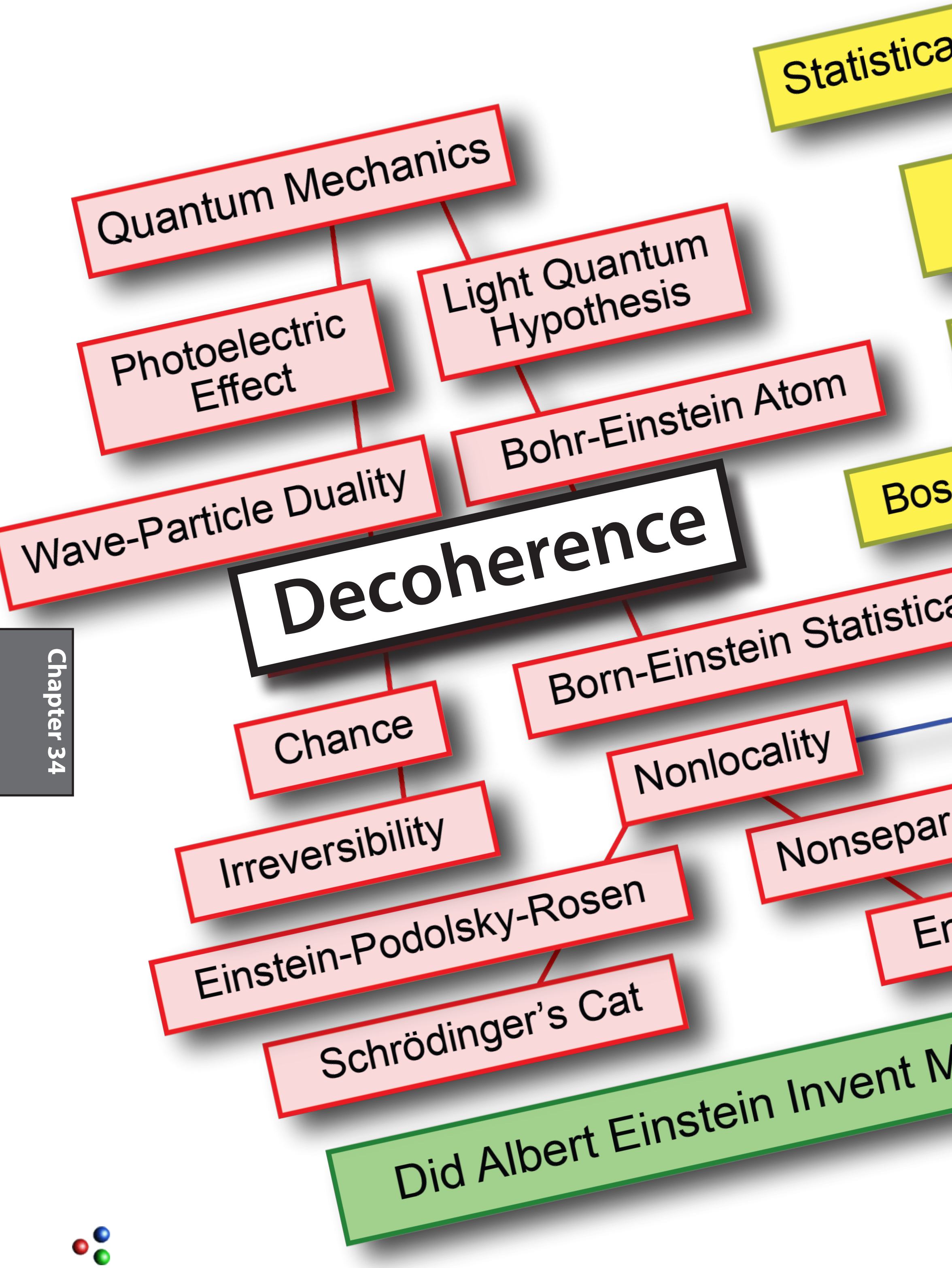
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Decoherence

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. The decoherence (which accounts for the disappearance) of macroscopic quantum effects is shown experimentally to be 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." John Bell drew a diagram with locations for what he called the "shifty split" between the experiment and the mind of the observer.[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

1 see chapter 32.

recording the information about what has been measured. It can be a photographic plate or an electron counter, anything capable of registering a quantum event, usually by releasing a cascade of metastable processes that amplify the quantum-level event to the macroscopic 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, 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, the experimenter is "free to choose" to measure, for example, 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). We do not create the particular value for the z-component of spin. This is a random choice made by Nature, as Dirac put it.

