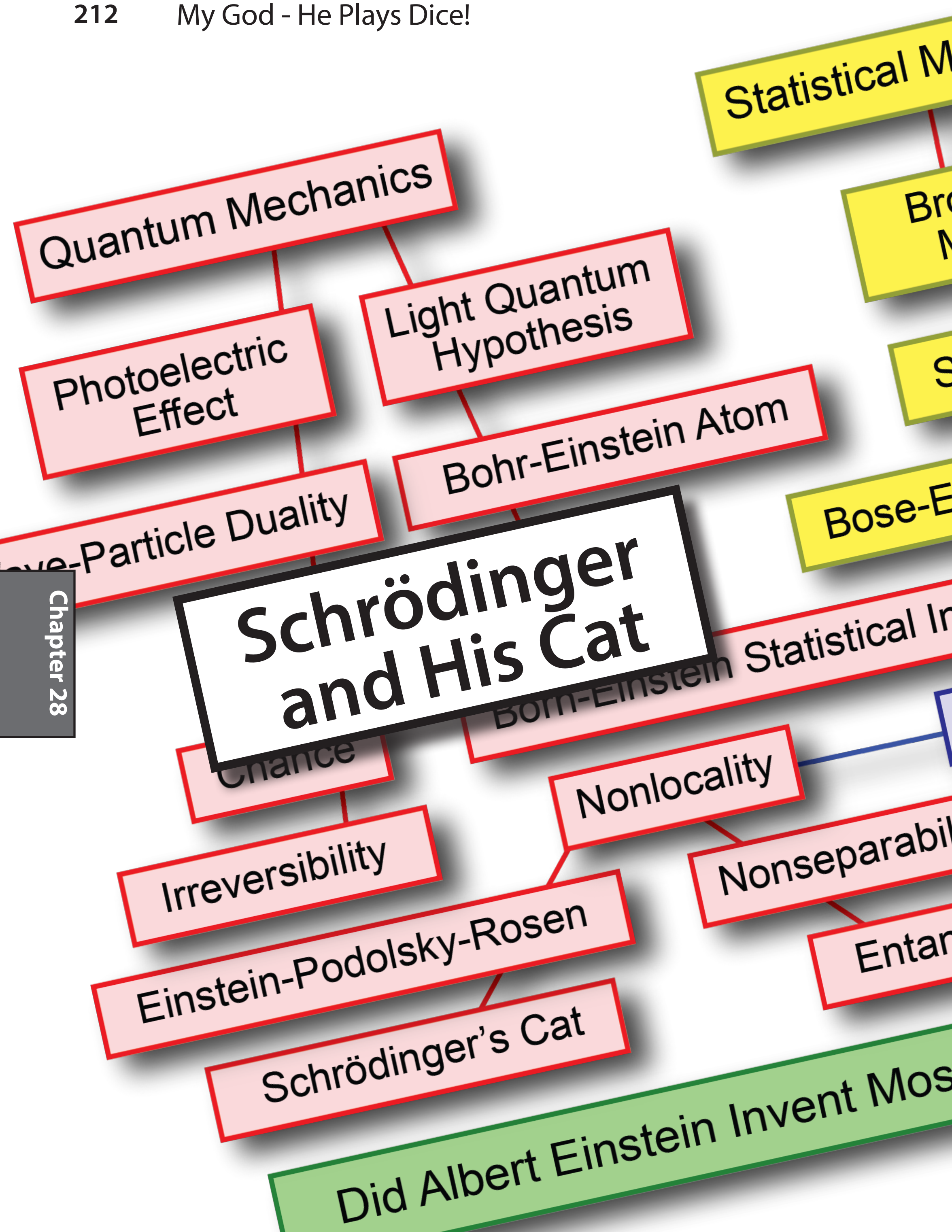
Chapter 28

Schrödinger and His Cat



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Schrödinger and His Cat

A few weeks after the May 15, 1935 appearance of the EPR article in the *Physical Review* in the U.S., Erwin Schrödinger wrote to Einstein to congratulate him on his "catching dogmatic quantum mechanics by its coat-tails."

