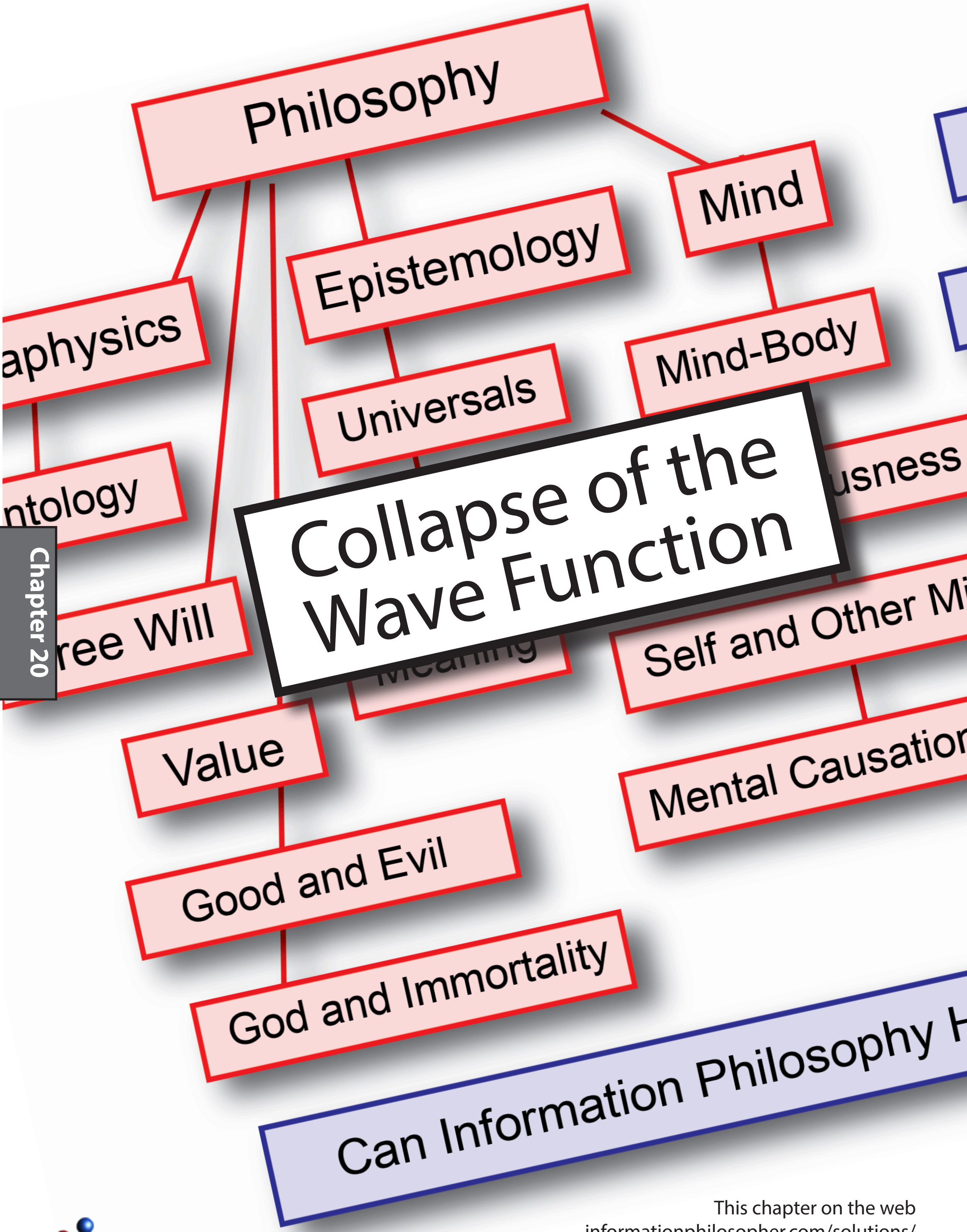
Chapter 20



This chapter on the web
informationphilosopher.com/solutions/
experiments/wave-function_collapse/

Collapse of the Wave Function

The probability amplitude wave function in quantum mechanics and its indeterministic collapse during a measurement is without doubt the most controversial problem in physics today. Of the several "interpretations" of quantum mechanics, more than half *deny the collapse* of the wave function[1]. Some of these deny quantum "jumps" and even the existence of particles!