The x-component after the measurement will be indeterminate, described as in a 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 describe properties of the quantum world as not existing until we make a measurement. We are "free to choose" the experiment to perform. If we measure position for example, the precise position value may not exist in some sense immediately before the measurement, according to the Copenhagen Interpretation. ALBERT EINSTEIN challenged this idea. His "objective reality" imagined a world in which particles and their continuous paths really exist.

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 lack of 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 say there are no "particles," and maybe no paths).
- to explain the *appearance* of discontinuous transitions between quantum states (Decoherentists say there are no "quantum jumps" either).
- to champion a "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 or "projection postulate."

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.

Decoherentists accept (even overemphasize) Dirac's principle of superposition. Some also accept the axiom of measurement, although some 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, i.e., 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 explained. In a universe with a single wave function, nothing ever happens.

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]

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

Some of the controversial positions in decoherence theory, including the denial of collapses and particles, come straight from the work of Erwin Schrödinger, for example in 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 waves. John Bell wrote an article with the same title.

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

Decoherence theorists 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 begin from 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 carrying 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. While this latter suggestion has been called "extravagant" [by John Bell] (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]

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" (for decoherentists it is 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."

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).

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

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

where

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

3 Joos et al. 2013, p.22

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

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

As Dirac forcefully told us,[4] this does not mean an individual system is in more than one of those states. That is just a "manner of speaking." It means that measurements of many similar systems will be found distributed among the states with the probabilities P_n.

Between measurements, the time evolution of a quantum system in such a superposition of states is described by a unitary transformation $U(t, t_0)$ 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 isolated from any external influences, it evolves continuously and deterministically in an exactly predictable (causal) manner.

This we take to be a central fact of Einstein's "objective reality." A system prepared in a state with certain properties (such as spin) conserves all those properties as it evolves without decohering.

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. It is the *origin of irreversibility*. Nothing like it is possible in classical mechanics. 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,

$i\hbar\, \delta\psi_a/\delta t = H\, \psi^a$.

The probability amplitude looks like a wave and the Schrödinger equation is a wave equation. But the wave is an abstract complex

4 See chapter 19.

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, going through both slits, for example. Particles, as such, never interfere (although they may collide).

Note that we never "see" a superposition of particles (or fragments of a particle) in distinct states. Particles are *not in two places at the same time* just because there is a probability of finding it in those two places! And note that a particle may be following a property-conserving path, although we cannot know that path.

When the particle interacts, with the measurement apparatus for example, we always find the 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 new location.

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. 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 Einstein as nonlocal behavior) to the newly found location of the particle.

Einstein worried 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. (See chapter 23.)

But the distributed probability at all other places is not something physical and substantial that must "move" to the newly found location. It is just abstract information.

Decoherence and 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 $\Sigma c_n | n >$ does not lead to definite pointer positions (with their empirically observed frequencies). If decoherence is neglected, one obtains their entangled superposition $\Sigma c_n | n > | \Phi_n >$, that is, a state that is different from all potential measurement outcomes.[5]

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 "nonclassical" 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".[6]

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.

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.

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5 *Decoherence and the Appearance of a Classical World in Quantum Theory*, p.20
6 *ibid.*, p.2.

Indeterministic quantum jumps are one of the defining characteristics of quantum mechanics, both the "old" quantum theory, where Bohr wanted continuous radiation to be emitted and absorbed discontinuously when his atom jumped between staionary states, and the 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 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! Nor can the theory predict the *time* when a 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.[7]

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."

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. But this is because large numbers of uncorrelated (incoherent) quantum events will "average out" and mask the

7 Pais, 2005, p.411

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 information present in the wave functions from information before the collision. But the new information may not be recorded anywhere (other than being implicit in the 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.

Without that erasure, information about initial conditions woould remain in the paths of all the particles, as Ludwig Boltzmann feared. This means that, in principle, the paths could be reversed to return to the initial, lower entropy, conditions (Loschmidt paradox).