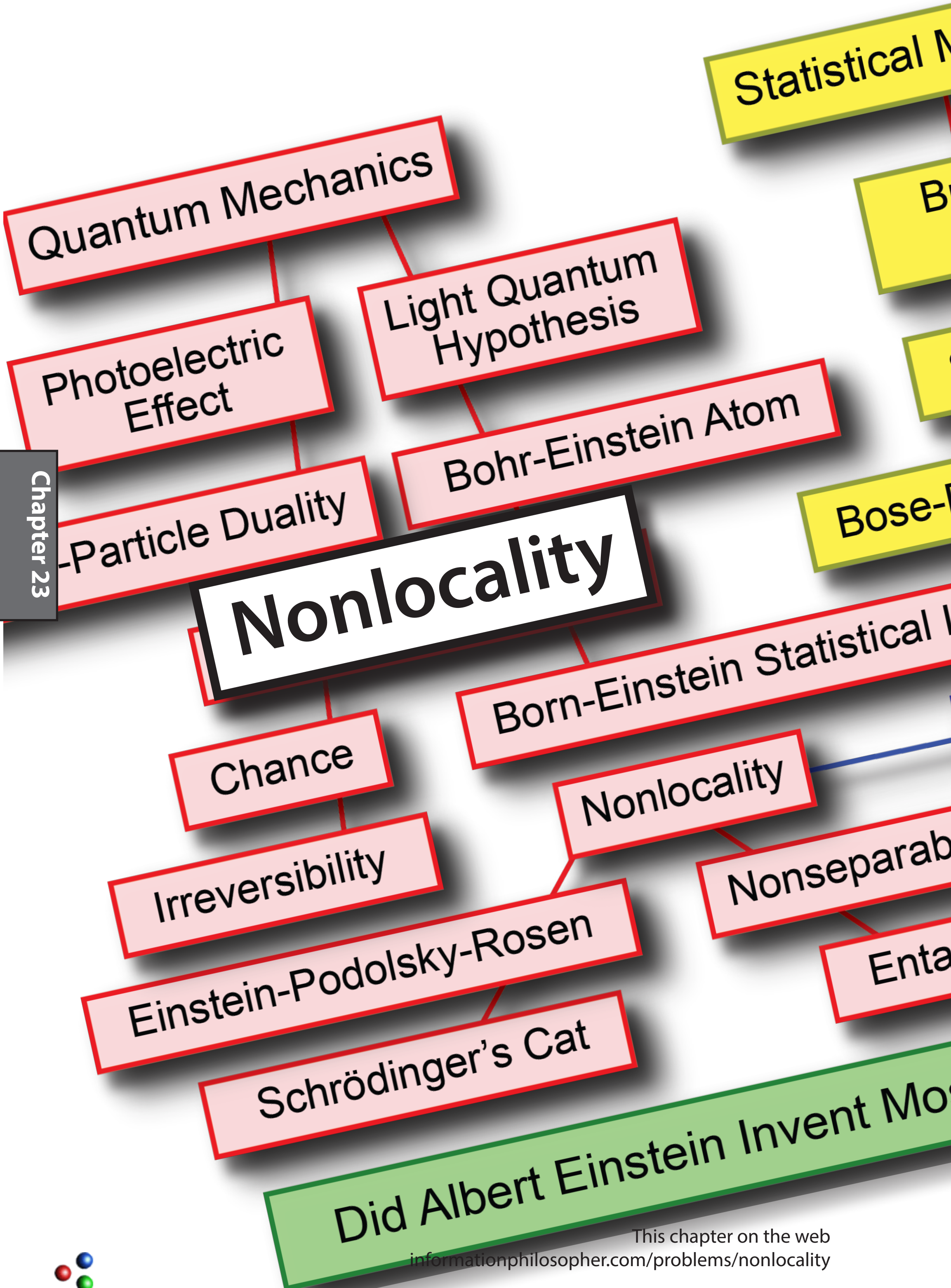


This chapter on the web
informationphilosopher.com/problems/nonlocality

Nonlocality at the Solvay Conference in 1927

Nonlocality is today strongly associated with the idea of entanglement (see chapter 29), but nonlocality was discovered as a property of a single quantum of light, whereas entanglement is a joint property of two quantum particles, depending on an even more subtle property called *nonseparability* (chapter 33).

