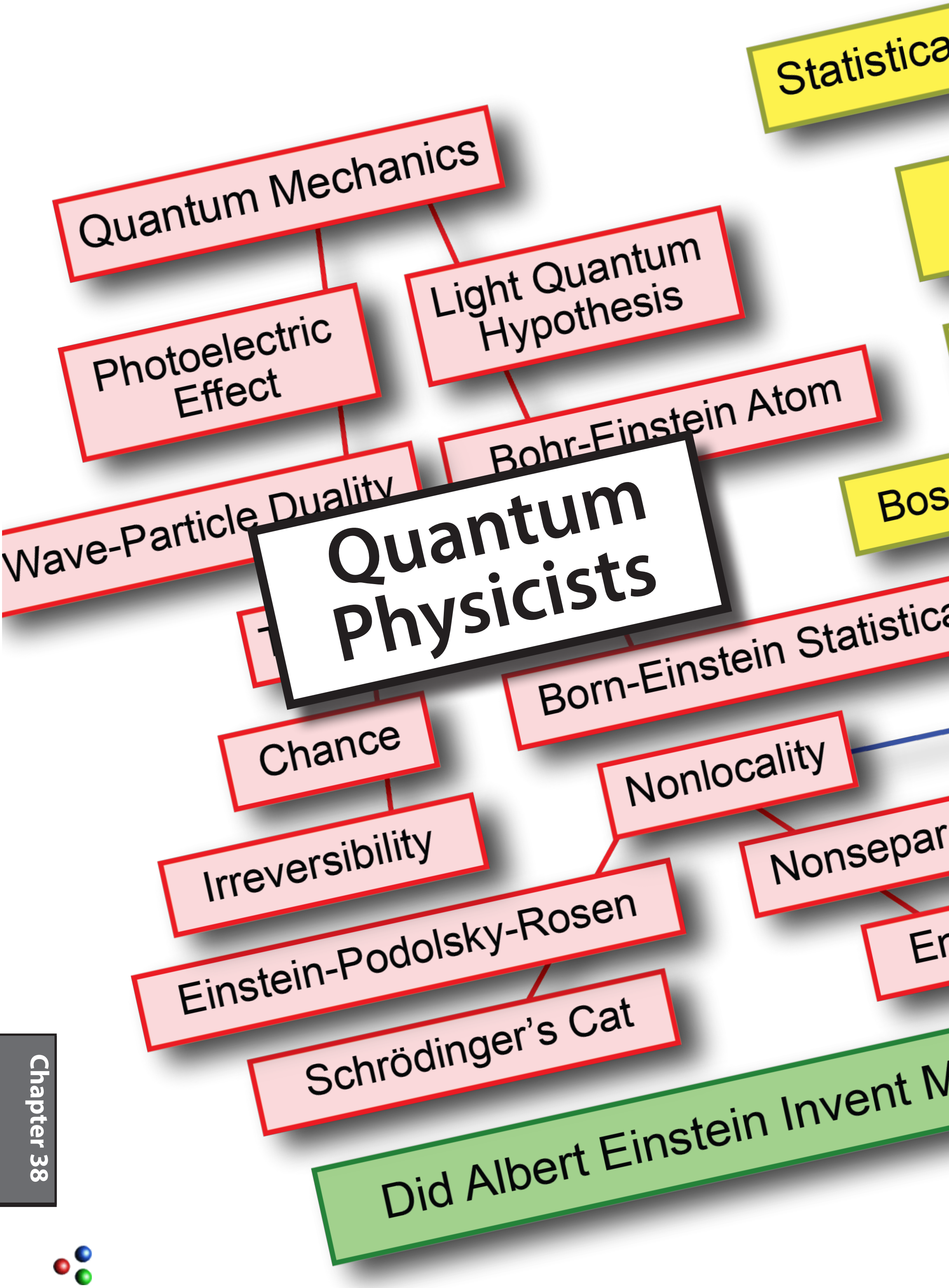
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The Quantum Physicists

John Stewart Bell

In 1964 John Bell showed how the 1935 “thought experiments” of Einstein, Podolsky, and Rosen (EPR) could be made into real experiments. He put limits on local “hidden variables” that might restore a deterministic physics in the form of what he called an “inequality,” the violation of which would confirm standard quantum mechanics.

Some thinkers, mostly philosophers of science rather than working quantum physicists, think that Bell’s work has restored the determinism in physics that Einstein had wanted and that Bell recovered the “local elements of reality” that Einstein hoped for.

But Bell himself came to the conclusion that local “hidden variables” will never be found that give the same results as quantum mechanics. This has come to be known as Bell’s Theorem.