So it is very important to understand the importance of what Paul Dirac called the *projection postulate* in quantum mechanics. The "collapse of the wave function" is also known as the "reduction of the wave packet." This usually describes the change from a system that can be seen as having many possible quantum states (Dirac's *principle of superposition*) to its randomly being found in only one of those possible states.

Although the collapse is historically thought to be *caused* by a measurement, and thus dependent on the role of a conscious observer[2] in preparing the experiment, collapses can occur whenever quantum systems interact (e.g., collisions between particles) or even spontaneously (radioactive decay).

The claim that a conscious observer is needed to collapse the wave function has injected a severely anthropomorphic element into quantum theory, suggesting that nothing happens in the universe except when physicists are making measurements. An extreme example is Hugh Everett III's Many Worlds theory, which says that the universe splits into two nearly identical universes whenever a binary measurement is made.

What is the Wave Function?

Perhaps the best illustration of the wave function is to show it passing though the famous slits in a two-slit experiment. It has been known for centuries that water waves passing through a small opening creates circular waves radiating outward from that opening. If there are two openings, the waves from each opening

---

1 See Other Interpretations of Quantum Mechanics on p.198
2 See The Role of the Conscious Observer on p.227

interfere with those from the other, producing waves twice as tall at the crests (or deep in the troughs) and cancelling perfectly where a crest from one meets a trough from the other.

When we send light waves through tiny slits, we see the same phenomenon.

Most of the light that reaches light detectors at the back lands right behind the barrier between the slits, which seems non-intuitive. Most amazingly, at some places there are null points, where no light at all appears in the interference pattern.

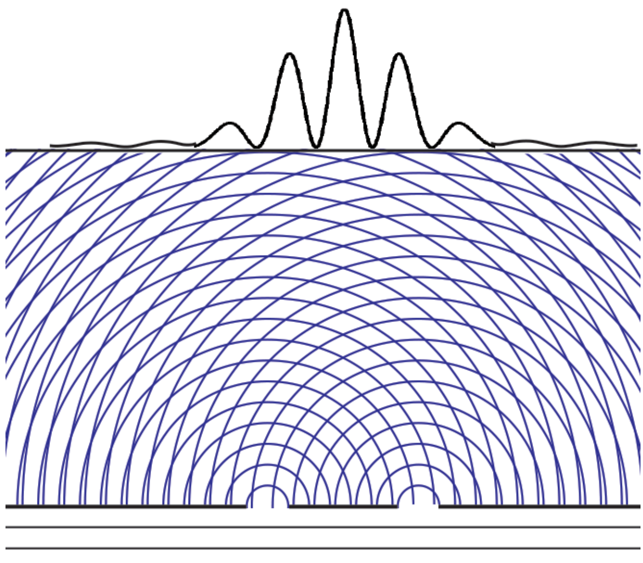


Figure 20-15. Interfering waves show crests and troughs.

Since Einstein's great hypothesis in 1905, we know that light actually consists of large numbers of individual photons, quanta of light. Our experiment can turn down the amount of light so low that we know there is only a single photon, a single particle of light in the experiment at any time. What we see then is the very slow accumulation of photons at the detectors, but with exactly the same overall interference pattern. And this leads to what Richard Feynman called not just a "mystery," but actually the "only mystery" in quantum mechanics. How can the particle go through both slits to interfere with itself?

We can show that a single particle does not interfere with itself. It may only go through one slit, but with two slits open, its possible motions are different from the case with only one slit. Look at the possibilities function with the right slit closed. We have a *completely different interference pattern*.

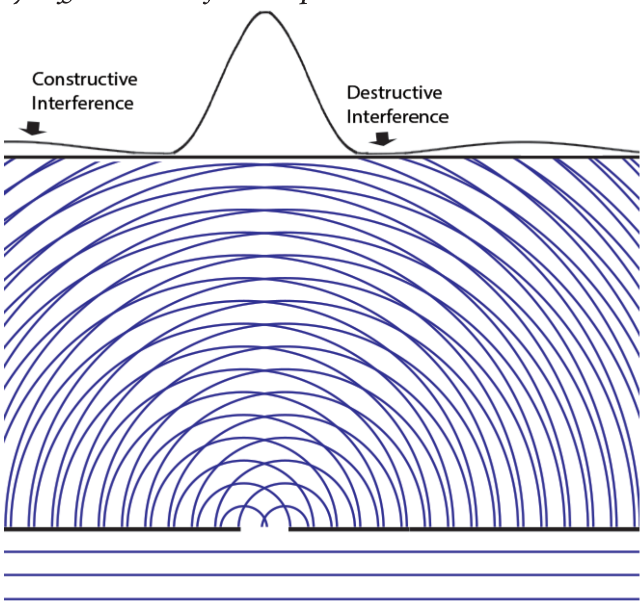


Figure 20-16. Many accounts say the interference fringes are lost, but there is still interference between particles that come from different parts of the slit.