Nonlocality is thought to be an essential element of light having wave and particle aspects, as Einstein described it first in 1909. But when understood as an "action-at-a-distance" faster than the speed of light, we shall show that this nonlocality *does not exist*.

We can visualize the wave function of quantum mechanics in the following way. It was Einstein who first said that the light wave tells us about probabilities of finding particles of light. Later Max Born made it quantitative. He identified the Schrödinger wave function Ψ as a probability amplitude whose squared modulus $|\Psi|^2$ gives the probability of finding a particle in a particular point.

We can think of Ψ as a "possibilities function," showing all the locations in space where there is a non-zero probability of finding a particle. The power of quantum mechanics is that we can *calculate* precisely the probability of finding the particle for each possibility.

Since Werner Heisenberg and Paul Dirac first discussed the "collapse" of the wave function (Dirac's projection postulate), it has been appropriate to say that "one of many possibilities has been made actual."

In the case of the photon, for example, it is localized when it has been scattered or absorbed by an electron. In the case of an electron, it might be a collision with another particle, or recombining with an ion to become bound in an atom, or absorbed into a metal and ejecting an electron as Einstein first explained.

The electron is actually never found at an infinitesimal point in four-dimensional space time, but remains "nonlocal" inside the minimal phase-space volume h^3 required by the uncertainty principle (for example, a particular electron orbital wave function and corresponding energy state).

Einstein was first to have seen single-particle nonlocality, in 1905, when he tried to understand how a spherical wave of light that goes off in many directions can be wholly absorbed at a single location. In his famous paper on the photoelectric effect (for which he was awarded the Nobel Prize), Einstein hypothesized that light must be transmitted from one place to another as a *discrete* and *physically localized quantum* of energy.

Einstein did not then use the term nonlocal or "local reality," but we can trace his thoughts backwards from 1927 and 1935 to see that quantum nonlocality (and later *nonseparability*) were always major concerns for him, because they are not easily made consistent with a *continuous* field theory and they both *appear* to be inconsistent with his principle of relativity.

Einstein clearly described wave-particle duality as early as 1909, over a dozen years before the duality was made famous by Louis de Broglie's thesis argued that clearly localized *material* particles also have a wavelike property. See chapter 9.

The fifth Solvay conference was titled "Electrons and Photons." It is no exaggeration to say that at that time, no physicist knew more than Einstein about electrons and photons. Yet he gave no major paper at the conference. He did give a short talk at a blackboard that prefigures his explosive EPR paper eight years later.

The fragments that remain of what Einstein actually said at the conference show a much deeper criticism of quantum mechanics. Einstein's nonlocality remarks were not a formal presentation and were not even reported in the conference proceedings. We know them only from brief notes on the general discussion and from what others tell us that Einstein said.

In his contribution to Paul Schilpp's volume on Einstein's work, Niels Bohr said that Einstein went to the blackboard and drew a diagram which Bohr reconstructed in 1949:

> At the general discussion in Como, we all missed the presence of Einstein, but soon after, in October 1927, I had the opportunity to meet him in Brussels at the Fifth Physical Conference of the Solvay Institute, which was devoted to the theme "Electrons and Photons." At the Solvay meetings,

Einstein had from their beginning been a most prominent figure, and several of us came to the conference with great anticipations to learn his reaction to the latest stage of the development which, to our view, went far in clarifying the problems which he had himself from the outset elicited so ingeniously. During the discussions, where the whole subject was reviewed by contributions from many sides and where also the arguments mentioned in the preceding pages were again presented, Einstein expressed, however, a deep concern over the extent to which causal account in space and time was abandoned in quantum mechanics.

To illustrate his attitude, Einstein referred at one of the sessions to the simple example, illustrated by Fig. 1, of a particle (electron or photon) penetrating through a hole or a narrow slit in a diaphragm placed at some distance before a photographic plate.

