The Einstein Bohr Debate

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Prof. John Norton's Einstein Seminar

March 29, 2023

Overview

1. **1927: Fifth Solvay International Conference**
   Bohr (mis)understands Einstein as attacking quantum indeterminacy (Heisenberg's uncertainty principle): Bohr discusses several thought experiments and shows why indeterminacy is not violated.

2. **1930: Sixth Solvay International Conference**
   Einstein's Box: Einstein introduces a thought experiment that is intended to refute the indeterminacy relation between time and energy. Bohr counters via Einstein's principle of equivalence between gravitational mass and inertial mass.

3. **EPR**

4. **Aftermath:** Einstein clarifies his position: QM is incomplete because it defies local realism. Bell proves that local realism is untenable.

Caveats

1. Bohr: "As regards the account of the conversations I am of course aware that I am relying only on my own memory, just as I am prepared for the possibility that many features of the development of quantum theory, in which Einstein has played so large a part, may appear to himself in a different light." (241)

2. Bohr (1927): "I feel myself in a very difficult position because I don't understand precisely the point that Einstein is trying to make." (Bacciagaluppi & Valentini 2009, 442)

3. Einstein (1927): "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 particular particle is found at a given point, assumes an entirely peculiar mechanism of action at a distance." (Bacciagaluppi & Valentini 2009, 441)

Participants at the conference

De Broglie:
"Einstein, who was hostile towards the pure probability interpretation from the depth of his heart, contradicted with troublesome objections which Bohr rejected with sharply-formulated considerations." (de Broglie 1953, 468)

Participants at the conference

Ehrenfest:
"Bohr towering completely over everybody. At first not understood at all, then step by step defeating everybody. [...] It was delightful for me to be present during the conversations between Bohr and Einstein. Like a game of chess. Einstein all the time with new examples. In a certain sense a sort of Perpetuum Mobile of the second kind to break the UNCERTAINTY RELATION. Bohr from out of philosophical smoke clouds constantly searching for the tools to crush one example after the other. Einstein like a jack-in-the-box, jumping out fresh every morning. Oh that was priceless. But I am almost without reservation pro Bohr and contra Einstein. His attitude to Bohr is now exactly like the attitude of the defenders of absolute simultaneity towards him." (Ehrenfest quoted in Mehra and Rechenberg 251f.)

Physicists side with Bohr.

- "By means of a number of thought experiments, Einstein attempted to demonstrate the incompleteness of the quantum mechanical description and to get around the indeterminism and the uncertainty relation. Each of these arguments was refuted in turn by Bohr." (Schwabl 2007, 391)
- "It is a curious twist of fate that the EPR paradox, which assumed locality in order to prove realism, led finally to the demise of locality and left the issue of realism undecided—the outcome (as Bell put it) Einstein would have liked least. Most physicists today consider that if they can't have local realism, there's not much point in realism at all, and for this reason nonlocal hidden variable theories occupy a rather peripheral niche." (Griffiths 2018, 587)
- "The consensus view of professional physicists has been that Bohr proved victorious in his defense of quantum theory, and definitively established the fundamental probabilistic character of quantum measurement." (Wiki)

Philosophers dislike Bohr.

"But neither Wheeler's nor Bohr's 'philosophical' musings have produced any viable and useful approach to understanding quantum theory." (anonymous reviewer)

Philipp's assessment

- Einstein and relativity:
  Einstein's thought experiments and his arguments may not always be convincing but his intuitions are spot-on and somehow sooner or later he arrives at the right results.

- Einstein and qm: not so much

- John: Einstein very much was a 19th century physicist.

- Bohr was ready to accept indeterminacy, non-locality (?), and operationalism, Einstein was not.

- Einstein consistently believed that any kind of physical theory "should describe 'the real state of the real system'" (Grinbaum 2017).

  This last point is where philosophers of physics typically agree with Einstein. (But by now everybody rejects local realism.)

Some formulas

(1) Light quanta: $E = h\nu$

(2) Canonical commutation relations: $[qp] = qp - pq = i\frac{h}{2\pi} = i\hbar$

(3) Heisenberg's uncertainty principle: $\Delta q \Delta p \approx h$

(4) Indeterminacy relation between energy and time: $\Delta E \Delta t \approx h$

Prelude: Bohr discusses some of the cornerstones of old quantum mechanics: Photoelectric effect, Franck-Hertz experiment, Stern-Gerlach effect, Compton scattering...