In his EPR paper, Einstein cleverly introduced *two particles* instead of one. Schrödinger gave us a two-particle wave function that describes both particles. The particles are identical, indistinguishable, and with indeterminate positions, although EPR described them as widely separated, one "here" and measurable "now" and the other distant and to be measured "later."

Einstein now shows that the mysterious nonlocality that he first saw when the wave function for a single particle disappears everywhere at the instant the particle is found, can also be happening for two particles. But he maintained that "system S_2 is independent of what is done with the system S_1", as we saw in the last chapter.

Schrödinger, the creator of wave mechanics, surprised Einstein by challenging the idea that two systems that had previously interacted can at some point be treated as *separated*. And, he said, a two-particle wave function ψ_{12} cannot be factored into a product of separated wave functions for each system, ψ_1 and ψ_2.

Einstein called this a "separability principle" (*Trennungsprinzip*). But the particles cannot actually separate until another quantum interaction separates, decoheres, and disentangles them.

Schrödinger published a famous paper defining his idea of "entanglement" a few months later. It began:

> When two systems, of which we know the states by their respective representatives, enter into temporary physical interaction due to known forces between them, and when after a time of mutual influence the systems separate again, then they can no longer be described in the same way as before, viz. by endowing each of them with a representative of its own. I would not call that one but rather the characteristic trait of quantum mechanics, the one that enforces its entire departure from classical lines of thought. By the interaction the two

> representatives (or ψ-functions) have become entangled. They can also be disentangled, or decohered, by interaction with the environment (other particles). An experiment by a human observer is not necessary. To disentangle them we must gather further information by experiment, although we knew as much as anybody could possibly know about all that happened. Of either system, taken separately, all previous knowledge may be entirely lost, leaving us but one privilege: to restrict the experiments to one only of the two systems. After reestablishing one representative by observation, the other one can be inferred simultaneously. In what follows the whole of this procedure will be called the disentanglement...
>
> Attention has recently [viz., EPR] been called to the obvious but very disconcerting fact that even though we restrict the disentangling measurements to one system, the representative obtained for the other system is by no means independent of the particular choice of observations which we select for that purpose and which by the way are entirely arbitrary. It is rather discomforting that the theory should allow a system to be steered or piloted into one or the other type of state at the experimenter's mercy in spite of his having no access to it. This paper does not aim at a solution of the paradox, it rather adds to it, if possible. [1]

Schrödinger says that the entangled system may become disentangled long before any measurements by a human observer. But if the particles continue on undisturbed, they may remain perfectly correlated for long times between measurements. Or they may decohere as a result of interactions with the environment, as proposed by decoherence theorists.

Schrödinger is perhaps the most complex figure in twentieth-century discussions of quantum mechanical uncertainty, ontological chance, indeterminism, and the statistical interpretation of quantum mechanics. His wave function and wave equation are the definitive tool for quantum mechanical calculations. They are of unparalleled accuracy. But Schrödinger's interpretations are extreme and in many ways out-of-step with standard quantum mechanics.

1 Schrödinger, 1935, p.555

Schrödinger denies quantum jumps and even the existence of objective particles, imagining them to be packets of his waves. He objects to Einstein's, and later Born's better known, interpretation of his waves as probability amplitudes. He denies uncertainty and is a determinist. His wave equation is deterministic.

Superposition

Schrödinger's wave equation is a *linear* equation. All its variables appear to the first power. This means that the sum of any two solutions to his equation is also a solution.

This property is what lies behind PAUL DIRAC's *principle of superposition* (chapter 19). Any wave function ψ can be a linear combination (or superposition) of multiple wave functions φ_n.

$\psi = \Sigma_n c_n \varphi_n$.

The φ_n are interpreted as possible eigenstates of a system, each with an eigenvalue E_n. The probability that the system is in eigenstate φ_n is $c_n{}^2$, provided their sum is normalized to unity,

$\Sigma_n c_n{}^2 = 1$.

If a system is in a superposition of two possible states, we can calculate the probabilities that in many experiments $c_1{}^2$ of them will be found in state φ_1 and $c_2{}^2$ of them will be found in state φ_2.