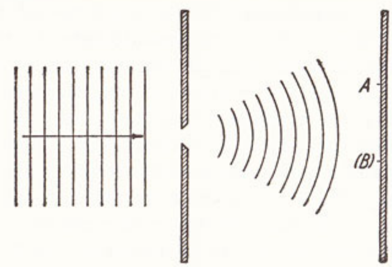


FIG. 1

On account of the diffraction of the wave connected with the motion of the particle and indicated in the figure by the thin lines, it is under such conditions not possible to predict with certainty at what point the electron will arrive at the photographic plate, but only to calculate the probability that, in an experiment, the electron will be found within any given region of the plate.

The "nonlocal" effect at point B is the probability of an electron being found at point B going to zero instantly (as if an "action at a distance") when an electron is localized at point A

The apparent difficulty, in this description, which Einstein felt so acutely, is the fact that, if in the experiment the electron is recorded at one point A of the plate, then it is out of the question of ever observing an effect of this electron at another point (B), although the laws of ordinary wave propagation offer no room for a correlation between two such events. [1]

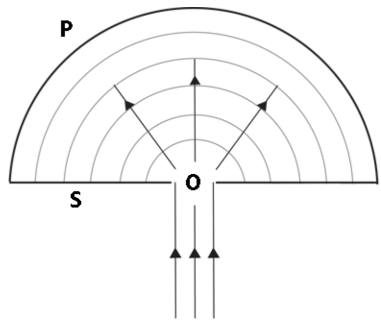
1 Schilpp, 1949, p. 211-213

And here are the notes on Einstein's actual remarks: [2]

MR ElNSTEIN. - Despite being conscious of the fact that I have not entered deeply enough into the essence of quantum mechanics, nevertheless I want to present here some general remarks.

One can take two positions towards the theory with respect to its postulated domain of validity, which I wish to characterise with the aid of a simple example.

Let S be a screen provided with a small opening O, and P a hemispherical photographic film of large radius. Electrons impinge on S in the direction of the arrows. Some of these go through O, and because of the smallness of O and the speed of the particles, are dispersed uniformly over the directions of the hemisphere, and act on the film.



Both ways of conceiving the theory now have the following in common. There are de Broglie waves, which impinge approximately normally on S and are diffracted at O. Behind S there are spherical waves, which reach the screen P and whose intensity at P is responsible [*massgebend*] for what happens at P.

We can now characterise the two points of view as follows.

1. Conception I. - The de Broglie-Schrödinger waves do not correspond to a single electron, but to a cloud of electrons extended in space. The theory gives no information about individual processes, but only about the ensemble of an infinity of elementary processes.

The waves give the probability or possibilities for a single electron being found at different locations in an ensemble of identical experiments.The waves "guide" the electrons to their positions, as will be seen in the two-slit experiment.

2. Conception II. - The theory claims to be a complete theory of individual processes. Each particle directed towards the screen, as far as can be determined by its position and speed,

The theory is not complete in this sense. It is a theory that makes probabilistic predictions that are confirmed perfectly by the statistics of many experiments.

2 Bacciagaluppi and Valentini, p.440

is described by a packet of de Broglie-Schrödinger waves of short wavelength and small angular width. This wave packet is diffracted and, after diffraction, partly reaches the film P in a state of resolution [*un etat de resolution*].

According to the first, purely statistical, point of view $|\psi|^2$ expresses the probability that there exists at the point considered a particular particle of the cloud, for example at a given point on the screen.

According to the second, $|\psi|^2$ expresses the probability that at a given instant the same particle is present at a given point (for example on the screen). Here, the theory refers to an individual process and claims to describe everything that is governed by laws.

By the same particle, Einstein means that the one individual particle has a possibility of being at more than one (indeed many) locations on the screen. This is so.

The second conception goes further than the first, in the sense that all the information resulting from I results also from the theory by virtue of II, but the converse is not true. It is only by virtue of II that the theory contains the consequence that the conservation laws are valid for the elementary process; it is only from II that the theory can derive the result of the experiment of Geiger and Bothe, and can explain the fact that in the Wilson chamber the droplets stemming from an α-particle are situated very nearly on continuous lines.