All theories that reproduce the predictions of quantum mechanics will be “nonlocal,” Bell concluded. Nonlocality is an element of physical reality and it has produced some remarkable new applications of quantum physics, including quantum cryptography and quantum computing.

Bell based his idea of real experiments on the 1952 work of David Bohm. Bohm proposed an improvement on the original EPR experiment (which measured position and momentum). Bohm’s reformulation of quantum mechanics postulates (undetectable) deterministic positions and trajectories for atomic particles, where the instantaneous collapse happens in a new “quantum potential” field that can move faster than light speed. But it is still a “nonlocal” theory.

So Bohm (and Bell) believed that nonlocal “hidden variables” might exist, and that some form of information could come into existence at remote “space-like separations” at speeds faster then light, if not instantaneously.

The original EPR paper was based on a question of Einstein's about two electrons fired in opposite directions from a central source with equal velocities. Einstein imagined them starting from a distance at t0 and approaching one another with high velocities, then for a short time interval from t1 to t1 + Δt in contact with one another, where experimental measurements could be made on the momenta, after which they separate. Now at a later time t2 it would be possible to make a measurement of electron 1's position and would therefore know the position of electron 2 without measuring it explicitly.

Einstein used the conservation of linear momentum to "know" the symmetric position of the other electron. This knowledge implies information about the remote electron that is available instantly. Einstein called this "spooky action-at-a-distance."

Bohm's 1952 thought experiment used two electrons that are prepared in an initial state of known total spin. If one electron spin is 1/2 in the up direction and the other is spin down or -1/2, the total spin is zero. The underlying physical law of importance is still a conservation law, in this case the conservation of angular momentum.

Since Bell's original work, many other physicists have defined other "Bell inequalities" and developed increasingly sophisticated experiments to test them. Most recent tests have used oppositely polarized photons coming from a central source. It is the total photon spin of zero that is conserved.

In his 1964 paper "On the Einstein-Podolsky-Rosen Paradox," Bell made the case for nonlocality.

> The paradox of Einstein, Podolsky and Rosen was advanced as a argument that quantum mechanics could not be a complete theory but should be supplemented by additional variables. These additional variables were to restore to the theory causality and locality. In this note that idea will be formulated mathematically and shown to be incompatible with the statistical predictions of quantum mechanics. It is the requirement of locality, or more precisely that the result of a measurement on one system be unaffected by operations on a distant sys-

> tem with which it has interacted in the past, that creates the essential difficulty. There have been attempts to show that even without such a separability or locality requirement no 'hidden variable' interpretation of quantum mechanics is possible. These attempts have been examined [by Bell] elsewhere and found wanting. Moreover, a hidden variable interpretation of elementary quantum theory has been explicitly constructed [by Bohm]. That particular interpretation has indeed a gross non-local structure. This is characteristic, according to the result to be proved here, of any such theory which reproduces exactly the quantum mechanical predictions.
>
> With the example advocated by Bohm and Aharonov, the EPR argument is the following. Consider a pair of spin one-half particles formed somehow in the singlet spin state and moving freely in opposite directions. Measurements can be made, say by Stern-Gerlach magnets, on selected components of the spins σ_1 and σ_2. If measurement of the component $\sigma_1 \bullet a$, where a is some unit vector, yields the value + 1 then, according to quantum mechanics, measurement of $\sigma_2 \bullet a$ must yield the value - 1 and vice versa. Now we make the hypothesis, and it seems one at least worth considering, that if the two measurements are made at places remote from one another the orientation of one magnet does not influence the result obtained with the other.
>
> Since we can predict in advance the result of measuring any chosen component of σ_2, by previously measuring the same component of σ_1, it follows that the result of any such measurement must actually be predetermined. Since the initial quantum mechanical wave function does not determine the result of an individual measurement, this predetermination implies the possibility of a more complete specification of the state.[1]

"Pre-determination" is too strong a term. The previous measurement just "determines" the later measurement.

Superdeterminism

During a mid-1980's interview by BBC Radio 3 organized by P. C. W. Davies and J. R. Brown, Bell proposed the idea of a "super-

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[1] "On the Einstein-Podolsky-Rosen Paradox," *Physics*, 1.3, p.195.

determinism" that could explain the correlation of results in two-particle experiments without the need for faster-than-light signaling. The two experiments need only have been pre-determined by causes reaching both experiments from an earlier time.

I was going to ask whether it is still possible to maintain, in the light of experimental experience, the idea of a deterministic universe?

