The interplay between nature and ourselves

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Written by

Magdalena Kersting

> Seemingly innocuous experiments can challenge the fundamental relationship between science and the scientist, the perceived object and the perceiving subject.

The room is pitch black. Carefully, the test person gropes for the button in front of her. A single flash appears for a split of a second. Almost too faint to be visible, the flicker could nearly be a product of imagination. Or was it? The experimental setup that probes the limits of human perception is simple. Immersed in total darkness, volunteers look into an optical system. Upon pressing a button, the system either emits single photons - or stays inactive. The task for the probands is to decide whether or not they saw the tiny particle of light.

More than any other sense, vision forms our link with the external world. We take in the environment through visual perception, and the photon experiment testifies to our physiological aptness as observers: humans can sense single photons. The human eye is a remarkably sensitive photodetector because the light-detecting cells in our eyes trigger signals in response to the feeblest glimmer.

On the surface, experiments with individual photons seem to probe the ultimate threshold of vision. Yet, suppose we dig a little deeper. In that case, the photon experiment illuminates an exciting link between two realms that have long stood apart: the external world and human experience. Since photons are objects of the quantum world, even seemingly innocuous experiments can challenge the fundamental relationship between science and the scientist, the perceived object and the perceiving subject.

To understand what is at stake, let's first consider the infamous double-slit experiment, the

> "one experiment, which has been designed to contain all of the mystery of quantum mechanics",

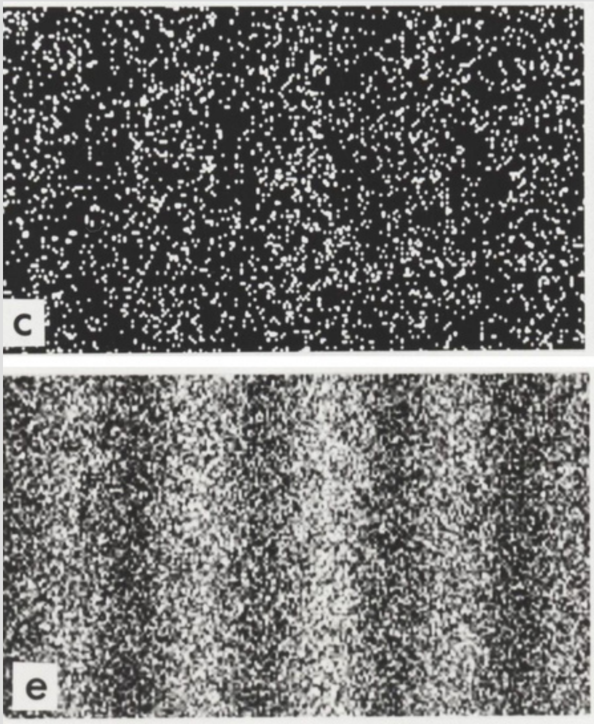
as Nobel laureate Richard Feynman put it.

In this experiment, light passes through two parallel slits in a barrier and creates a pattern of several bright and dark bands on a photo plate behind the slits. This pattern is reminiscent of the intricate inference patterns that water ripples create when they overlap. The scientific conclusion is straight-forward: light is a wave; it can interfere with itself.

Originally designed to demonstrate this wave-nature of light, the double-slit experiment held a surprise in store for physicists in the early 1900s. At that time, it became clear that light must be made up of discrete units of energy, a discovery that would later earn Albert Einstein the Nobel Prize in physics. The idea of photons as particles of light was born. And with it the conundrum of the wave-particle duality: how can light behave like a wave if it is made up of point-like entities?

Common sense tells us that a stream of individual photons should behave like any classical particle. One by one, each photon will either go through one slit or the other before hitting the photo plate. Over time, we expect that small dots of individual impacts will pile up on the plate to create two distinct bands of light corresponding to the two slits. However, that is not what we observe.

In the experimental setup, we can reduce the brightness of the light source to ensure that there is always only one photon going through the barrier at a time. Yet, the inference pattern so characteristic of waves emerges



Individual particle detections build the characteristic interference pattern of the double-slit experiment. Source: Dr. Tonomura and Belsazar, CC BY-SA 3.0 <https://creativecommons.org/licenses/by-sa/3.0>, via Wikimedia Commons

gradually as single photons accumulate on the plate – it is as if each photon simultaneously goes through both slits and interferes with itself!

"We have two contradictory pictures of reality; separately neither of them fully explains the phenomena of light, but together they do", Einstein observed.

But it's not just particles behaving like waves that make the double-slit experiment so puzzling. Say we position a particle detector at the slits to measure which path a photon follows. Then the inference pattern on the plate will vanish, and we just observe two bright bands. It appears to make a difference whether or not we look. The very act of perceiving the photon alters experimental outcomes!

More mystifying still, the outcome seems to depend on what we know, not what we measure. Somewhat incredulously, the inference pattern will reappear if we erase the result that determines the photon's path before we look at it. The conscious knowledge of the observing scientist seems to play a decisive role in shaping reality. Does reality not exist until observed? In fact, that is what the founding fathers of quantum mechanics speculated. Eminent physicist Niels Bohr asserted, "it is clearly impossible to distinguish sharply between the phenomena themselves and their conscious perception".

