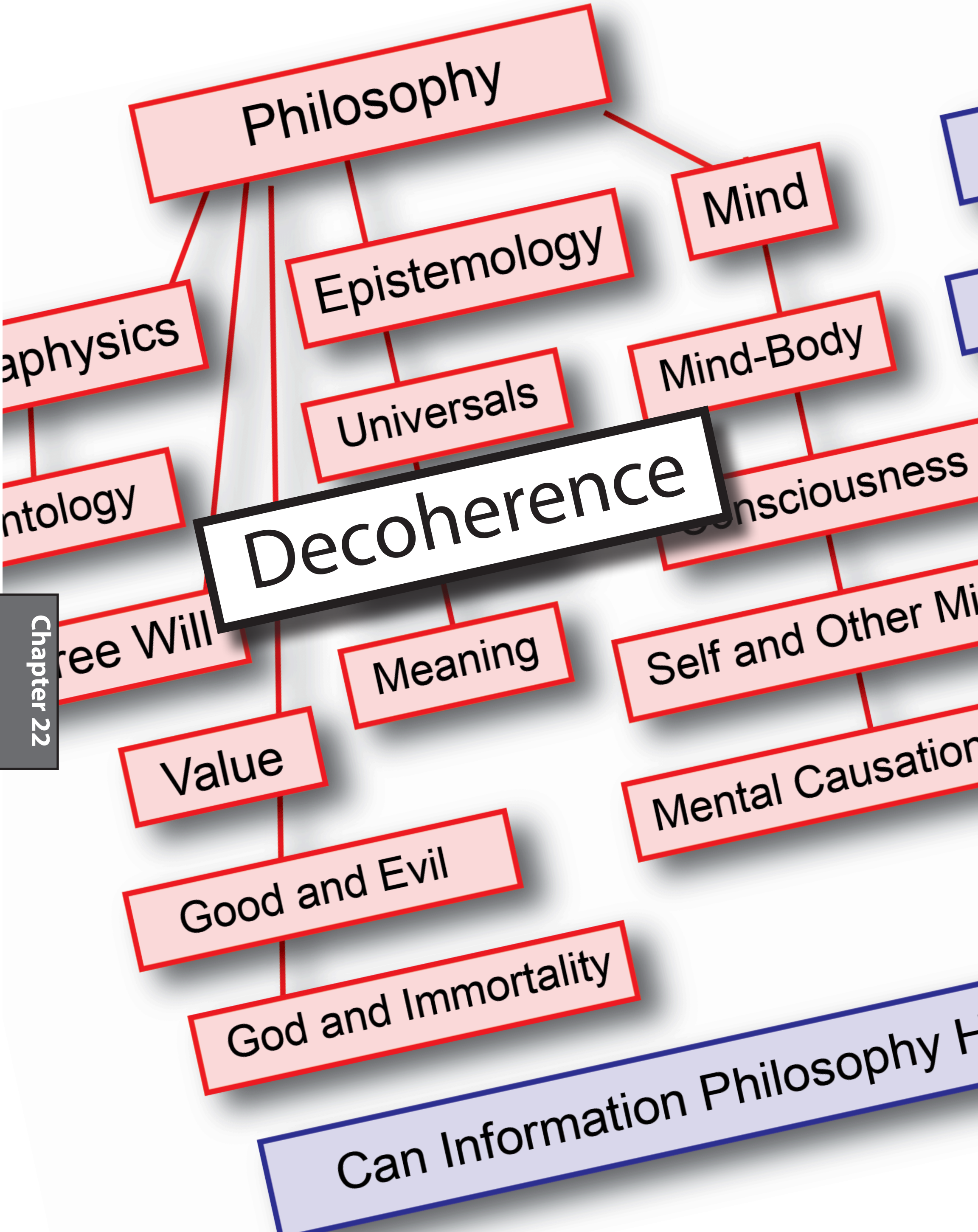

This chapter on the web
informationphilosopher.com/problems/decoherence

Decoherence

Decoherence is the study of interactions between a quantum system (generally a very small number of microscopic particles like electrons, photons, atoms, molecules, etc. - often just a single particle) and the larger macroscopic environment, which is normally treated "classically," that is, by ignoring quantum effects, but which decoherence theorists study quantum mechanically. Decoherence theorists attribute the absence of macroscopic quantum effects like interference (which is a coherent process) to interactions between a quantum system and the larger macroscopic environment.