Information Physics Explains the Two-Slit Experiment

Although we cannot say anything about a single particle's whereabouts, information philosophy can help us to see clearly in these two figures that while it may only go through one slit, what goes through the two slits and what it is that interferes with itself is *abstract information*, the mathematical probability of finding the particle at each of the possible places it may go.

Neither matter nor energy, we call this abstract information the "possibilities function." The wave function is exploring all the possible locations where a particle may be found. So the quantum wave going through the slit is an abstract number, neither material nor energy, just a probability. It is *information* about where particles of matter (or particles of light if we shoot photons at the slit) will be found when we record them. Only large numbers of experiments reveal the wave nature and its interference. The location of a single particle is indeterminate, the result of ontological chance.

But the average locations of millions of particles shows the wave-like interference and demonstrates the *causal* power of the *immaterial* and abstract possibilities function. For example, no particle lands at the null points!

Now information philosophy accepts that information needs matter for its embodiment and energy for its communication. So where is the "possibilities function" embodied? Before we explain that, let's first review why this function is said to "collapse."

When Einstein first considered this problem in 1905, he thought of the light wave as *energy* spread out everywhere in the wave. So it was energy that he thought might be traveling faster than light, violating his brand new principle of relativity (published just two months after his light quantum paper). Let's visualize his concern.

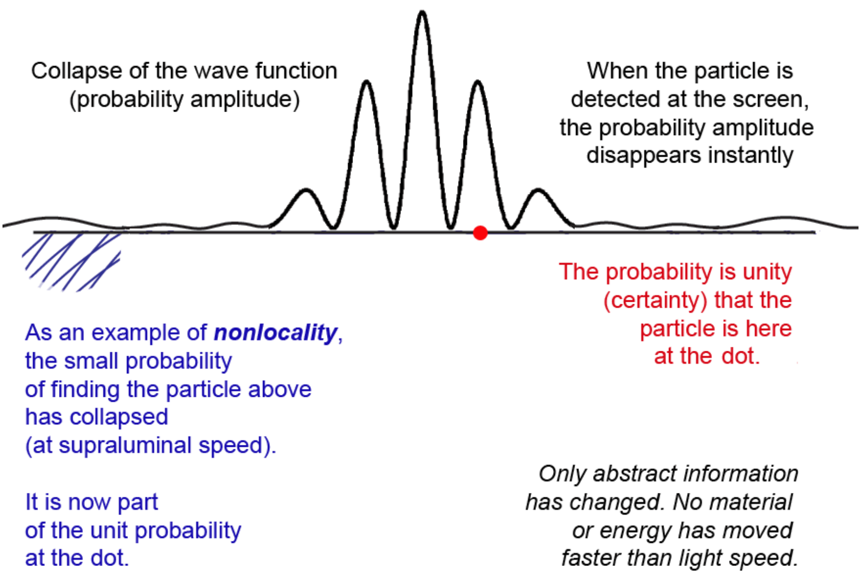


Figure 20-17. Once the particle appears anywhere, the possibilities of it appearing anywhere else must immediately vanish.

Einstein assumed

> the energy of a beam of light from a point source (according to the Maxwellian theory of light or, more generally, according to any wave theory) is continuously spread over an ever increasing volume... In accordance with the assumption to be considered here, the energy of a light ray spreading out from a point source is not continuously distributed over an increasing space but consists of a finite number of energy quanta which are localized at points in space, which move without dividing, and which can only be produced and absorbed as complete units.[3]

The interfering probability amplitude waves disappear instantly everywhere once the particle is detected, but we left a small fragment of interfering waves on the left side of the figure to ask a question first raised by Einstein in 1905.

What happens to the small but finite probability that the particle might have been found at the left side of the screen? How has that probability instantaneously (with "action-at-a-distance faster than light speed) been collected into the unit probability at the dot?

The answer provided by information philosophy is that nothing collapsed, nothing moved at any speed. The wave function is not energy or matter, it is only abstract information that tells us the probabilities of various possibilities.