> [Bell] You know, one of the ways of understanding this business is to say that the world is super-deterministic. That not only is inanimate nature deterministic, but we, the experimenters who imagine we can choose to do one experiment rather than another, are also determined. If so, the difficulty which this experimental result creates disappears.
>
> [Davies] Free will is an illusion - that gets us out of the crisis, does it?
>
> [Bell] That's correct. In the analysis it is assumed that free will is genuine, and as a result of that one finds that the intervention of the experimenter at one point has to have consequences at a remote point, in a way that influences restricted by the finite velocity of light would not permit. If the experimenter is not free to make this intervention, if that also is determined in advance, the difficulty disappears.[2]

Bell's superdeterminism would deny the important "free choice" of the experimenter (originally suggested by NIELS BOHR and WERNER HEISENBERG) and later explored by JOHN CONWAY and SIMON KOCHEN. Conway and Kochen claim that the experimenters' free choice requires that atoms must have free will, something they call their Free Will Theorem.

Following John Bell's idea, Nicholas Gisin and Antoine Suarez argue that something might be coming from "*outside space and time*" to correlate results in their own experimental tests of Bell's Theorem. ROGER PENROSE and STUART HAMEROFF have proposed causes coming "backward in time" to achieve the perfect EPR correlations, as has philosopher HUW PRICE.

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[2] *The Ghost in the Atom*, P.C.W. Davies and J. Brown, ch.3, p.47

A Preferred or "Special" Frame?

A little later in the same BBC interview, Bell suggested that a preferred frame of reference might help to explain nonlocality and entanglement.

> [Davies] Bell's inequality is, as I understand it, rooted in two assumptions: the first is what we might call objective reality - the reality of the external world, independent of our observations; the second is locality, or non-separability, or no faster-than-light signalling. Now, Aspect's experiment appears to indicate that one of these two has to go. Which of the two would you like to hang on to?
>
> [Bell] Well, you see, I don't really know. For me it's not something where I have a solution to sell! For me it's a dilemma. I think it's a deep dilemma, and the resolution of it will not be trivial; it will require a substantial change in the way we look at things. But I would say that the cheapest resolution is something like going back to relativity as it was before Einstein, when people like Lorentz and Poincare thought that there was an aether - a preferred frame of reference - but that our measuring instruments were distorted by motion in such a way that we could not detect motion through the aether. Now, in that way you can imagine that there is a preferred frame of reference, and in this preferred frame of reference things do go faster than light. But then in other frames of reference when they seem to go not only faster than light but backwards in time, that is an optical illusion.[3]

The standard explanation of entangled particles usually begins with an observer A, often called Alice, and a distant observer B, known as Bob. Between them is a source of two entangled particles. The two-particle wave function describing the indistinguishable particles cannot be separated into a product of two single-particle wave functions.

The problem of faster-than-light signaling arises when Alice is said to measure particle A and then puzzle over how Bob's (later)

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[3] *ibid.*, pp.48-49

measurements of particle B can be perfectly correlated, when there is not enough time for any “influence” to travel from A to B.

Now as John Bell knew very well, there are frames of reference moving with respect to the laboratory frame of the two observers in which the time order of the events can be reversed. In some moving frames Alice measures first, but in others Bob measures first.

Back in the 1960’s, C. W. Rietdijk and Hilary Putnam argued that physical determinism could be proved to be true by considering the experiments and observers A and B in a “spacelike” separation and moving at high speed with respect to one another. Roger Penrose developed a similar argument in his book The Emperor’s New Mind. It is called the Andromeda Paradox.

If there is a preferred frame of reference, surely it is the one in which the origin of the two entangled particles is at rest. Assuming that Alice and Bob are also at rest in this preferred frame and equidistant from the origin, we arrive at the simple picture in which any measurement that causes the two-particle wave function to collapse makes both particles appear simultaneously at determinate places (just what is needed to conserve energy, momentum, angular momentum, and spin).

The EPR “paradox” is the result of a naive non-relativistic description of events. Although the two events (measurements of particles A and B) are simultaneous in our preferred frame, the space-like separation of the events means that from Alice’s point of view, any knowledge of event B is out in her future. Bob likewise sees Alice’s event A out in his future. These both cannot be true. Yet they are both true (and in some sense neither is true). Thus the paradox.

Instead of just one particle making an appearance in the collapse of a single-particle wave function, in the two-particle case, when either particle is measured, we know instantly those properties of the other particle that satisfy the conservation laws, including its location equidistant from, but on the opposite side of, the source, and its other properties such as spin.

Let's look at an animation of the two-particle wave function expanding from the origin and what happens when, say, Alice makes a measurement.

You can compare the collapse of the two-particle probability amplitude above to the single-particle collapse here.

We can also ask what happens if Bob is not at the same distance from the origin as Alice. When Alice detects the particle (with say spin up), at that instant the other particle also becomes determinate (with spin down) at the same distance on the other side of the origin. It now continues, in that determinate state, to Bob's measuring apparatus.