DeBroglie 1925: "wave-corpuscle duality was not confined to the properties of radiation, but was equally unavoidable in accounting for the behaviour of material particles." (207)

Einstein was sympathetic to all of this but had some reservations: "Yet, a certain difference in attitude and outlook remained, since, with his mastery for co-ordinating apparently contrasting experience without abandoning continuity and causality, Einstein was perhaps more reluctant to renounce such ideals than someone for whom renunciation in this respect appeared to be the only way open to proceed with the immediate task of co-ordinating the multifarious evidence regarding atomic phenomena, which accumulated from day to day in the exploration of this new field of knowledge." (206)

Heisenberg (1925) marks the beginning of modern quantum mechanics.

(2) Canonical commutation relations: $[qp] = qp - pq = i\frac{h}{2\pi} = i\hbar$

(In classical mechanics, by contrast, all observables commute.)

(3) Heisenberg's uncertainty principle: $\Delta q \Delta p \approx h$

More accurate: $\Delta q \Delta p \geq \frac{\hbar}{2}$

Heisenberg's uncertainty principle is one of the most interesting features of qm and it is the focus of the 1927 Bohr-Einstein debate.

1927: Fifth Solvay International Conference

Einstein introduces thought experiments that are supposed to contradict the uncertainty principle.

Remember:
Bohr (1927): "I feel myself in a very difficult position because I don't understand precisely the point that Einstein is trying to make."
(Bacciagaluppi & Valentini 2009, 442)

Einstein (1927): "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 particular particle is found at a given point, assumes an entirely peculiar mechanism of action at a distance." (Bacciagaluppi & Valentini 2009, 441)

This is to say that Bohr might have misunderstood Einstein's point.
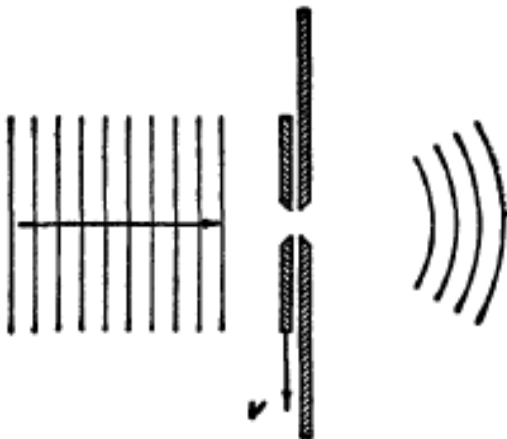
Shutter experiment

FIG. 2b

Indeterminacy between energy and time

Δt... time interval during which the shutter leaves the hole open
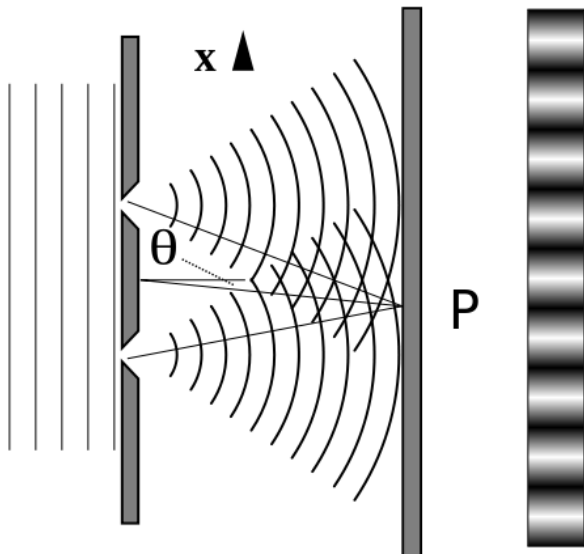
$\nu \approx 1/\Delta t$

From $E = h\nu$ we get

(4) $\Delta E \Delta t \approx h$

Comment: Bohr discusses this prominently on p. 214 but this does not seem to play an important role in what follows.

Ordinary double slit

Ordinary double slit

A source emits single photons/electrons $\rightarrow$ We don't know through which slit they go $\rightarrow$ We observe interference pattern.