They maintain that no system can be completely isolated from the environment. Decoherence, they say, accounts for the disappearance of macroscopic quantum effects, and is experimentally correlated with the loss of isolation.

Niels Bohr maintained that a macroscopic apparatus used to "measure" quantum systems must be treated classically. John von Neumann, on the other hand, assumed that everything is made of quantum particles, even the mind of the observer. This led him and Werner Heisenberg to say that a "cut" must be located somewhere between the quantum system and the mind, which would operate in a sort of "psycho-physical parallelism."[1]

A main characteristic of quantum systems is the appearance of wavelike interference effects. These only show up in large numbers of repeated identical experiments that make measurements on single particles at a time. Interference is never directly "observed" in a single experiment. When interference is present in a system, the system is called "coherent." Decoherence then is the loss or suppression of that interference.

Interference experiments require that the system of interest is extremely well isolated from the environment, except for the "measurement apparatus." This apparatus must be capable of recording the information about what has been measured. It can

1 Not to be confused with *panpsychism*.

be a photographic plate or an electron counter, anything capable of registering a quantum level event, usually by releasing a cascade of metastable processes that amplify the quantum-level event to the macroscopic "classical" world, where an "observer" can see the result.

This does not mean that specific quantum level events are determined by that observer (as noted by several of the great quantum physicists - Max Born, Pascual Jordan, Erwin Schrödinger, Paul Dirac, and textbook authors Landau and Lifshitz, Albert Messiah, and Kurt Gottfried, among others). Quantum processes are happening all the time. Most quantum events are never observed, let alone measured, though they can be inferred from macroscopic phenomenological observations.

To be sure, those quantum events that are "measured" in a physics experiment which is set up to measure a certain quantity are dependent on the experimenter and the design of the experiment. To measure the electron spin in a Stern-Gerlach experiment, for example, the experimenter is "free to choose" to measure the z-component of the spin, rather than the x- or y-component. This will influence quantum level events in the following ways:

The experimental outcome will produce a definite value for the z-component of the spin (either $+1/2$ or $-1/2$)

The x-component of the spin after the measurement will be in a linear combination/superposition of $+1/2$ or $-1/2$ states

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

It is in this sense that Bohr and Heisenberg described properties of the quantum world as not existing until we make a measurement. We have a "free choice" which experiment we perform, what we measure. If we measure position for example, the precise position value did not exist immediately before the measurement.

On the other hand, we can not create the particular value for the position. This is a "*random choice made by nature*," as Dirac put it.

The Decoherence Program

The "decoherence program" of H. Dieter Zeh, Erich Joos, Wojciech Zurek, John Wheeler, Max Tegmark, and others has multiple aims -

• to show how classical physics emerges from quantum physics. They call this the "quantum to classical transition."

• to explain the failure to see any macroscopic superpositions of quantum states (e.g., Schrödinger's Cat as a superposition of live and dead cats).

• in particular, to identify the mechanism that suppresses ("decoheres") interference between states as something involving the "environment" beyond the system and measuring apparatus.

• to explain the *appearance* of particles following paths (they actually say there are no "particles," and maybe no paths).

• to explain the *appearance* of discontinuous transitions between quantum states (they say there are no "quantum jumps" either)

• to champion an Everett-style "universal wave function" (as a superposition of states) that evolves in a "unitary" fashion (i.e., deterministically) according to the Schrödinger equation.

• to clarify and perhaps solve the measurement problem, which they define as the lack of macroscopic superpositions.

• to explain the "arrow of time."

• to revise the foundations of quantum mechanics by changing some of its assumptions, notably challenging the "collapse" of the wave function.

Decoherence theorists say that they add no new elements to quantum mechanics (such as "hidden variables") but they do deny one of the three basic assumptions - namely Dirac's *projection postulate*. This is the method used to calculate the probabilities of various outcomes, which probabilities are confirmed to several significant figures by the statistics of large numbers of identically prepared experiments.

Decoherence theorists accept (even overemphasize) Dirac's *principle of superposition*. Some decoherence theorists also accept the *axiom of measurement*, although some of them question the link between eigenstates and eigenvalues.