Recall Bell's description of the process (quoted above), with its mistaken bias toward assuming *first one measurement* is made, and the *other measurement* is made later.

If measurement of the component σ1 • a, where a is some unit vector, yields the value + 1 then, according to quantum mechanics, measurement of σ2 • a must yield the value — 1 and vice versa... Since we can predict in advance the result of measuring any chosen component of σ2, by previously measuring the same component of σ1, it follows that the result of any such measurement must actually be predetermined.

Since the collapse of the two-particle wave function is indeterminate, nothing is pre-determined, although σ2 is indeed determined once σ1 is measured.

In 1987, Bell contributed an article to a centenary volume for Erwin Schrödinger entitled *Are There Quantum Jumps?* Schrödinger denied such jumps or any collapses of the wave function. Bell's title was inspired by two articles with the same title by Schrödinger in 1952 (Part I, Part II).

Just a year before Bell's death in 1990, physicists assembled for a conference on 62 Years of Uncertainty (referring to Werner Heisenberg's 1927 principle of indeterminacy).

John Bell's contribution to the conference was an article called "*Against Measurement*." In it he attacked Max Born's statistical interpretation of quantum mechanics. And he praised the new ideas of GianCarlo Ghirardi and his colleagues, Alberto Rimini and Tomaso Weber:

> In the beginning, Schrödinger tried to interpret his wavefunction as giving somehow the density of the stuff of which the world is made. He tried to think of an electron as represented by a wavepacket — a wave-function appreciably different from zero only over a small region in space. The extension of that region he thought of as the actual size of the electron — his electron was a bit fuzzy. At first he thought that small wavepackets, evolving according to the Schrödinger equation, would remain small. But that was wrong. Wavepackets diffuse, and with the passage of time become indefinitely extended, according to the Schrödinger equation. But however far the wavefunction has extended, the reaction of a detector to an electron remains spotty. So Schrödinger's 'realistic' interpretation of his wavefunction did not survive.
>
> Then came the Born interpretation. The wavefunction gives not the density of stuff, but gives rather (on squaring its modulus) the density of probability. Probability of what exactly? Not of the electron being there, but of the electron being found there, if its position is 'measured.'
>
> Why this aversion to 'being' and insistence on 'finding'? The founding fathers were unable to form a clear picture of things on the remote atomic scale. They became very aware of the intervening apparatus, and of the need for a 'classical' base from which to intervene on the quantum system. And so the shifty split.
>
> The kinematics of the world, in this orthodox picture, is given a wavefunction (maybe more than one?) for the quantum part, and classical variables — variables which have values — for the classical part: (Ψ(t, q, ...), X(t),...). The Xs are somehow macroscopic. This is not spelled out very explicitly. The dynamics is not very precisely formulated either. It includes a Schrödinger equation for the quantum part, and some sort of classical mechanics for the classical part, and 'collapse' recipes for their interaction.
>
> It seems to me that the only hope of precision with the dual (Ψ, x) kinematics is to omit completely the shifty split, and let both Ψ and x refer to the world as a whole. Then the xs must not be confined to some vague macroscopic scale, but must extend to

all scales. In the picture of de Broglie and Bohm, every particle is attributed a position x(t). Then instrument pointers — assemblies of particles have positions, and experiments have results. The dynamics is given by the world Schrödinger equation plus precise 'guiding' equations prescribing how the x(t)s move under the influence of Ψ. Particles are not attributed angular momenta, energies, etc., but only positions as functions of time. Peculiar 'measurement' results for angular momenta, energies, and so on, emerge as pointer positions in appropriate experimental setups. Considerations of KG [Kurt Gottfried] and vK [N. G. van Kampen] type, on the absence (FAPP) [For All Practical Purposes] of macroscopic interference, take their place here, and an important one, is showing how usually we do not have (FAPP) to pay attention to the whole world, but only to some subsystem and can simplify the wave-function... FAPP.

The Born-type kinematics (Ψ, X) has a duality that the original 'density of stuff' picture of Schrödinger did not. The position of the particle there was just a feature of the wavepacket, not something in addition. The Landau—Lifshitz approach can be seen as maintaining this simple non-dual kinematics, but with the wavefunction compact on a macroscopic rather than microscopic scale. We know, they seem to say, that macroscopic pointers have definite positions. And we think there is nothing but the wavefunction. So the wavefunction must be narrow as regards macroscopic variables. The Schrödinger equation does not preserve such narrowness (as Schrödinger himself dramatised with his cat). So there must be some kind of 'collapse' going on in addition, to enforce macroscopic narrowness. In the same way, if we had modified Schrödinger's evolution somehow we might have prevented the spreading of his wavepacket electrons. But actually the idea that an electron in a ground-state hydrogen atom is as big as the atom (which is then perfectly spherical) is perfectly tolerable — and maybe even attractive. The idea that a macroscopic pointer can point simultaneously in different directions, or that a cat can have several of its nine lives at the same time, is harder to swallow. And if we have no extra variables X to express macroscopic definiteness, the wavefunction itself must be narrow in macroscopic directions in the configuration space. This the Landau—Lifshitz collapse brings about. It does so in a