Quantum pioneer Werner Heisenberg took a similar position stating that "We can no longer speak of the behaviour of the particle independently of the process of observation. As a final consequence, the natural laws formulated mathematically in quantum theory no longer deal with the elementary particles themselves but with our knowledge of them (…) science no longer confronts nature as an objective observer but sees itself as an actor in this interplay between man and nature (...) In other words, method and object can no longer be separated."

science no longer confronts nature as an objective observer

What is remarkable about these statements is that they come from the same scientists who developed quantum mechanics. Studying quantum phenomena, Bohr and Heisenberg were led to question the very assumption underlying scientific inquiry. For centuries, science had remarkable success because of its strict separation of the perceiving scientist from the perceived objects. At most, the role of the scientist was that of a passive observer of a world governed by objective laws of nature. In science, there was no place for subjective experience. Yet, quantum physics seemed to suggest otherwise.

In the past century, quantum mechanics has grown into one of the most powerful and accurate theories in physics. In parallel, interpretations of quantum mechanics have proliferated as physicists and philosophers have grappled with the theory's conceptual absurdities.

Niels Bohr and Albert Einstein thought deeply about the many conundrums of quantum physics.
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How does the mathematical formalism correspond to our observations and our perceptions of phenomena? How are we to solve the mystery of our quantum reality?

It is here that the photon experiment involving the human eye helps us see the advantages that subjectivity brings to science. Suppose we become the test apparatus in the experiment, pressing buttons and perceiving photons in the dark. In that case, we take a participatory role in the detection of particles. And the explicit introduction of personal experiences may be all that is needed to solve the vexing paradoxes of the quantum world. At least according to QBism, a relatively recent interpretation of quantum mechanics that puts the perceiving subject at the centre of the quantum machinery.

What may sound heretical at first, provides an elegant way to restore the balance between subjective experience and objective reality in science. QBism abandons the view that the scientist stands outside of nature. Instead, physics gets personal: it becomes the study of how we navigate the world and how we make sense of our experiences while doing so.

Already Bohr hinted at such a personal interpretation of quantum mechanics when he said

"In our description of nature the purpose is not to disclose the real essence of the phenomena but only to track down, so far as it is possible, relations between the manifold aspects of our experience".

According to QBism, quantum mechanics studies aspects of our experiences as we interact with the world. Rather than describing elements of reality, the equations that govern the quantum world encode our personal experiences. The abstract formalism relates the expectations of a scientist about the possible outcomes of her actions to the actual outcomes she perceives. Depending on these perceptions, the scientist will update her equations to make better judgements in the future. From that vantage point, quantum mechanics becomes a powerful conceptual tool that the scientist uses to organise her experiences.

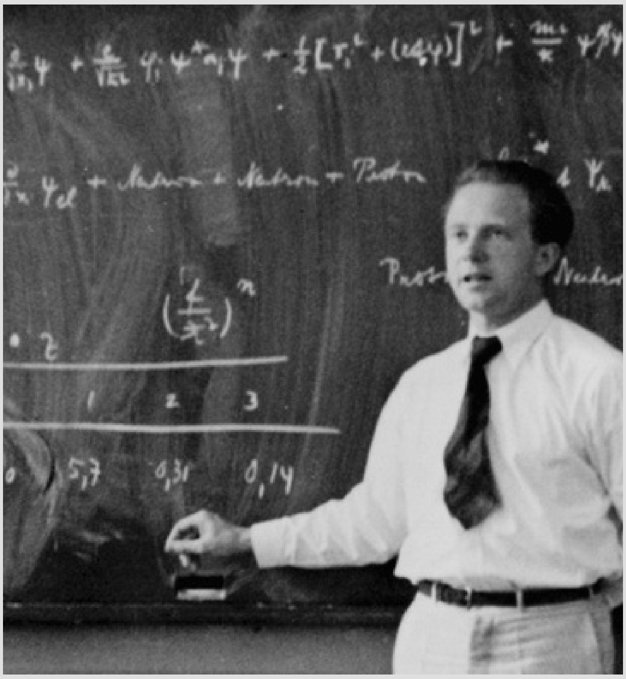
Crucially, the scientist does not change reality by merely looking at it; she only changes her expectations for her subsequent experiences. Each measurement outcome becomes a personal experience tied to the scientist. And since experiences cannot exist before they are experienced, measurement outcomes cannot exist before the measurement either. Thus, there is nothing weird about the double-slit experiment. For a QBist, the apparent paradox only arises because we conflate our expectations for possible outcomes. The scientist falsely links her expectation for one hypothetical scenario to her expectation for another.

Sitting in a dark room and looking out for glimpses of light, we are certainly more inclined to accept that some features of quantum mechanics are subjective in nature. If we embrace the centrality of human perception in our attempts to understand the world, then QBism doesn't seem too outlandish an interpretation: quantum mechanics deals with the experiences of the objective world that belong to each and every one of us.

Or, as Bohr would say:

> “Physics is to be regarded not so much as the study of something a priori given, but as the development of methods for ordering and surveying human experience.”

According to Richard Feynman, the double-slit experiment is the "one experiment, which has been designed to contain all of the mystery of quantum mechanics". Source: Timm Weitkamp, CC BY 3.0 DE <https://creativecommons.org/licenses/by/3.0/de/deed.en>, via Wikimedia Commons



Werner Heisenberg received the Nobel Prize in Physics for "for the creation of quantum mechanics". Source: Science Photo Library, NTB scanpix. (https://ndla.no/article/9441). CC BY-NC-SA 4.0.

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