But on the other hand, I have objections to make to conception II. The scattered wave directed towards P does not show any privileged direction. 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 in two or several places on the screen. But the interpretation, according to which $|\psi|^2$ expresses the probability that this particle is found at a given point, assumes an entirely peculiar mechanism of action at a distance, which prevents the wave continuously distributed in space from producing an action in two places on the screen.

Einstein is right that the one elementary process has a possibility of action elsewhere, but that could not mean producing an actual second particle. That would contradict conservation laws.

The "mechanism" of action-at-a-distance is simply the disappearance of possibilities elsewhere when a particle is actualized (localized) somewhere

Chapter 23

In my opinion, one can remove this objection only in the following way, that one does not describe the process solely by the Schrödinger wave, but that at the same time one localises the particle during the propagation. I think that Mr de Broglie is right to search in this direction. If one works solely with the Schrödinger waves, interpretation II of $|\psi|^2$ implies to my mind a contradiction with the postulate of relativity.

Here Einstein's "objective reality" pictures a localized particle propagating under the guidance of Schrödinger's wave function. De Broglie's idea will be developed 25 years later by David Bohm, who will add an explicit potential traveling faster than the speedof light, which Einstein will reject.

I should also like to point out briefly two arguments which seem to me to speak against the point of view II. This [view] is essentially tied to a multi-dimensional representation (configuration space), since only this mode of representation makes possible the interpretation of $|\psi|^2$ peculiar to conception II. Now, it seems to me that objections of principle are opposed to this multi-dimensional representation. In this representation, indeed, two configurations of a system that are distinguished only by the permutation of two particles of the same species are represented by two different points (in configuration space), which is not in accord with the new results in statistics. Furthermore, the feature of forces of acting only at small spatial distances finds a less natural expression in configuration space than in the space of three or four dimensions.[3]

The permutation of two identical particles does not produce two different points in multidimensional (configuration space). For example, interchange of the two electrons in the filled first electron shell, $1s^2$, just produces a change of sign for the antisymmetric two-particle wave function, no difference for $|\psi|^2$.

Bohr's reaction to Einstein's presentation has been preserved. He didn't understand a word! He ingenuously claims he does not know what quantum mechanics is. His response is vague and ends with simple platitudes.

MR BOHR. I feel myself in a very difficult position because I don't understand what precisely is the point which Einstein wants to [make]. No doubt it is my fault.

As regards general problem I feel its difficulties. I would put [the] problem in [an]other way. I do not know what quantum mechanics is. I think we are dealing with some mathematical methods which are adequate for description of our experiments Using a rigorous wave theory we are claiming something which

3 Bacciagaluppi and Valentini, pp.440-442

> the theory cannot possibly give. [We must realise] that we are away from that state where we could hope of describing things on classical theories. [I] Understand [the] same view is held by Born and Heisenberg. I think that we actually just try to meet, as in all other theories, some requirements of nature, but [the} difficulty is that we must use words which remind [us] of older theories. The whole foundation for causal spacetime description is taken away by quantum theory, for it is based on [the] assumption of observations without interference. ... excluding interference means exclusion of experiment and the whole meaning of space and time observation ... because we [have] interaction [between object and measuring instrument] and thereby we put us on a quite different standpoint than we thought we could take in classical theories. If we speak of observations we play with a statistical problem There are certain features complementary to the wave pictures (existence of individuals). ...
>
> The saying that spacetime is an abstraction might seem a philosophical triviality but nature reminds us that we are dealing with something of practical interest. Depends on how I consider theory. I may not have understood, but I think the whole thing lies [therein that the] theory is nothing else [but] a tool for meeting our requirements and I think it does. [4]

Twenty-two years later, in Bohr's contribution to the Schilpp volume, he had no better response to Einstein's 1927 concerns. Bohr chose to retell the story of how he and Heisenberg refuted every attempt by Einstein to attack the uncertainty principle.

Although Bohr seems to have missed Einstein's point completely, Heisenberg at least came to understand it. In his 1930 lectures at the University of Chicago, Heisenberg presented a critique of both particle and wave pictures, including a new example of Einstein's nonlocal action-at-a-distance, using reflected and transmitted waves at a mirror surface that Einstein had developed since 1927.