> rather vague way, at rather vaguely specified times.
>
> In the Ghirardi—Rimini—Weber scheme (see the contributions of Ghirardi, Rimini, Weber, Pearle, Gisin and Diosi presented at *62 Years of Uncertainty*, Erice, Italy, 5-14 August 1989) this vagueness is replaced by mathematical precision. The Schrödinger wavefunction even for a single particle, is supposed to be unstable, with a prescribed mean life per particle, against spontaneous collapse of a prescribed form. The lifetime and collapsed extension are such that departures of the Schrödinger equation show up very rarely and very weakly in few-particle systems. But in macroscopic systems, as a consequence of the prescribed equations, pointers very rapidly point, and cats are very quickly killed or spared.
>
> The orthodox approaches, whether the authors think they have made derivations or assumptions, are just fine FAPP — when used with the good taste and discretion picked up from exposure to good examples. At least two roads are open from there towards a precise theory, it seems to me. Both eliminate the shifty split. The de Broglie—Bohm-type theories retain, exactly, the linear wave equation, and so necessarily add complementary variables to express the non-waviness of the world on the macroscopic scale. The GRW-type theories have nothing in the kinematics but the wavefunction. It gives the density (in a multidimensional configuration space!) of stuff. To account for the narrowness of that stuff in macroscopic dimensions, the linear Schrödinger equation has to be modified, in this GRW picture by a mathematically prescribed spontaneous collapse mechanism.
>
> The big question, in my opinion, is which, if either, of these two precise pictures can be redeveloped in a Lorentz invariant way.
>
> ...All historical experience confirms that men might not achieve the possible if they had not, time and time again, reached out for the impossible. (Max Weber)
>
> ...we do not know where we are stupid until we stick our necks out. (R. P. Feynman)[4]

On the 22nd of January 1990, Bell gave a talk explaining his theorem at CERN in Geneva.

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[4] "Against Measurement," in *62 Years of Uncertainty*,

> It just is a fact that quantum mechanical predictions and experiments, in so far as they have been done, do not agree with [my] inequality. And that's just a brutal fact of nature...that's just the fact of the situation; the Einstein program fails, that's too bad for Einstein, but should we worry about that?
>
> I cannot say that action at a distance is required in physics. But I can say that you cannot get away with no action at a distance. You cannot separate off what happens in one place and what happens in another. Somehow they have to be described and explained jointly.
>
> Bell gives three reasons for not worrying.
>
> Nonlocality is unavoidable, even if it looks like "action at a distance."
>
> Because the events are in a spacelike separation, either one can occur before the other in some relativistic frame, so no "causal" connection can exist between them.
>
> No faster-than-light signals can be sent using entanglement and nonlocality.

He concluded:

> So as a solution of this situation, I think we cannot just say 'Oh oh, nature is not like that.' I think you must find a picture in which perfect correlations are natural, without implying determinism, because that leads you back to nonlocality. And also in this independence as far as our individual experiences goes, our independence of the rest of the world is also natural. So the connections have to be very subtle, and I have told you all that I know about them. Thank you.

As Bell may have seen, it is therefore not a "measurement" by a conscious observer that is needed to "collapse" wave functions. It is the irreversible interaction of the quantum system with another system, whether quantum or approximately classical. The interaction must be one that changes the information about the system. And that means a local entropy decrease and overall entropy increase to make the information stable enough to be observed by an experimenter and therefore be a measurement.

David Bohm

Although David Bohm is perhaps best known for his work exploring the possibilities of “hidden variables” that would eliminate quantum indeterminacy and restore complete determinism to physics, he was a first-class quantum physicist who understood the quantum theory better than most working physicists who never questioned its formalism.

Bohm was pressed to develop hidden variables by his mentor Einstein, who thought Bohm was young enough and smart enough to produce the mathematical arguments that the older generation of “determinist” physicists like Erwin Schrödinger, Max Planck, and others had not been able to accomplish.

Bohm inspired John Bell to develop tests or “inequalities” that would need to be satisfied by hidden variables. To this date, every test has violated the inequalities and shown that the quantum theory cannot be replaced by one with hidden variables.