As Dirac explained, superposition is a mathematical tool that predicts the statistical outcomes of many identical experiments. But an individual system, for example a photon or material particle, is not actually in two states at the same time. Dirac said that's just a "manner of speaking."

> We have obtained a description of the photon throughout the experiment, which rests on a new rather vague idea of a photon being partly in one state and partly in another...
>
> The original state must be regarded as the result of a kind of superposition of the two or more new states, in a way that cannot be conceived on classical ideas...
>
> When we say that the photon is distributed over two or more given states the description is, of course, only qualitative...
>
> We must, however, get used to the new relationships between the states which are implied by this manner of speaking and must build up a consistent mathematical theory governing them.

> The description which quantum mechanics allows us to give is merely a manner of speaking which is of value in helping us to deduce and to remember the results of experiments and which never leads to wrong conclusions. One should not try to give too much meaning to it. [2]

Nevertheless, around the time of EPR, Einstein began an attack on Dirac's principle of superposition, which was then amplified by Erwin Schrödinger to become two of the greatest mysteries in today's quantum physics, Schrödinger's Cat, and Entanglement.

Before we discuss these, we will look at how Einstein and Schrödinger engaged in a major debate about the two particles in EPR. Can they act on one another "at a distance?" Do they ever separate as independent particles, when they interact with other particles, for example?

Schrödinger's Cat

Schrödinger's goal for his infamous cat-killing box was to discredit certain non-intuitive implications of quantum mechanics, of which his wave mechanics was the second formulation. Schrödinger's wave mechanics is more *continuous* and more deterministic than Werner Heisenberg's matrix mechanics.

Schrödinger never liked Niels Bohr's idea of "quantum jumps" between Bohr's "stationary states" - the different "energy levels" in an atom. Bohr's second "quantum postulate" said that the jumps between discrete states emitted (or absorbed) energy in the amount $h\nu = E_m - E_n$.

Bohr did not accept Albert Einstein's 1905 hypothesis that the emitted radiation is a *discrete* localized particle quantum of energy $h\nu$. Until well into the 1920's, Bohr (and Max Planck, himself the inventor of the quantum hypothesis) believed radiation was a *continuous* wave. This was at the root of wave-particle duality, which Einstein saw as early as 1909.

It was Einstein who originated the mistaken suggestion that the *superposition* of Schrödinger's wave functions implies that two different physical states can exist at the same time. As we have seen, it was based on what Paul Dirac called a "manner of speaking" that a single system is "distributed" over multiple states. This was

2 Dirac, 1930, p.5

a serious interpretational error that plagues the foundation of quantum physics to this day.[3]

We never actually "see" or measure any system (whether a microscopic electron or a macroscopic cat) in two distinct states. Quantum mechanics simply predicts a significant probability of the system being found in these different states. And these probability predictions are borne out by the statistics of large numbers of identical experiments.

Einstein wrote to Schrödinger with the idea that the decay of a radioactive nucleus could be arranged to set off a large explosion. Since the moment of decay is unknown, Einstein argued that the superposition of decayed and undecayed nuclear states implies the superposition of an explosion and no explosion. It does not. In both the microscopic and macroscopic cases, quantum mechanics simply estimates the probability amplitudes for the two cases.

Schrödinger devised a variation of Einstein's provocative idea in which the random radioactive decay would kill a cat. Observers could not know what happened until the box is opened.

The details of the tasteless experiment include:

- a Geiger counter which produces an avalanche of electrons when an alpha particle passes through it
- a bit of radioactive material with a decay half-life likely to emit an alpha particle in the direction of the Geiger counter during a time T
- an electrical circuit energized by the electrons which drops a hammer
- a flask of a deadly hydrocyanic acid gas, smashed open by the hammer.

The gas will kill the cat, but the exact time of death is unpredictable and random because of the irreducible quantum indeterminacy in the time of decay (and the direction of the decay particle, which might miss the Geiger counter!).