Heisenberg wrote:

> In relation to these considerations, one other idealized experiment (due to Einstein) may be considered. We imagine a photon which is represented by a wave packet built up out of Maxwell waves. It will thus have a certain spatial extension

4 Bacciagaluppi and Valentini, pp, 442-443

> and also a certain range of frequency. By reflection at a semi-transparent mirror, it is possible to decompose it into two parts, a reflected and a transmitted packet. There is then a definite probability for finding the photon either in one part or in the other part of the divided wave packet. After a sufficient time the two parts will be separated by any distance desired; now if an experiment yields the result that the photon is, say, in the reflected part of the packet, then the probability of finding the photon in the other part of the packet immediately becomes zero. The experiment at the position of the reflected packet thus exerts a kind of action (reduction of the wave packet) at the distant point occupied by the transmitted packet, and one sees that this action is propagated with a velocity greater than that of light. However, it is also obvious that this kind of action can never be utilized for the transmission of signals so that it is not in conflict with the postulates of the theory of relativity. [5]

Heisenberg has seen that the point of "Einstein's experiment" was nonlocality, not an attack on his uncertainty principle. We shall see that for the next ten years at least, and in many cases for the rest of Einstein's life, followers of the Copenhagen Interpretation were convinced that Einstein was stuck in the past, primarily interested in denying their work and restoring determinism to physics.

If Heisenberg had read (or reread) Einstein's 1905 article on the light-quantum hypothesis at this time, he would have surely seen that Einstein's light wave had "immediately become zero" everywhere when all its energy is absorbed in the metal and an electron is ejected by the photoelectric effect.

It is only Einstein's mistaken assumption that a light wave consists of some form of energy distributed everywhere (a cloud of electrons) that there is a conflict with special relativity. But there is also a worrisome simultaneity of events in a spacelike separation.

Once we see the wave as just a mathematical abstract function that gives the probability of finding a particle of light, the conflict with relativity disappears. When a particle is found in one place, the probabilities of it being elsewhere simply disappear.

There is nothing happening faster than light in the sense of material or energy coming instantly from all directions to appear at a single point. Nonlocality is just the *appearance* of something moving faster than light speed. There is no "action-at-a-distance."

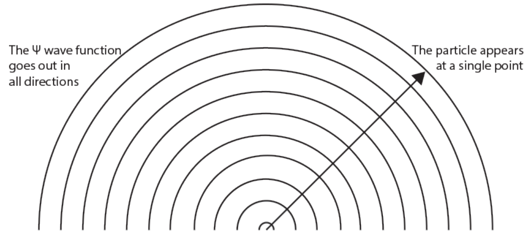
5 Heisenberg, 1930, p.39

If nonlocality is defined as an "action" by one particle on another in a spacelike separation ("at a distance") at speeds faster than light, then nonlocality simply does not exist.

"Collapse" of the Wave Function

As Einstein's blackboard drawing at the Solvay Conference shows us, the wave function propagates like a light wave in all directions, but when the particle appears, it is found at a single point.

Using Einstein's idea of "objective reality," without any interactions that could change the momentum, the particle must have traveled in a straight line from the origin to the point where it is found.



And although we cannot know the actual path taken by any particle, Einstein strongly believed that such paths exist in his "local" and "objective reality."

Einstein tells us the wave represents the probability of finding the particle. (Today it is the absolute square of the complex wave function $|\Psi|^2$ that gives us the probability.) All directions are equally probable until the moment when the particle is found somewhere. At that moment, the probability of its being elsewhere goes to zero.

This has been interpreted as a "collapse." If the wave had been carrying energy in all directions, or matter as Schrödinger thought, energy and matter would indeed have had to "collapse" to the point.

But nothing moves in this picture. It is just that the probability wave disappears when the particle appears. The use of the word "collapse," with its connotation of objects falling together, was an unfortunate choice.

Everything physical that is happening in this picture is happening locally! There is nothing nonlocal going on. But then why was Einstein worried? What did he see in 1927?