A source emits single photons/electrons $\rightarrow$ We include detectors at the slits. $\rightarrow$ We know through which slit they go $\rightarrow$ No interference pattern

Einstein's argument

An experimental setup is possible (at least in principle) such that for each photon I know which slit it has passed but still there will be an interference pattern. Accordingly, quantum indeterminacy is violated. Quantum mechanics is incomplete.
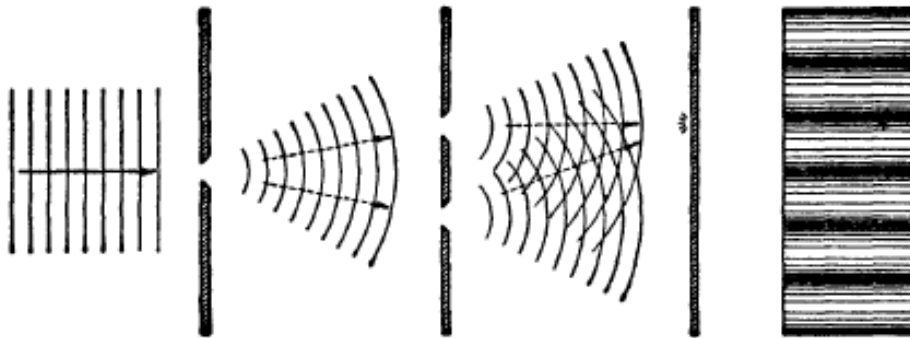
Einstein experiment

FIG. 3

The idea

Conservation of momentum: The sum of momenta of two interacting systems must be conserved. Here the two systems are screen 1 and the particle that passes through slit 1. If after passing slit 1 the particle is deflected toward the upper slit in screen 2, screen 1 will experience a recoil in the opposite direction (downwards), and vice versa. Thus, by measuring these infinitesimal recoils of screen 1, I know through which slit the particles pass in screen 2, and still there will be an interference pattern.

Bohr's response

Bohr: No interference pattern will appear.

"A closer examination showed, however, that the suggested control of the momentum transfer would involve a latitude in the knowledge of the position of the diaphragm which would exclude the appearance of the interference phenomena in question." (217)

"This point is of great logical consequence, since it is only the circumstance that we are presented with a choice of either tracing the path of a particle or observing interference effects, which allows us to escape from the paradoxical necessity of concluding that the behaviour of an electron or a photon should depend on the presence of a slit in the diaphragm through which it could be proved not to pass. We have here to do with a typical example of how the complementary phenomena appear under mutually exclusive experimental arrangements." (217f.)

Bohr's move

Here Bohr makes the crucial move of applying the uncertainty relation between position and momentum to screen 1 (a macroscopic object).

By determining the momentum of screen 1, I affect its position.

The position of screen 1 is affected such that the interference pattern disappears.

Question: Since Copenhagen people typically make a strict distinction between macroscopic measuring devices and quantum objects, Bohr's move might be problematic.

The movable slit
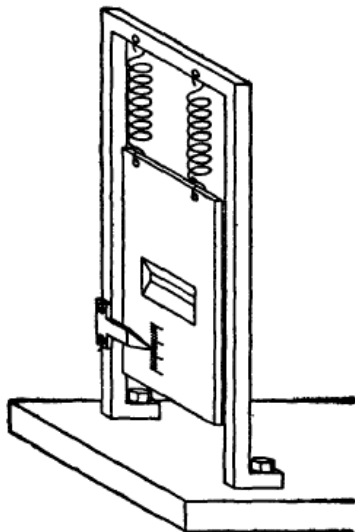
When a particle passes through a slit of width d, the uncertainty regarding the momentum of the particle approximates $\frac{h}{d}$.

When I precisely measure the momentum of the recoil of the screen, I can determine the momentum of the particle exactly.

$\rightarrow$ The uncertainty principle is refuted.

Response: For this to work, I must know the momentum of the screen precisley before the particle passes the slit.

Determining the momentum of the screen to accuracy Δp leads to an uncertainty in the position of the screen approximating $\frac{h}{\Delta p}$

This affects the position of the slit. Thus, if the recoil of the screen is determined, I lose precise knowledge of the position of the particle.

1930: Sixth Solvay International Conference

Einstein challenged $\Delta E \Delta t \approx h$ by exploiting $E = mc^2$.

