement apparatus in the above case allows us to locate the "cut" precisely at those components of the "adequately classical and deterministic" apparatus that put the apparatus in an *irreversible* stable state providing *new information* to the observer.

6 informationphilosopher.com/problems/measurement/#birefringence
7 See appendix B for details

John Bell drew a diagram to show the various possible locations for what he called the "shifty split." Information physics shows us that the correct location for the boundary is the first of Bell's possibilities.

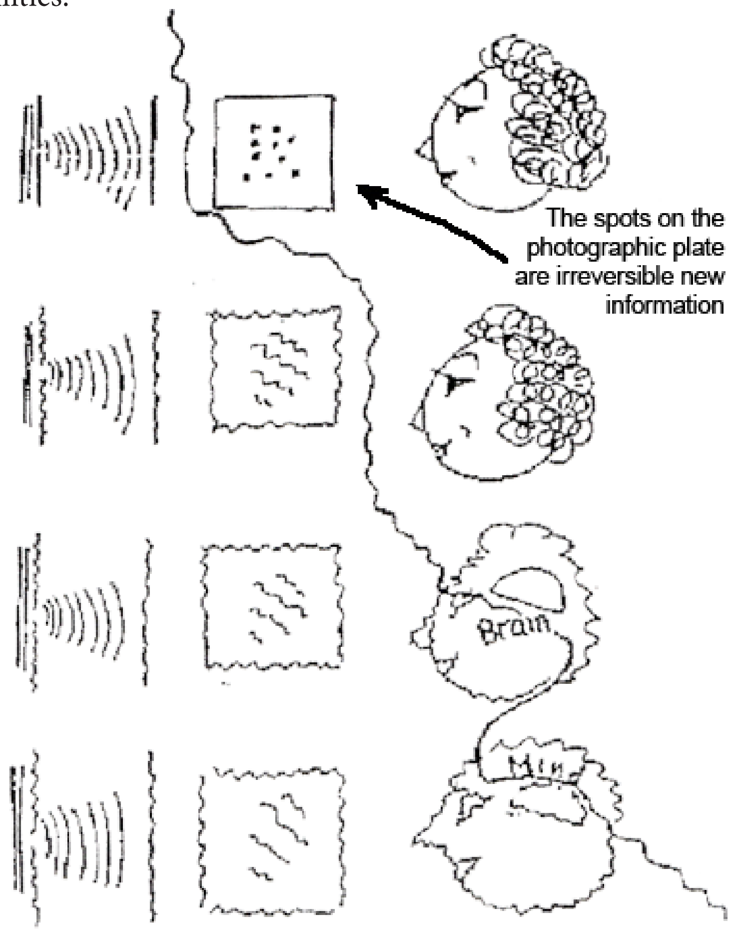

Figure 18-14. John Bell's illustration of the "shifty split."

The Role of the Conscious Observer

In 1941, Carl von Weizsäcker described the measurement problem as an interaction between a Subject and an Object, a view shared by the philosopher of science Ernst Cassirer.

Fritz London and Edmond Bauer made the strongest case for the critical role of a conscious observer in 1939:

> "So far we have only coupled one apparatus with one object. But a coupling, even with a measuring device, is not yet a measurement. A measurement is achieved only when the position of the pointer has been observed. It is precisely this increase of knowledge, acquired by observation, that gives the observer the right to choose among the different components of the mixture predicted by theory, to reject those which are not observed, and to attribute thenceforth to the object a new wave function, that of the pure case which he has found.
>
> "We note the essential role played by the consciousness of the observer in this transition from the mixture to the pure case. Without his effective intervention, one would never obtain a new function." [8]

In 1961, Eugene Wigner made quantum physics even more subjective, claiming that a quantum measurement requires a conscious observer, without which nothing ever happens in the universe.

> "When the province of physical theory was extended to encompass microscopic phenomena, through the creation of quantum mechanics, the concept of consciousness came to the fore again: it was not possible to formulate the laws of quantum mechanics in a fully consistent way without reference to the consciousness All that quantum mechanics purports to provide are probability connections between subsequent impressions (also called "apperceptions") of the consciousness, and even though the dividing line between the observer, whose consciousness is being affected, and the observed physical object can be shifted towards the one or the other to a considerable degree [cf., von Neumann] it cannot be eliminated." [9]

Other physicists were more circumspect. Niels Bohr contrasted Paul Dirac's view, which stressed the randomness of the outcome, with that of Heisenberg, who stresses the observer's "free choice" of what is to be measured:

> 'The question was whether, as to the occurrence of individual effects, we should adopt a terminology proposed by Dirac, that we were concerned with a choice on the part of "nature," or, as suggested by Heisenberg, we should say that we have to do with a choice on the part of the "observer" constructing the measuring instruments and reading their recording. Any such terminology would, however, appear dubious since, on the one

8 Theory of Observation in Quantum Mechanics, in Wheeler and Zurek, p.251
9 Remarks on the Mind-Body Question, in Wheeler and Zurek, p.169