The decoherence program hopes to offer insights into several other important phenomena:

• What Zurek calls the "einselection" (environment-induced superselection) of preferred states (the so-called "pointer states") in a measurement apparatus.

• The role of the observer in quantum measurements.

• Nonlocality and quantum entanglement (which is used to "derive" decoherence).

• The origin of irreversibility (by "continuous monitoring").

• The approach to thermal equilibrium.

The decoherence program finds unacceptable the following aspects of the standard quantum theory:

• Quantum "jumps" between energy eigenstates.

• The "apparent" collapse of the wave function.

• In particular, explanation of the collapse as a "mere" increase of information.

• The "appearance" of "particles."

• The "inconsistent" Copenhagen Interpretation - quantum "system," classical "apparatus."

• The "insufficient" Ehrenfest Theorems.

Decoherence theorists admit that some problems remain to be addressed, especially the "problem of outcomes." Without the collapse postulate, it is not clear how definite outcomes are to be explained.

As Tegmark and Wheeler put it:

> The main motivation for introducing the notion of wave-function collapse had been to explain why experiments produced specific outcomes and not strange superpositions of outcomes...it is embarrassing that

> nobody has provided a testable deterministic equation specifying precisely when the mysterious collapse is supposed to occur.[2]

Some of the controversial positions in decoherence theory, including the denial of collapses and particles, come straight from the work of Schrödinger, for example his 1952 essays "Are There Quantum Jumps?" (Part I and Part II), where he denies the existence of "particles," claiming that everything can be understood as his waves alone.

Other important sources for decoherence theorists include: Hugh Everett III and his "relative state" or "many world" interpretation of quantum mechanics; Eugene Wigner's article on the problem of measurement; and John Bell's reprise of Schrödinger's arguments against quantum jumps.

Decoherence advocates therefore look to other attempts to formulate quantum mechanics. Also called "interpretations," these are more often reformulations, with different basic assumptions about the foundations of quantum mechanics. Most assume the "universal" applicability of the unitary time evolution that results from the Schrödinger wave equation. They include these formulations::

- DeBroglie-Bohm "pilot-wave" or "hidden variables".
- Everett-DeWitt "relative-state" or "many worlds".
- Ghirardi-Rimini-Weber "spontaneous collapse".

Note that these "interpretations" are often in serious conflict with one another. Where Schrödinger thinks that waves alone can explain everything (there are no particles in his theory), David Bohm thinks that particles not only exist but that every particle has a definite position that is a "hidden parameter" of his theory. H. Dieter Zeh, the founder of decoherence, sees

> one of two possibilities: a modification of the Schrödinger equation that explicitly describes a collapse (also called "spontaneous localization") or an Everett type interpretation, in which all measurement outcomes are assumed to exist in one formal superposition, but to be perceived separately as a consequence of their dynamical autonomy resulting from decoherence. It was John Bell who called Everett's many-worlds picture "extravagant," While this latter suggestion has been called "extravagant"

2 *Scientific American*, February 2001, p.75.

> (as it requires myriads of co-existing quasi-classical "worlds"), it is similar in principle to the conventional (though nontrivial) assumption, made tacitly in all classical descriptions of observation, that consciousness is localized in certain semi-stable and sufficiently complex subsystems (such as human brains or parts thereof) of a much larger external world. Occam's razor, often applied to the "other worlds", is a dangerous instrument: philosophers of the past used it to deny the existence of the interior of stars or of the back side of the moon, for example. So it appears worth mentioning at this point that environmental decoherence, derived by tracing out unobserved variables from a universal wave function, readily describes precisely the apparently observed "quantum jumps" or "collapse events."[3]

The information interpretation of quantum mechanics[4] also has explanations for the measurement problem, the arrow of time, and the emergence of adequately, i.e., statistically determined classical objects. However, I-Phi does it while accepting the standard assumptions of orthodox quantum physics.

We briefly review the standard theory of quantum mechanics and compare it to the "decoherence program," with a focus on the details of the measurement process. We divide measurement into several distinct steps, in order to clarify the supposed "measurement problem" (mostly the lack of macroscopic state superpositions) and perhaps "solve" it.