The argument

We have a box that contains radiation (photons). The box has a hole that can be opened/closed by a shutter via a clock-work within the box. At a moment t that we control (and thus know precisely) we open the box and a photon escapes. We weigh the box before and after the photon escaped. We know the difference is mass precisely and since $E = mc^2$ we know precisely the energy of the photon when it escaped.
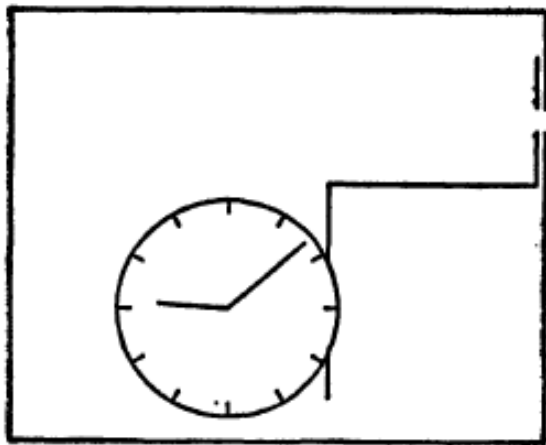
Einstein's box
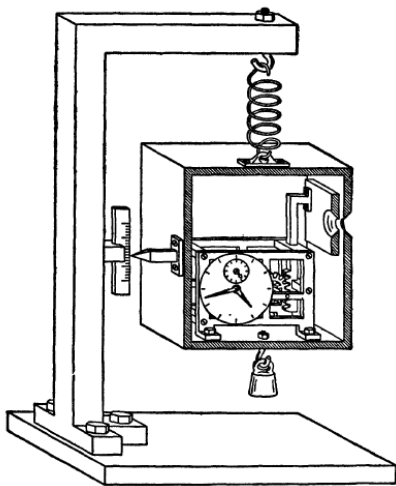

FIG. 7

Einstein's box

Fig. 8

Bohr's response

Bohr considered this argument/thought experiment "a serious challenge" (226). In fact, Bohr, at first, did not have a response. On the next conference day, however, he convinced the community that the problem can be solved by recourse to general relativity, exploiting the principle of equivalence between gravitational mass and inertial mass and the phenomenon of gravitational redshift (aka Einstein shift).

Bohr's response

The weighing of the box is performed with accuracy Δm by adding a suitable load (with mass m) such that the box is back in its zero position on the scale. The position on the the scale is read off by the pointer with accuracy Δq.

Determining the position of the box will involve a minimal latitude Δp such that $\Delta q \Delta p \approx h$.

The latitude Δp must be smaller than the total momentum $T \cdot g \cdot \Delta m$.
T... the time the whole balancing procedure requires
g... gravitational field strength (9.8 N/kg)

Thus,

$$\Delta p \approx \frac{h}{\Delta q} < T \cdot g \cdot \Delta m$$

Bohr's response

Bohr now introduces the redshift formula (a consequence of GR):

$$\frac{\Delta T}{T} = \frac{1}{c^2} g \Delta q$$

Together with our above result

$$\Delta p \approx \frac{h}{\Delta q} < T \cdot g \cdot \Delta m$$

this yields:

$$\Delta T > \frac{h}{c^2 \Delta m}$$

Bohr's response

Our result

$$\Delta T > \frac{h}{c^2 \Delta m}$$

together with

$$E = mc^2$$

yields

$$\Delta T \cdot \Delta E > h$$

qed

EPR: Bohm version

A neutral pion π^0 decays into an electron and a positron

$$\pi^0 \rightarrow e^- + e^+$$

We assume the electron and the positron are flying off in opposite directions. Importantly, the pion is a spin-0 particle. Electrons and positrons are spin-1/2 particles. Conservation of angular momentum requires that they have opposite spins. More precisley, the entangled system is described by the following singlet state:

$$\frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$$
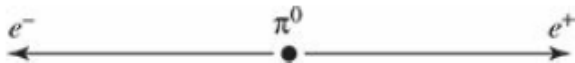
EPR: Bohm version

The electron flies off to Bob, the positron to Alice. Bob and Alice are far away. Bob conducts a spin measurement, the electron is in the state spin-up. Bob knows instantly that the positron is in the state spin-down.

Realists ala Einstein: It is not the measurement that determines the value, the value pre-exists the measurement.

This is because (assuming locality) Bob's measurement on the electron cannot influence the positron.

However, if measurements reveal pre-existing values, then qm is not complete. (Because qm only allows probabilistic predictions.)

EPR: qm is incomplete.