> hand, it is hardly reasonable to endow nature with volition in the ordinary sense, while, on the other hand, it is certainly not possible for the observer to influence the events which may appear under the conditions he has arranged. To my mind, there is no other alternative than to admit that, in this field of experience, we are dealing with individual phenomena and that our possibilities of handling the measuring instruments allow us only to make a choice between the different complementary types of phenomena we want to study.' [10]

Landau and Lifshitz said clearly that quantum physics was independent of any observer:

> "In this connection the 'classical object' is usually called apparatus, and its interaction with the electron is spoken of as measurement. However, it must be most decidedly emphasised that we are here not discussing a process of measurement in which the physicist-observer takes part. By measurement, in quantum mechanics, we understand any process of interaction between classical and quantum objects, occurring apart from and independently of any observer." [11]

David Bohm agreed that what is observed is distinct from the observer:

> "If it were necessary to give all parts of the world a completely quantum-mechanical description, a person trying to apply quantum theory to the process of observation would be faced with an insoluble paradox. This would be so because he would then have to regard himself as something connected inseparably with the rest of the world. On the other hand,the very idea of making an observation implies that what is observed is totally distinct from the person observing it." [12]

And John Bell said:

> "It would seem that the [quantum] theory is exclusively concerned about 'results of measurement', and has nothing to say about anything else. What exactly qualifies some physical systems to play the role of 'measurer'? Was the wavefunction of the world waiting to jump for thousands of millions of years until a single-celled living creature appeared? Or did it have to wait a little longer, for some better qualified system... with a Ph.D.? If the theory is to apply to anything but highly idealised laboratory operations, are we not obliged to admit that more or less 'measurement-like' processes are going on more or less all the time, more or less everywhere? Do we not have jumping then all the time?" [13]

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10 *Atomic Physics and Human Knowledge*, Niels Bohr, p.51

11 *Quantum Mechanics,* Lev Landau and Evgeny Lifshitz, p.2

12 *Quantum Theory*, David Bohm, p.584

13 "Against Measurement," in *Speakable and Unspeakable in Quantum Mechanics*, p. 216)

Three Essential Steps in a "Measurement" and "Observation"

We can distinguish three required elements in a measurement that can clarify the ongoing debate about the role of a conscious observer.

1) In standard quantum theory, the first required element is the collapse of the wave-function. This is the Dirac *projection postulate* and von Neumann **Process 1**.

However, the collapse might not leave a determinate record. If nothing in the environment is macroscopically affected so as to leave an indelible record of the collapse, we can say that no information about the collapse is created. The overwhelming fraction of collapses are of this kind. Moreover, information might actually be destroyed. For example, collisions between atoms or molecules in a gas that erase past information about their paths.

2) If the collapse occurs when the quantum system is entangled with a macroscopic measurement apparatus, a well-designed apparatus will also "collapse" into a correlated "pointer" state.

As we showed above for photons, the detector in the upper half of a Stern-Gerlach apparatus will fire, indicating detection of an electron with spin up. As with photons, if the probability amplitude | *up* > in the upper half does not collapse as the electron is detected, it can still be recombined with the probability amplitude | *down* > in the lower half to reconstruct the unseparated beam.

When the apparatus detects a particle, the second required element is that it produce a determinate record of the event. But this is impossible without an irreversible thermodynamic process that involves: *a*) the creation of at least one bit of new information (negative entropy) and *b*) the transfer away from the measuring apparatus of an amount of positive entropy (generally much, much) greater than the information created.

Notice that no conscious observer need be involved. We can generalize this second step to an event in the physical world that was not designed as a measurement apparatus by a physical scientist, but nevertheless leaves an indelible record of the collapse of a quantum state. This might be a highly specific single event, or the macroscopic consequence of billions of atomic-molecular level of events.

3) Finally, the third required element is an indelible determinate record that can be looked at by an observer (presumably conscious, although the consciousness itself has nothing to do with the measurement).

When we have all three of these essential elements, we have what we normally mean by a measurement and an observation, both involving a human being.

When we have only the first two, we can say metaphorically that the "universe is measuring itself," creating an information record of quantum collapse events. For example, every hydrogen atom formed in the early recombination era is a record of the time period when macroscopic bodies could begin to form. A certain pattern of photons records the explosion of a supernova billions of light years away. When recorded by the CCD in a telescope, it becomes a potential observation at a later time when an astronomer looks at the data.

Craters on the back side of the moon have for billions of years recorded collisions with solar system debris. But that could become observations only when the first NASA Apollo mission circled the moon.

Quantum Collapses Can Produce New Information

But they are *not measurements*, or even observations, until the existence of a semi-permanent record has been made first.

And that permanence requires positive entropy to be carried away from the event, whether in a physics lab, on the back of the moon, in a distant supernova, or a photon emitted by an atom in the cosmic microwave background.

If the positive entropy is not carried away, there is no permanent (or semi-permanent) record to be observed.

In that case, the new information is simply destroyed. The vast fraction of all quantum collapses do not produce lasting new information. Just as the vast fraction of negative entropy streams available do not create any new information structures.[14]

14 See Appendix B for more details,