The idea of probability - or possibilities - "collapsing" is much easier to understand than something material or energetic gathering itself suddenly in one location. Probability and possibilities are abstract ideas. They are *immaterial*.

It was at the Solvay conference in Brussels in 1927, twenty-two years after Einstein first tried to understand what is happening when the wave collapses, when he noted;

> "If $| \psi |^2$ were simply regarded as the probability that at a certain point a given particle is found at a given time, it could happen that the same elementary process produces an action ... assumes an entirely peculiar mechanism of action at a distance." [4]

Einstein later came to call this *spukhafte Fernwerkungen*, "spooky action at a distance." It is now known as *nonlocality*.

3 "A Heuristic Viewpoint on the Production and Transformation of Light," English translation - American Journal of Physics, 33, 5, 367

4 *Quantum Theory at the Crossroads*, Bacciagaluppi and Valentini, 2009. p.442

Where Is Information About Probabilities Embodied?

Information philosophy can now answer this critical part of the mystery. The information is not embodied in energy, as Einstein finally realized. It is also not embodied in the matter of a particle, such as an electron. Einstein said that quantum mechanics is "incomplete" because the particle has no definite position before a measurement. He was right. But that is not because the particle is distributed in space.

What is distributed in space is seen clearly in the figures above, the waves of probability information. But where is that information embodied? The answer is astonishingly simple. It is embodied in the material of the experimental apparatus. It is in the "boundary conditions" of the wall with its slits and the screen with its detectors.

The waves are simply the mathematical solutions of the Schrödinger wave equation given the boundary conditions and the wavelength of the particles. When one slit is closed, the abstract "possibilities function" looks quite different from the two-slit open case. The mystery of how the particle going through one slit is aware that the other slit is open or closed is completely solved.

We can regard those mathematical possibilities as the values of what Einstein in 1921 called a "ghost field" or "leading field" that predicts the probability of finding his light quanta. A few years later, inspired by Einstein, Louis de Broglie called it a "pilot wave" in his 1924 thesis. Then in 1926, Max Born used Einstein's idea as the basis for a "statistical interpretation" of quantum mechanics. He wrote:

> I shall recall a remark that *Einstein* made about the behavior of the wave field and light quanta. He said that perhaps the waves only have to be wherever one needs to know the path of the corpuscular light quanta, and in that sense, he spoke of a "ghost field." It determines the probability that a light quantum - viz., the carrier of energy and impulse – follows a certain path; however, the field itself is ascribed no energy and no impulse.
>
> ... from the complete analogy between light quanta and electrons, one might consider formulating the laws of electron motion in a similar manner. This is closely related to regarding the *de Broglie-Schrödinger* waves as "ghost fields," or better yet, "guiding fields."

> ... The paths of these corpuscles are determined only to the extent that they are constrained by the law of energy and impulse; moreover, only a probability that a certain path will be followed will be determined by the function ψ. One can perhaps summarize this, somewhat paradoxically, as: The motion of the particle follows the laws of probability, but the probability itself propagates in accord with causal laws.[5]

The sudden change in probability also occurs in the Einstein-Podolsky-Rosen experiments, where measurement of one particle transmits neither matter or energy to the other "entangled" particle. Instead, new information has come into the universe instantaneously. That information, together with conservation of angular momentum, makes the state of the coherently entangled second particle *certain*, however far away it might be after the measurement.[6]

The standard "orthodox" interpretation of quantum mechanics includes the *projection postulate*. This is the idea that once one of the possibilities becomes actual at one position, the probabilities for actualization at all other positions becomes instantly zero. New information has appeared, but there is no information transfer that could be used to communicate that information.

The *principle of superposition* tells us that before a measurement, a system may be in one of many possible states. In the two-slit experiment, this includes all the possible positions where $|\psi(x)|^2$ is not zero. Once the quantum system (the photon or electron) interacts with a specific detector at the screen, all other possibilities vanish. It is unfortunate that the word "collapse" was chosen, since it suggests some physical motion, where nothing at all is moving when probabilities change.

When we deny the appropriateness of the word "collapse," we do not deny the underlying indeterministic physics. Just as in philosophy, where it is the language used that is often the source of confusion, we find that thinking about the information involved, rather than the words, clarifies the problem in physics.

---

5 Quantum mechanics of collision processes (*Quantenmechanik der Stoßvorgänge*), *Zeitschrift für Physik*. 38 (1926), 803-827

6 See the next chapter for the two-particle wave function.