The most famous example of probability-amplitude-wave interference is the two-slit experiment. Interference is between the probability amplitudes whose absolute value squared gives us the probability of finding the particle at various locations behind the screen with the two slits in it.

Finding the particle at a specific location is said to be a "measurement."[5]

In standard quantum theory, a measurement is made when the quantum system is "projected" or "collapsed" or "reduced" into a single one of the system's allowed states. If the system was "prepared" in one of these "eigenstates," then the measurement will find it in that state with probability one (that is, with certainty).

3 *Decoherence and the Appearance of a Classical World in Quantum Theory*, p.22
4 See chapter 17.
5 See chapter 18.

However, if the system is prepared in an arbitrary state ψ_a, it can be represented as being in a linear combination of the system's basic energy states φ_n.

$\psi_a = \Sigma\, c_n \mid n >.$

where

$c_n = < \psi_a \mid \varphi_n >.$

It is said to be in "superposition" of those basic states. The probability P_n of its being found in state φ_n is

$P_n = < \psi_a \mid \varphi_n >^2 = c_n^{\ 2}\,.$

Between measurements, the time evolution of a quantum system in such a superposition of states is described by a unitary transformation $U(t_0, t_1)$ that preserves the same superposition of states as long as the system does not interact with another system, such as a measuring apparatus. As long as the quantum system is completely isolated from any external influences, it evolves continuously and deterministically in an exactly predictable (causal) manner.

Whenever the quantum system does interact however, with another particle or an external field, its behavior ceases to be causal and it evolves discontinuously and indeterministically. This acausal behavior is uniquely quantum mechanical. Nothing like it is possible in classical mechanics. Most attempts to "reinterpret" or "reformulate" quantum mechanics are attempts to eliminate this discontinuous acausal behavior and replace it with a deterministic process.

We must clarify what we mean by "the quantum system" and "it evolves" in the previous two paragraphs. This brings us to the mysterious notion of "wave-particle duality." In the wave picture, the "quantum system" refers to the deterministic time evolution of the complex probability amplitude or quantum state vector ψ_a, according to the "equation of motion" for the probability amplitude wave ψ_a, which is the Schrödinger equation,

$ih/2\pi\ \delta\psi_a/\delta t = H\,\psi_a.$

The probability amplitude looks like a wave and the Schrödinger equation is a wave equation. But the wave is an abstract quantity whose absolute square is the probability of finding a quantum particle somewhere. It is distinctly not the particle, whose exact position is unknowable while the quantum system is evolving deterministically. It is the probability amplitude wave that interferes with itself. Particles, as such, never interfere (although they may collide).

Note that we never "see" the superposition of particles in distinct states. There is no microscopic superposition in the sense of the macroscopic superposition of live and dead cats.[6]

When the particle interacts, with the measurement apparatus for example, we always find a whole particle. It suddenly appears. For example, an electron "jumps" from one orbit to another, absorbing or emitting a discrete amount of energy (a photon). When a photon or electron is fired at the two slits, its appearance at the photographic plate is sudden and discontinuous. The probability wave instantaneously becomes concentrated at the location of the particle.

There is now unit probability (certainty) that the particle is located where we find it to be. This is described as the "collapse" of the wave function.[7] Where the probability amplitude might have evolved under the unitary transformation of the Schrödinger equation to have significant non-zero values in a very large volume of phase space, all that probability suddenly "collapses" (faster than the speed of light, which deeply bothered Albert Einstein in 1905) to the location of the particle.

Einstein said that some mysterious "spooky action-at-a-distance" must act to prevent the appearance of a second particle at a distant point where a finite probability of appearing had existed just an instant earlier.

Whereas the abstract probability amplitude moves continuously and deterministically throughout space, the concrete particle moves discontinuously and indeterministically to a particular point in space.

For this collapse to be a "measurement," the new information about which location (or state) the system has collapsed into must be recorded somewhere in order for it to be "observable" by a scientist. But the vast majority of quantum events - e.g., particle collisions that change the particular states of quantum particles before

6 See chapter 23.
7 See chapter 20.

and after the collision - do not leave an indelible record of their new states anywhere (except implicitly in the particles themselves).

We can imagine that a quantum system initially in state ψ_a has interacted with another system and as a result is in a new state φ, without any macroscopic apparatus around to record this new state for a "conscious observer."