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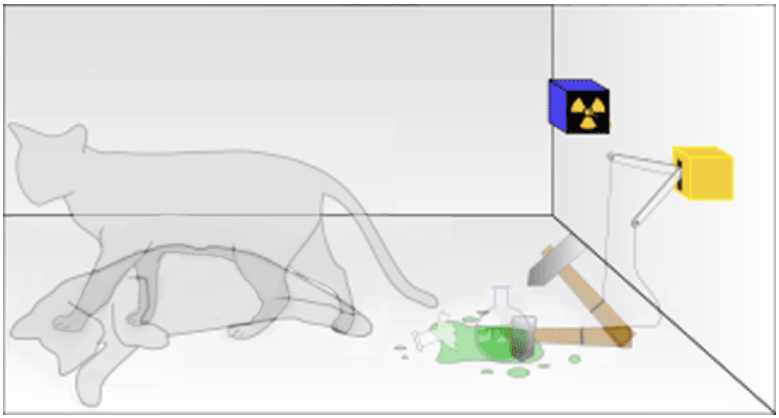
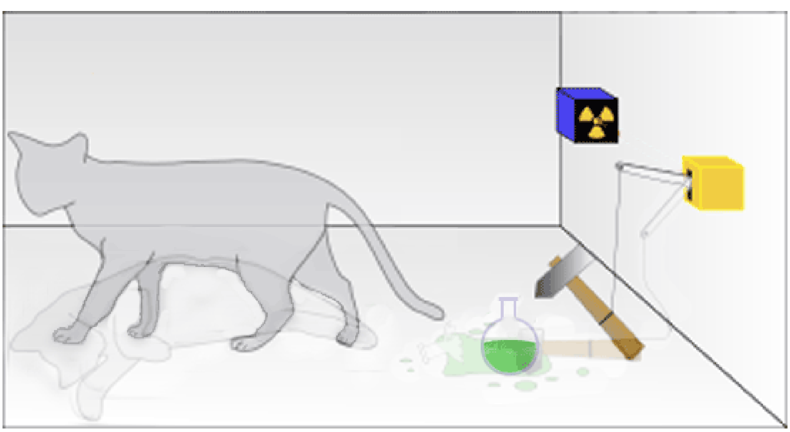
3 See Dirac's "manner of speaking" in chapter 19.

This thought experiment is widely misunderstood. It was meant (by both Einstein and Schrödinger) to suggest that quantum mechanics describes the simultaneous (and obviously contradictory) existence of a live and dead cat. Here is the famous diagram with a cat both dead and alive.

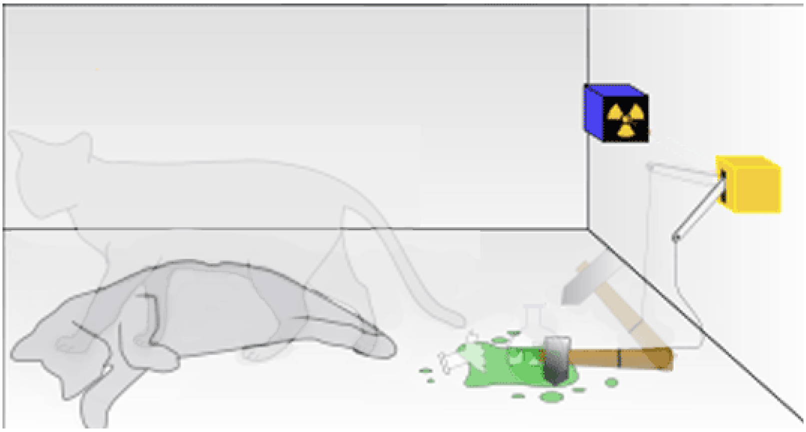


If we open the box at the time T when there is a 50% probability of an alpha particle emission, the most a physicist can know is that there is a 50% chance that the radioactive decay will have occurred and the cat will be observed as dead or dying.

If the box were opened earlier, say at T/2, there is only a 25% chance that the cat has died. Schrödinger's superposition of live and dead cats would look like this.



If the box were opened later, say at 2T, there is only a 25% chance that the cat is still alive. Quantum mechanics is giving us only statistical information - knowledge about probabilities.



Schrödinger is simply wrong that the mixture of nuclear wave functions accurately describing decay can be magnified to world to describe a macroscopic mixture of live cat and dead cat wave functions and the simultaneous existence of live and dead cats.