The Measurement Process

David Bohm was particularly clear on the process of measurement. He said it involved macroscopic irreversibility, which was a sign and a consequence of treating the measuring apparatus as a macroscopic system that could not itself be treated quantum mechanically. The macroscopic system could, in principle, be treated quantum mechanically, but Bohm said its many degrees of internal freedom would destroy any interference effects. This is the modern theory of quantum decoherence.

Bohm’s view is consistent with the information-philosophy solution to the measurement problem. A measurement has only been made when new information has come into the world and adequate entropy has been carried away to insure the stability of the information long enough for it to be observed by the “conscious” observer.

In his 1950 textbook *Quantum Theory*, Bohm discusses measurement in chapter 22, section 12.

> 12. Irreversibility of Process of Measurement and Its Fundamental Role in Quantum Theory.
>
> From the previous work it follows that a measurement process is

irreversible in the sense that, after it has occurred, re-establishment of definite phase relations between the eigenfunctions of the measured variable is overwhelmingly unlikely. This irreversibility greatly resembles that which appears in thermodynamic processes, where a decrease of entropy is also an overwhelmingly unlikely possibility.*

Because the irreversible behavior of the measuring apparatus is essential for the destruction of definite phase relations and because, in turn, the destruction of definite phase relation's is essential for the consistency of the quantum theory as a whole, it follows that thermodynamic irreversibility enters into the quantum theory in an integral way. This is in remarkable contrast to classical theory, where the concept of thermodynamic irreversibility plays no fundamental role in the basic sciences of mechanics and electrodynamics. Thus, whereas in classical theory fundamental variables (such as position or momentum of an elementary particle) are regarded as having definite values independently of whether the measuring apparatus is reversible or not, in quantum theory we find that such a quantity can take on a well defined value only when the system is coupled indivisibly to a classically describable system undergoing irreversible processes. The very definition of the state of any one system at the microscopic level therefore requires that matter in the large shall

* There is, in fact, a close connection between entropy and the process of measurement. See L. Szilard, , 53, 840, 1929. The necessity for such a connection can be seen by considering a box divided by a partition into two equal parts, containing an equal number of gas molecules in each part. Suppose that in this box is placed a device that can provide a rough measurement of the position of each atom as it approaches the partition. This device is coupled automatically to a gate in the partition in such a way that the gate will be opened if a molecule approaches the gate from the right, but closed if it approaches from the left. Thus, in time, all the molecules can be made to accumulate on the left-hand side. In this way, the entropy of the gas decreases. If there were no compensating increase of entropy of the mechanism, then the second law of thermodynamics would be violated. We have seen, however, that in practice, every process which can provide a definite measurement disclosing in which side of the box the molecule actually is, must also be attended by irreversible changes in the measuring apparatus. In fact, it can be shown that these changes must be at least large enough to compensate for the decrease in entropy of the gas. Thus, the second law of thermodynamics cannot actually be violated in this way. This means, of course, that Maxwell's famous "sorting demon " cannot operate, if he is made of matter obeying all of the laws of physics. (See L. Brillouin, American Scientist, 38, 594, 1950.)

> undergo irreversible processes. There is a strong analogy here to the behavior of biological systems, where, likewise, the very existence of the fundamental elements (for example, the cells) depends on the maintenance of irreversible processes involving the oxidation of food throughout an organism as a whole. (A stoppage of these processes would result in the dissolution of the cell.)

Niels Bohr

Among all the major scientists of the twentieth century, Niels Bohr may have most wanted to be considered a philosopher. Bohr thought that his concept of complementarity, developed in the same weeks as Werner Heisenberg was formulating his uncertainty principle, could explain many great philosophical issues. Complementarity in the form of wave-particle duality lies at the core of the Copenhagen interpretation of quantum mechanics. Over the years, Bohr suggested complementarity could illuminate the mind/body problem, it might provide for the difference between organic and inorganic matter, and it could underlie other classic dualisms like subject/object, reason versus passion, and even free volition versus causality.

Like any educated person of his time, Bohr knew of Kant's phenomemal/noumenal dualism. He often spoke as if the goal of complementarity was to reconcile opposites. He likened it to the eastern yin and yang, and his grave is marked with the yin/yang symbol.

Bohr was often criticized for suggesting that both A and Not-A could be the case. This was the characteristic sign of Georg W.F. Hegel's dialectical materialism. Had Bohr absorbed some Hegelian thinking? Another Hegelian trait was to speak indirectly and obscurely of the most important matters, and this was Bohr's way, to the chagrin of many of his disciples. They called it "obscure clarity." They hoped for clarity and but got mostly fuzzy thinking when Bohr stepped outside of quantum mechanics.