H. D. Zeh describes how quantum systems may be "measured" without the recording of information.

> It is therefore a plausible experimental result that the interference disappears also when the passage [of an electron through a slit] is "measured" without registration of a definite result. The latter may be assumed to have become a "classical fact" as soon as the measurement has irreversibly "occurred". A quantum phenomenon may thus "become a phenomenon" without being observed. This is in contrast to Heisenberg's remark about a trajectory coming into being by its observation, or a wave function describing "human knowledge". Bohr later spoke of objective irreversible events occurring in the counter. However, what precisely is an irreversible quantum event? According to Bohr this event can not be dynamically analyzed.
>
> Analysis within the quantum mechanical formalism demonstrates nonetheless that the essential condition for this "decoherence" is that complete information about the passage is carried away in some objective physical form. This means that the state of the environment is now quantum correlated (entangled) with the relevant property of the system (such as a passage through a specific slit). This need not happen in a controllable way (as in a measurement): the "information" may as well form uncontrollable "noise", or anything else that is part of reality. In contrast to statistical correlations, quantum correlations characterize real (though nonlocal) quantum states - not any lack of information. In particular, they may describe individual physical properties, such as the non-additive total angular momentum J^2 of a composite system at any distance.[8]

The Measurement Process

In order to clarify the measurement process, we separate it into several distinct stages, as follows:

A particle collides with another microscopic particle or with a macroscopic object (which might be a measuring apparatus).

8 *Decoherence and the Appearance...*, pp.13-14

In this scattering problem, we ignore the internal details of the collision and say that the incoming initial state ψ_a has changed asymptotically (discontinuously, and randomly, viz., wave-function collapse) into the new outgoing final state φ_n.

Note that if we prepare a very large number of identical initial states ψ_a , the fraction of those ending up in the final state φ_n is just the probability

$|< \psi_a \mid \varphi_n >|^2$.

The information that the system was in state ψa has been lost (its path information has been erased; it is now "noise," as Zeh describes it). New information exists (implicitly in the particle, if not stored anywhere else) that the particle is in state φ_n.

If the collision is with a large enough (macroscopic) apparatus, it might be capable of recording the new system state information, by changing the quantum state of the apparatus into a "pointer state" correlated with the new system state.

"Pointers" could include the precipitated silver-bromide molecules of a photographic emulsion, the condensed vapor of a Wilson cloud chamber, or the cascaded discharge of a particle detector.

But this new information will not be indelibly recorded unless the recording apparatus can transfer entropy away from the apparatus greater than the negative entropy equivalent of the new information (to satisfy the second law of thermodynamics). This is the second requirement in every two-step creation of new information in the universe.

The new information could be meaningful to an information processing agent who could not only observe it but understand it. Now neurons would fire in the mind of the conscious observer that von Neumann and Wigner thought was necessary for the measurement process to occur at all.

Von Neumann (perhaps influenced by the mystical thoughts of Niels Bohr about mind and body as examples of his "complementarity") saw three levels in a measurement;

• the system to be observed, including light up to the retina of the observer.

• the observer's retina, nerve tracts, and brain

• the observer's abstract "ego."

John Bell asked tongue-in-cheek whether no wave function could collapse until a scientist with a Ph.D. was there to observe it. He drew a famous diagram of what he called von Neumann's "shifty split."

Bell shows that one could place the arbitrary "cut" (Heisenberg called it the "Schnitt") at various levels without making any difference.

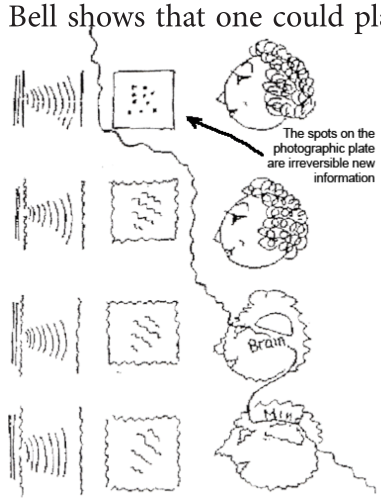

Figure 22-25. Bell's "shifty split."

But an "objective" observer-independent measurement ends when irreversible new information has been indelibly recorded (in the photographic plate of Bell's drawing).