Instead of a linear combination of pure quantum states, with quantum interference between the states, i.e.,

$| \text{Cat} > = (1/\sqrt{2}) \,|\, \text{Live} > + (1/\sqrt{2}) \,|\, \text{Dead} >$,

quantum mechanics tells us only that there is 50% chance of finding the cat in either the live or dead state, i.e.,

Cats = (1/2) Live + (1/2) Dead.

Just as in the quantum case, this probability prediction is confirmed by the statistics of repeated identical experiments, but no interference between these states is seen.

What do exist simultaneously in the macroscopic world are genuine alternative possibilities for future events. There is the real possibility of a live or dead cat in any particular experiment. Which one is found is irreducibly random, unpredictable, and a matter of pure chance.

Genuine alternative possibilities is what bothered physicists like Einstein, Schrödinger, and Max Planck who wanted a return to deterministic physics. It also bothers determinist and compatibilist philosophers who have what William James calls an "antipathy to chance." Ironically, it was Einstein himself, in 1916, who discovered the existence of irreducible chance, in the elementary interactions of matter and radiation.

Until the information comes into existence, the future is indeterministic. Once information is macroscopically encoded, the past is determined.

How Does "Objective Reality" Resolve The Cat Paradox?

As soon as the alpha particle sets off the avalanche of electrons in the Geiger counter (an irreversible event with an entropy increase), new information is created in the world.

For example, a simple pen-chart recorder attached to the Geiger counter could record the time of decay, which a human observer could read at any later time. Notice that, as usual in information creation, energy expended by a recorder increases the entropy more than the increased information decreases it, thus satisfying the second law of thermodynamics.

Even without a mechanical recorder, the cat's death sets in motion biological processes that constitute an equivalent, if gruesome, recording. When a dead cat is the result, a sophisticated autopsy can provide an approximate time of death, because the cat's body is acting as an event recorder. There never is a superposition (in the sense of the simultaneous existence) of live and dead cats.

The cat paradox points clearly to the information physics solution to the problem of measurement. Human observers are not required to make measurements. In this case, information is in the cat's body, the cat is the observer.

In most physics measurements, any new information is captured by an apparatus well before any physicist has a chance to read any dials or pointers that indicate what happened. Indeed, in today's high-energy particle interaction experiments, the data may be captured but not fully analyzed until many days or even months of computer processing establishes what was observed. In this case, the experimental apparatus is the observer.

And, in general, the universe is its own observer, able to record (and sometimes preserve) the information created.

The basic assumption made in Schrödinger's cat thought experiments is that the deterministic Schrödinger equation describing a microscopic superposition of decayed and non-decayed radioactive nuclei evolves deterministically into a macroscopic superposition of live and dead cats.

But since the essence of a "measurement" is an interaction with another system (quantum or classical) that creates information to be seen (later) by an observer, the interaction between the nucleus and the cat is more than enough to collapse the wave function. Calculating the probabilities for that collapse allows us to estimate the probabilities of live and dead cats. These are probabilities, not probability amplitudes. They do not interfere with one another.

After the interaction, they are not in a superposition of states. We always have either a live cat or a dead cat, just as we always observe a complete photon after a polarization measurement and not a superposition of photon states, as Dirac explains so simply and clearly in his *Principles of Quantum Mechanics*.[4]

The original cat idea of Schrödinger, and Einstein, was to make fun of standard quantum mechanics. But the cat has taken on a life of its own, as we shall see in later chapters. Some interpretations of quantum mechanics, based entirely on a universal wave function, are puzzled by the absence of *macroscopic* superpositions. They say quantum mechanics involves *microscopic* superpositions like particles being in two places at the same time, going through both slits in the two-slit experiment for example. So why no macroscopic superpositions like Schrödinger's Cat?

The short answer is very simple. There are no microscopic superpositions either. As we saw in chapter 19, Dirac tells us that superpositions are just a "manner of speaking." Any real system is always in a single state. Treating it as in a superposition of some other basis states is a mathematical tool for making statistical predictions about large numbers of experiments.

The particular radioactive nucleus in Schrödinger's example is always either not yet decayed or already decayed!

4 Dirac, 1930, p.5