Bohr might very much have liked the current two-stage model for free will incorporating both randomness and an adequate statistical determinism. He could have seen it as a shining example of his complementarity.

As a philosopher, Bohr was a logical positivist, greatly influenced by Ernst Mach. He put severe epistemological limits on knowing the Kantian "things in themselves," just as Immanuel Kant had put limits on reason. The British empiricist philosophers John Locke and David Hume had put the "primary" objects beyond the reach of our "secondary" sensory perceptions. In this respect, Bohr shared the positivist views of many other empirical scientists, especially Mach.

Bohr seemed to deny the existence of an "objective reality," but clearly knew and said that the physical world is largely independent of human observations. In classical physics, the physical world is assumed to be completely independent of the act of observing the world.

Copenhageners were proud of their limited ability to know. Bohr said:

There is no quantum world. There is only an abstract quantum physical description. It is wrong to think that the task of physics is to find out how nature is. Physics concerns what we can say about nature.

Agreeing with many twentieth-century analytic language philosophers, Bohr and Heisenberg emphasized the importance of conventional language as a tool for knowledge. Since language evolved to describe the familiar world of "classical" objects in space and time, they insisted that somewhere between the quantum world and the classical world there must come a point when our observations and measurements can be expressible in classical concepts. They argued that a measurement apparatus and a particular observation must be describable classically in order for it to be understood and become knowledge in the mind of the observer. And controversially, they maintained that a measurement is not complete until it is knowledge in the mind of a "conscious observer."

In quantum physics, Bohr and Heisenberg said that the result of an experiment depends on the free choice of the experimenter as to what to measure. The quantum world of photons and electrons might look like waves or look like particles depending on what we look for, rather than what they "are" as "things in themselves."

Free Choice in Quantum Mechanics

"Free choice" is an important term in the debates about quantum mechanics and physical reality. It was introduced by Niels Bohr in his response to Albert Einstein's famous challenge to the "completeness" of quantum mechanics.

Einstein, with his Princeton colleagues Boris Podolsky and Nathan Rosen, claimed that their EPR experiment requires the addition of further parameters or "hidden variables" to restore a deterministic picture of the "elements of reality."

In classical physics, such elements of reality include simultaneous values for the position and momentum of elementary particles like electrons.

In quantum mechanics, Bohr and Werner Heisenberg claimed that such properties could not be said to exist precisely before an experimenter decides to make a measurement.

This "freedom of choice" of the experimenter includes the freedom of which specific property to measure for. If the position is measured accurately, the (complementary conjugate and non-commuting variable) momentum is necessarily indeterminate.

For many years, Bohr described the reason for this as "uncertainty," as in Heisenberg's famous "uncertainty principle." Bohr initially described this as an epistemological problem. Heisenberg's first explanation assumed that the measuring apparatus "disturbed" a particle in the act of measurement.

The popular but mistaken thought experiment known as "Heisenberg's Microscope" showed that low-energy long-wavelength photons would not disturb an electron's momentum, but their long waves provided a blurry picture at best, so they lacked the resolving power to measure the position accurately. Conversely, if a high-energy, short wavelength photon was used (e.g., a gamma-ray), it might measure momentum, but the recoil of the electron would be so large that its position became uncertain.

But Bohr showed Heisenberg was mistaken. One could correct for the disturbance (the recoil) but could not eliminate the limits on resolving power of the measuring instrument. In his later years, Bohr stopped describing Heisenberg's principle as "uncertainty" and referred to it as "indeterminacy," the word Heisenberg himself had originally used (unbestimmtheit).

Δt is the time it takes the wave packet to pass a certain point.

$\Delta \nu$ is the range of frequencies of the superposed waves.

In space instead of time, the wave packet is length Δx

and the range of waves per centimeter is $\Delta \sigma$

In his "Como Lecture," which introduced Bohr's famous notion of "complementarity," Bohr cleverly derived Heisenberg's indeterminacy principle solely from space-time considerations. A "wave-packet" with significant values in a spatially limited volume can be made from a superposition of plane waves with a range of frequencies.

Bohr showed that the range of frequencies $\Delta \nu$ needed so the wave packet is kept inside length of time Δt is related as

$\Delta \nu \, \Delta t = 1.$

A similar argument in space relates the physical size of a wave packet Δx to the variation in the number of waves per centimeter $\Delta \sigma$. σ is the so-called wave number $= 1 / \lambda$ (the wavelength):

$\Delta \sigma \, \Delta x = 1.$

If we multiply both sides of the above equations by Planck's constant h, and use the relation between energy and frequency $E = h\nu$ (and the similar relation between momentum and wavelength $p = h\sigma = h / \lambda$), the above become the Heisenberg indeterminacy relations:

$\Delta E \, \Delta t = h, \qquad \Delta p \, \Delta x = h.$

This must have dazzled and perhaps upset Heisenberg. Bohr had used only the space and time properties of waves to derive Heisenberg's physical limits! Bohr was obviously impressed by the new de Broglie - Schrödinger wave mechanics. Could they produce a theory that did not need Einstein's point-like light particles?