Von Neumann's physical and mental levels are perhaps better discussed as the mind-body problem.[9] It is not really the measurement problem in quantum physics.[10]

The Measurement Problem

So what exactly is the "measurement problem?"

For decoherence theorists, the unitary transformation of the Schrödinger equation cannot alter a superposition of microscopic states. Why then, when microscopic states are time evolved into macroscopic ones, don't macroscopic superpositions emerge? According to H. D. Zeh:

> Because of the dynamical superposition principle, an initial superposition $\Sigma\, c_n \mid n >$ does not lead to definite pointer positions (with their empirically observed frequencies). If decoherence is neglected, one

9 See chapter 13.
10 See chapter 18.

> obtains their entangled superposition $\Sigma c_n \mid n > \mid \Phi_n >$, that is, a state that is different from all potential measurement outcomes.[11]

And according to Erich Joos, another founder of decoherence:

> It remains unexplained why macro-objects come only in narrow wave packets, even though the superposition principle allows far more "non-classical" states (while micro-objects are usually found in energy eigenstates). Measurement-like processes would necessarily produce nonclassical macroscopic states as a consequence of the unitary Schrödinger dynamics. An example is the infamous Schrödinger cat, steered into a superposition of "alive" and "dead".[12]

The fact that we don't see superpositions of macroscopic objects is the "measurement problem," according to Zeh and Joos.

An additional problem is that decoherence is a completely unitary process (Schrödinger dynamics) which implies time reversibility. What then do decoherence theorists see as the origin of irreversibility? Can we time reverse the decoherence process and see the quantum-to-classical transition reverse itself and recover the original coherent quantum world?

To "relocalize" the superposition of the original system, we need only have complete control over the environmental interaction. This is of course not practical, just as LUDWIG BOLTZMANN found in the case of JOSEF LOSCHMIDT's reversibility objection.[13]

Does irreversibility in decoherence have the same rationale - "not possible for all practical purposes" - as in classical statistical mechanics?

According to more conventional thinkers, the measurement problem is the failure of the standard quantum mechanical formalism (Schrödinger equation) to completely describe the nonunitary "collapse" process. Since the collapse is irreducibly indeterministic, the time of the collapse is completely unpredictable and unknowable. Indeterministic quantum jumps are one of the defining characteristics of quantum mechanics, both the "old" quantum theory, where Bohr wanted radiation to be emitted and absorbed discontinuously when his atom jumped between stationary states, and the

11 *Decoherence and the Appearance*... p.20
12 *Decoherence and the Appearance*...p.2. And see chapter 23.
13 See chapter 25.

modern standard theory with the Born-Jordan-Heisenberg-Dirac "*projection postulate*."

To add new terms to the Schrödinger equation in order to control the time of collapse is to misunderstand the irreducible chance at the heart of quantum mechanics, as first seen clearly, in 1917, by Albert Einstein. When he derived his *A* and *B* coefficients for the emission and absorption of radiation, he found that an outgoing light particle must impart momentum *hν/c* to the atom or molecule, but the direction of the momentum can not be predicted! Neither can the theory predict the time when the light quantum will be emitted.

Such a random time was not unknown to physics. When Ernest Rutherford derived the law for radioactive decay of unstable atomic nuclei in 1900, he could only give the probability of decay time. Einstein saw the connection with radiation emission:

> It speaks in favor of the theory that the statistical law assumed for [spontaneous] emission is nothing but the Rutherford law of radioactive decay.[14]

But the inability to predict both the time and direction of light particle emissions, said Einstein in 1917, is "a weakness in the theory..., that it leaves time and direction of elementary processes to chance (Zufall, ibid.)." It is only a weakness for Einstein, of course, *because* his God does not play dice. Decoherence theorists too appear to have what William James called an "antipathy to chance."

We have several possible alternatives for eigenvalues. Measurement simply makes one of these actual, and it does so, said Max Born, in proportion to the absolute square of the probability amplitude wave function ψ_n. In this way, ontological chance enters physics, and it is partly this fact of quantum randomness that bothered Einstein (whose relativity theories are deterministic) and Schrödinger (whose equation of motion is deterministic).

What Decoherence Gets Right

Allowing the environment to interact with a quantum system, for example by the scattering of low-energy thermal photons or high-energy cosmic rays, or by collisions with air molecules, surely will suppress quantum interference in an otherwise isolated experiment.