EPR: Bohr's analysis

1935: "Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?"

Criterion of EPR: "If, without in any way disturbing a system, we can predict with certainty (i.e., with probability equal to unity) the value of a physical quantity, then there exists an element of physical reality corresponding to this physical quantity."

Exploiting entanglement EPR concludes: "According to their criterion, the authors therefore conclude that quantum mechanics does not 'provide a complete description of the physical reality,' and they express their belief that it should be possible to develop a more adequate account of the phenomena." (232)

"Due to the lucidity and apparently incontestable character of the argument, the paper of Einstein, Podolsky and Rosen created a stir among physicists and has played a large role in general philosophical discussion. Certainly the issue is of a very subtle character and suited to emphasize how far, in quantum theory, we are beyond the reach of pictorial visualization." (232)

"It will be seen, however, that we are here dealing with problems of just the same kind as those raised by Einstein in previous discussions, and, in an article which appeared a few months later, I tried to show that from the point of view of complementarity the apparent inconsistencies were completely removed." (232)

Bohr vs classical ideal of causality and physical reality

"Indeed the *finite interaction between object and measuring agencies* conditioned by the very existence of the quantum of action entails–because of the impossibility of controlling the reaction of the object on the measuring instruments, if these are to serve their purpose-the necessity of a final renunciation of the classical ideal of causality and a radical revision of our attitude towards the problem of physical reality." (232f.)

Bohr vs the EPR criterion of physical reality

"From our point of view we now see that the wording of the abovementioned criterion of physical reality proposed by Einstein, Podolsky, and Rosen contains an *ambiguity* as regards the meaning of the expression '*without in any way disturbing a system*.' Of course there is in a case like that just considered no question of a mechanical disturbance of the system under investigation during the last critical stage of the measuring procedure. But even at this stage there is essentially the question of *an influence on the very conditions which define the possible types of predictions regarding the future behaviour of the system*. Since these conditions constitute an inherent element of the description of any phenomenon to which the term 'physical reality' can be properly attached, we see that the argumentation of the mentioned authors does not justify their conclusion that quantum-mechanical description is essentially incomplete." (234)

"which forces us to an attitude towards the problem of explanation recalling ancient wisdom, that when searching for harmony in life one must never forget that in the drama of existence we are ourselves both actors and spectators." (236)

Einstein on physical reality

"Physics is an attempt conceptually to grasp reality as it is thought independently of its being observed. In this sense one speaks of 'physical reality.'" (Notes, 81)

Einstein on measurements revealing pre-existing values

"The individual system (before the measurement) has a definite value of q (i.e., p) for all variables of the system, and more specifically, that value which is determined by a measurement of this variable. Proceeding from this conception, he will state: The Ψ-function is no exhaustive description of the real situation of the system but an incomplete description; it expresses only what we know on the basis of former measurements concerning the system." (Notes, 83)

Einstein on locality

"But on one supposition we should, in my opinion, absolutely hold fast: the real factual situation of the system S2 is independent of what is done with the system S1, which is spatially separated from the former." (Notes, 85)

"Für die relative Unabhängigkeit räumlich distanter Dinge (A und B) ist die Idee characteristisch: äussere Beeinflussung von A hat keinen *unmittelbaren* Einfluss auf B; dies ist als 'Prinzip der Nahewirkung' bekannt, das nur in der Feld-Theorie konsequent angewendet ist." (Dialectica, 321f.)

Einstein on the EPR paradox

"By this way of looking at the matter it becomes evident that the paradox forces us to relinquish one of the following two assertions:

(1) the description by means of the Ψ-function is *complete*

(2) the real states of spatially separated objects are independent of each other.

On the other hand, it is possible to adhere to (2), if one regards the Ψ-function as the description of a (statistical) ensemble of systems (and therefore relinquishes (1))." (Reply, 682)

Einstein's ensemble interpretation

"One arrives at very implausible theoretical conceptions, if one attempts to maintain the thesis that the statistical quantum theory is in principle capable of producing a complete description of an individual physical system. On the other hand, those difficulties of theoretical interpretation disappear, if one views the quantum-mechanical description as the description of ensembles of systems. [...] I am convinced that everyone who will take the trouble to carry through such reflections conscientiously will find himself finally driven to this interpretation of quantum- theoretical description (the Ψ-function is to be understood as the description not of a single system but of an ensemble of systems)." (Reply, 671)