He saw events at two points (A and B in his drawing) in a spacelike separation occurring "simultaneously," a concept that his new special theory of relativity says is *impossible* in any absolute sense.

A related nonlocality or "impossible simultaneity" is involved in the mystery of entanglement. See chapters 26 to 29.

The Two-Slit Experiment

Although Einstein's presentation at the fifth Solvay conference was an unprepared modest talk at the blackboard, his debates with Bohr at morning breakfast and evening dinner have become world famous, thanks to Bohr and his associates bragging about how they won every point against Einstein.

It is not obvious that Bohr understood what exactly Einstein waas debating about, as we saw in his remarks after Einstein's talk. Bohr said he was defending against Einstein's attack on the uncertainty principle. And uncertainty did come up, when Einstein tried to defend his "objective reality" view that the electron (or photon) must go through just one slit in the famous two-slit experiment.

Bohr described their debate with another figure.

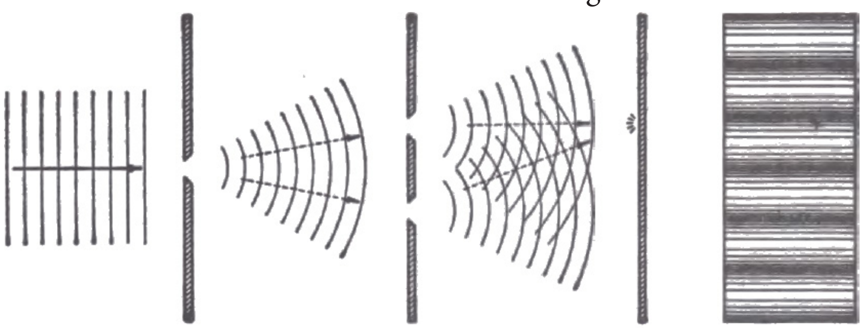


FIG. 3

He said,

> as indicated by the broken arrows, the momentum transferred to the first diaphragm ought to be different if the electron was assumed to pass through the upper or the lower slit in the second diaphragm, Einstein suggested that a control of the momentum transfer would permit a closer analysis of the phenomenon and, in particular, to decide through which of the two slits the electron had passed before arriving at the plate. [6]

Note that Einstein was hoping to establish the path of the particle, Bohr' was touting his idea of *complementarity*, which says we can *either* trace the path of a particle *or* observe interference effects, but not both at the same time.

6 Schilpp, 1949, p.216-217

The Copenhagen Interpretation (see next chapter) maintains that it is impossible to acquire any information about particle paths between measurements. This is true. Without measurements we know nothing. But Copenhagen, especially Heisenberg, insisted that the 'path' only comes into being because we observe it.

This leads to the anthropomorphic view that particles have no definite properties until they are measured. Einstein's view is that just becuse we don't know what is going on from moment to moment, it does not mean that properties are not being conserved. The moon is there even when we are not looking, etc.

We will return to the "one deep mystery" in the two-slit experiment in chapter 33.

Nature's Choice and the Experimenter's Choice

In the same session at Solvay where Einstein raised objections to the Copenhagen Interpretation, Bohr described a discussion about randomness in quantum events and the "free choice" of an experimenter as to what to measure. In the latter case, Heisenberg is correct. The measurement does define the properties seen.

> On that occasion an interesting discussion arose also about how to speak of the appearance of phenomena for which only predictions of statistical character can be made. The question was whether, as to the occurrence of individual effects, we should adopt a terminology proposed by Dirac, that we were concerned with a choice on the part of "nature" or, as suggested by Heisenberg, we should say that we have to do with a choice on the part of the "observer" constructing the measuring instruments and reading their recording. Any such terminology would, however, appear dubious since, on the one hand, it is hardly reasonable to endow nature with volition in the ordinary sense, while, on the other hand, it is certainly not possible for the observer to influence the events which may appear under the conditions he has arranged. To my mind, there is no other alternative than to admit that, in this field of experience, we are dealing with individual phenomena and that our possibilities of handling the measuring instruments allow us only to make a choice between the different complementary types of phenomena we want to study.[7]

7 *ibid.*, p.223