14 Abraham Pais," "*Subtle is the Lord...*", p.411

But this is because large numbers of uncorrelated (incoherent) quantum events will "average out" and mask the quantum phenomena. It does not mean that wave functions are not collapsing. They are, at every particle interaction.

Decoherence advocates describe the environmental interaction as "monitoring" of the system by continuous "measurements."

Decoherence theorists are correct that every collision between particles entangles their wave functions, at least for the short time before decoherence suppresses any coherent interference effects of that entanglement.

But in what sense is a collision a "measurement." At best, it is a "pre-measurement."

It changes the path information that was present in the wave functions before the collision. But the new information may not be have been recorded anywhere (other than being implicit in the new state of the system).

All interactions change the state of a system of interest, but not all leave the "pointer state" of some measuring apparatus with new information about the state of the system.

So environmental monitoring, in the form of continuous collisions by other particles, is changing the specific information content of both the system, the environment, and a measuring apparatus (if there is one). But if there is no recording of new information (negative entropy created locally), the system and the environment may be in thermodynamic equilibrium.

Equilibrium does not mean that decoherence monitoring of every particle is not continuing.

It is. There is no such thing as a "closed system." Environmental interaction is always present.

If a gas of particles is not already in equilibrium, they may be approaching thermal equilibrium. This happens when any non-equilibrium initial conditions (Zeh calls these a "conspiracy") are being "forgotten" by erasure of path information during collisions. Information about initial conditions is implicit in the paths of all the particles. This means that, in principle, the paths could be reversed to return to the initial, lower entropy, conditions (the Loschmidt paradox).[15]

Erasure of path information could be caused by quantum particle-particle scattering (our standard view) or by decoherence "monitoring." How are these two related?

What Decoherence Gets Wrong

Decoherence makes no testable predictions that differ from standard quantum mechanics nor does it make calculations any easier. In short, decoherence is just a *way of talking* about quantum mechanics and especially the several interpretations that deny the collapse of the wave function.[16]

Quantum Interactions Do Not Create Lasting Information

The overwhelming number of collisions of microscopic particles like electrons, photons, atoms, molecules, etc, do not result in observable information about the collisions. The lack of observations and observers does not mean that there have been no "collapses" of wave functions. The idea that the time evolution of the deterministic Schrödinger equation continues forever in a unitary transformation that leaves the wave function of the whole universe undecided and in principle reversible at any time, is an absurd and unjustified extrapolation from the behavior of the ideal case of a single perfectly isolated particle.

The principle of microscopic reversibility applies only to such an isolated particle, something unrealizable in nature, as the decoherence advocates know with their addition of environmental "monitoring." Experimental physicists can isolate systems from the environment enough to "see" the quantum interference (but again, only in the statistical results of large numbers of identical experiments).

The Transition from Quantum to Classical World

In the standard quantum view, the emergence of macroscopic objects with classical behavior arises statistically for two reasons involving large numbers:

15 See chapter 25.
16 See chapter 20.

The law of large numbers (from probability and statistics)

When a large number of material particles is aggregated, properties emerge that are not seen in individual microscopic particles. These properties include, solidity, classical laws of motion, gravitational orbits, etc.

When a large number of quanta of energy (photons) are aggregated, properties emerge that are not seen in individual light quanta. These properties include continuous radiation fields with wavelike interference.

The law of large quantum numbers. This is Bohr's Correspondence Principle, which he used to show quantum mechanics approaches classical mechanics in the limit of large quantum numbers.

Decoherence and Standard Quantum Mechanics

Can we explain the following in terms of standard quantum mechanics?

• the decoherence of quantum interference effects by the environment

• their measurement problem, viz., the absence of macroscopic superpositions of states

• the emergence of "classical" adequately determined macroscopic objects

• the logical compatibility and consistency of two dynamical laws - the unitary transformation and the discontinuous "collapse" of the wave function

• the entanglement of "distant" particles and the appearance of "nonlocal" effects such as those in the Einstein-Podolsky-Rosen experiment

Let's consider these point by point.