Einstein accepting the uncertainty principle

"They are apparently all of the opinion that Heisenberg's indeterminacy-relation (the correctness of which is, from my own point of view, rightfully regarded as finally demonstrated) [...]" (Reply, 666)

Einstein vs. positivism

"What I dislike in this kind of argumentation is the basic positivistic attitude, which from my point of view is untenable, and which seems to me to come to the same thing as Berkeley's principle, esse est percipi." (Reply, 669)

Consider here Ehrenfest (as remembered by Bohr):

"I remember also how at the peak of the discussion Ehrenfest, in his affectionate manner of teasing his friends, jokingly hinted at the apparent similarity between Einstein's attitude and that of the opponents of relativity theory" (218)

The accusation

"The above mentioned essays by Bohr and Pauli contain a historical appreciation of my efforts in the area of physical statistics and quanta and, in addition, an accusation which is brought forward in the friendliest of fashion. In briefest formulation this latter runs as follows: 'Rigid adherence to classical theory.'" (Reply, 675)

Thank You!

What Einstein really said in 1927
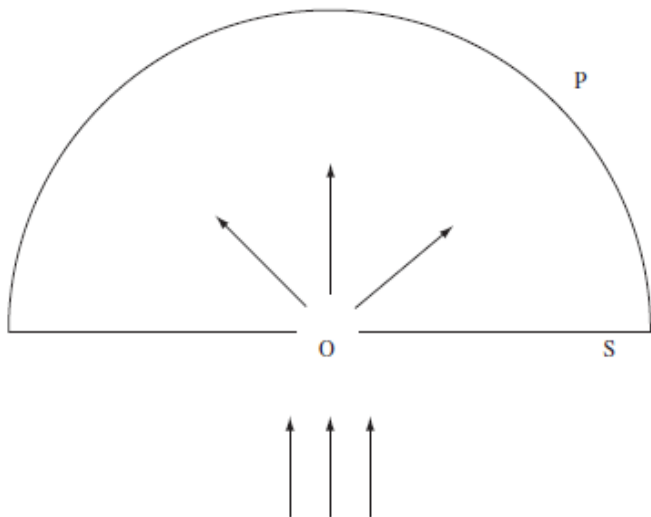
What Einstein really said in 1927

"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 quoted in Bacciagaluppi & Valentini 2009, 441)

Accordingly, Einstein may have been the first to argue that qm leads to "spooky action at a distance" - eight years before the EPR paper.

But is Einstein's argument good?

One might say he simply misunderstands what probability means: "For example, it might be thought that, since we are talking about a probability distribution for just one particle, it is a matter of pure logic that only one detection can occur." (Bacciagaluppi & Valentini 2009, 176; see Shimony 2005)

However, Bacciagaluppi & Valentini 2009 and Hardy 1995 argue that Einstein has a point.

Einstein on EPR

It is well-known that Einstein was unhappy with the EPR paper (which was written by Podolsky). Why?

- The EPR paper does not mention action at a distance, nonlocality, Fernwirkung, etc.
- Instead, EPR focuses on the uncertainty principle - Einstein in a letter to Schrödinger: "ist mir wurst" - "I couldn't care less."

Bohr's conception of complementarity in the context of EPR

"The later, consistent concept of complementarity, is part of a completely different picture. Bohr, in the EPR rejoinder, endorses the indefinability thesis in its strongest form: an operationally ill-defined property cannot meaningfully be said to pertain to the object; and this meaninglessness implies that the object really does not have this property." (Held 1995, 891)

"This, however, is a position which is incompatible with the earlier realism. It is, in effect, the conviction that only the variables we actually decide to specify by choosing an experiment have determinate values. What is real is only what we actually observe in a specified arrangement. This is a non-realist position which differs radically from the earlier conception. Bohr well realizes that his new interpretation constitutes 'a radical revision of our attitude towards the problem of physical reality', and it constitutes, in fact, a 'radical revision' of his own realist attitude." (Held 1995, 892)

Bell on Bohr

"Moreover, in my opinion, all students should be introduced to it [Bohmian mechanics], for it encourages flexibility and precsion of thought. In particular, it illustrates very explictly Bohr's insight that the result of a 'measurement' does not in general reveal some preexisting property of thr 'system', but is a product of both 'system' and 'apparatus." (Bell 1987, xiii f.)