The standard explanation for the decoherence of quantum interference effects by the environment is that when a quantum system interacts with the very large number of quantum systems in a macroscopic object, the averaging over independent phases cancels out (decoheres) coherent interference effects.[17]

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

In order to study interference effects, a quantum system is isolated from the environment as much as possible. Even then, note that microscopic interference is never "seen" directly by an observer. It is *inferred* from probabilistic theories that explain the statistical results of many identical experiments. Individual particles are never "seen" as superpositions of particles in different states. When a particle is seen, it is always the whole particle and nothing but the particle. The absence of macroscopic superpositions of states, such as the infamous linear superposition of live and dead Schrödinger Cats, is therefore no surprise.[18]

The standard quantum-mechanical explanation for the emergence of "classical" adequately determined macroscopic objects is that they result from a combination of a) Bohr's correspondence principle in the case of large quantum numbers. together with b) the familiar law of large numbers in probability theory, and c) the averaging over the phases. Heisenberg indeterminacy relations still apply, but the individual particles' indeterminacies average out, and the remaining macroscopic indeterminacy is practically unmeasurable.

Perhaps the two dynamical laws would be inconsistent if applied to the same thing at exactly the same time. But the "collapse" of the wave function (von Neumann's **Process 1**, Pauli's measurement of the first kind) and the unitary transformation that describes the deterministic evolution of the probability amplitude wave function (von Neumann's **Process 2**) are used in a temporal sequence.

When you hear or read that electrons are *both* waves and particles, think "either-or" - first a wave of *possibilities*, then an *actual* particle. One process describes their continuous deterministic evolution (while isolated) along their mean free paths to the next collision or interaction. The other then describes what happens when quantum systems interact, in a collision or a measurement, when they make a discontinuous jump into a new state. One dynamical law applies to the wave picture, the other to the particle picture.

The paradoxical appearance of nonlocal "influences" of one particle on an entangled distant particle, at velocities greater than light

18 See chapter 23.

speed, are a consequence of a poor understanding of both the wave and particle aspects of quantum systems. The confusion usually begins with a statement such as "consider a particle *A* here and a distant particle *B* there."[19] When entangled in a two-particle probability amplitude wave function, the two identical particles are "neither here nor there," just as the single particle in a two-slit experiment does not "go through" one of the slits.

It is the single-particle probability amplitude wave that must "go through" both slits if it is to interfere. For a two-particle probability amplitude wave that starts its deterministic time evolution when the two identical particles are produced, it is only the probability of finding the particles that evolves according to the unitary transformation of the Schrödinger wave equation. It says nothing about where the particles "are."

Now if and when a particle is measured somewhere, we can then label it particle *A*. Conservation of energy and momentum tell us immediately that the other identical particle is now symmetrically located on the other side of the central source of particles. If the particles are electrons (as in David Bohm's version of EPR), conservation of spin tells us that the now distant particle B must have its spin opposite to that of particle A, since they were produced with a total spin of zero.

Nothing is sent from particle *A* to *B*. The deduced properties are the consequence of conservation laws that are true for much deeper reasons than the puzzles of nonlocal entanglement. The mysterious instantaneous values for their properties is exactly the same mystery that bothered Einstein in 1905 about a single-particle wave function having values all over a photographic screen at one instant, then having values only at the position of the located particle in the next instant, apparently violating his then very new theory of special relativity.

To summarize: Decoherence by interactions with environment can be explained perfectly by multiple "collapses" of the probability amplitude wave function during interactions with environment particles. Microscopic interference is never "seen" directly by an

19 See chapter 21 for details.

observer. Interference is deduced from the statistical results of large numbers of experiments, each one of which has no superpositions.

We therefore never "see" macroscopic superpositions of live and dead cats. The "transition from quantum to classical" systems is the consequence of laws of large numbers. But there is only one world, the quantum world. The "classical world" is how the quantum world looks when there are a large number of particles, or even a single atomic system when it is in a state with large quantum numbers, according to Bohr's *correspondence principle*.

The quantum dynamical laws necessarily include two phases or processes, as John von Neumann showed, one needed to describe the continuous deterministic motions of probability amplitude waves and the other the discontinuous indeterministic motions of physical particles.

The attempt by decoherence theorists to ignore the discontinuous collapse of the wave function in a measurement is a failure, like all other attempts since Hugh Everett, though it is a very popular one.