Bohr was pleased that Schrödinger's wave function provided a "natural" explanation for the "quantum numbers" of the "stationary states" in his quantum postulate. They are the nodes in the wave function. On the other hand, Schrödinger hoped to eliminate the "unnatural" quantum jumps in Bohr's quantum postulate by resonances in the wave field.

Quantum mechanics requires a fundamental "indeterminacy" that is ontological, a characteristic of the wave function whether or not it is observed. The experimenter can get different results, depending on the choice of measurement apparatus and the property or attribute measured.

EPR argued (mistakenly) that entangled particles could be regarded as separate systems (the indistinguishable particles are in fact described by an inseparable two-particle wave function), and since the experimenter can choose which type of measurement to make on the first system, it would make an instantaneous difference in the state and properties of the second system, however far away, without in any way "disturbing" the second system, but violating special relativity.

> We see therefore that, as a consequence of two different measurements performed upon the first system, the second system may be left in states with two different wave functions. On the other hand, since at the time of measurement the two systems no longer interact, no real change can take place in the second system in consequence of anything that may be done to the first system. This is, of course, merely a statement of what is meant by the absence of an interaction between the two systems. Thus, it is possible to assign two different wave functions to the same reality (the second system after the interaction with the first).
>
> (Physical Review, 47, 777, 1935))

In his 1935 reply to Einstein, Podolsky, and Rosen, Bohr denied that the limitations on simultaneously measuring complementary properties implied any incompleteness:

> My main purpose in repeating these simple, and in substance well-known considerations, is to emphasize that in the phenomena concerned we are not dealing with an incomplete description

characterized by the arbitrary picking out of different elements of physical reality at the cost of sacrificing other such elements, but with a rational discrimination between essentially different experimental arrangements and procedures which are suited either for an unambiguous use of the idea of space location or for a legitimate application of the conservation theorem of momentum. Here Bohr introduces the freedom of the experimenter Any remaining appearance of arbitrariness concerns merely our freedom of handling the measuring instruments characteristic of the very idea of experiment. In fact, the renunciation in each experimental arrangement of the one or the other of two aspects of the description of physical phenomena, - the combination of which characterizes the method of classical physics, and which therefore in this sense may be considered as complementary to one another, - depends essentially on the impossibility in the field of quantum theory, of accurately controlling the reaction of the object on the measuring instruments, i.e., the transfer of momentum in case of position measurements, and the displacement in case of momentum measurements. Not only epistemological human ignorance of values, but even definitions of physical quantities are an impossibility. Just in this last respect any comparison between quantum mechanics and ordinary statistical mechanics, - however useful it may be for the formal presentation of the theory, — is essentially irrelevant. Indeed we have in each experimental arrangement suited for the study of proper quantum phenomena not merely to do with an ignorance of the value of certain physical quantities, but with the impossibility of defining these quantities in an unambiguous way.

The last remarks apply equally well to the special problem treated by Einstein, Podolsky and Rosen, which has been referred to above, and which does not actually involve any greater intricacies than the simple examples discussed above. The particular quantum-mechanical state of two free particles, for which they give an explicit mathematical expression, may be reproduced, at least in principle, by a simple experimental arrangement, comprising a rigid diaphragm with two parallel slits, which are very narrow compared with their separation, and through each of which one particle with given initial momentum passes independently of the other. If the momentum of this diaphragm is measured accurately before as well as after the passing of the particles, we shall in fact know the sum of the components perpendicular to the slits of the momenta of the two escaping particles, as well as the difference of their initial positional coordinates in the same direction; while of course the conjugate quantities, i.e., the difference of the components of their momenta, and the sum of their positional coordinates, are entirely unknown.* In this arrangement, it is therefore clear that a subsequent single measurement either of the position or of the momentum of one of the particles will automatically determine the position or momentum, respectively, of the other particle with any accuracy; at least if the wave-length corresponding to the free motion of each particle is sufficiently short compared with the width of the slits. As pointed out by the named authors, we are therefore faced at this stage with a completely free choice whether we want to determine the one or the other of the latter quantities by a process which does not directly interfere with the particle concerned.

Like the above simple case of the choice between the experimental procedures suited for the prediction of the position or the momentum of a single particle which has passed through a slit in a diaphragm, we are, in the "freedom of choice" offered by the last arrangement, just concerned with a discrimination between different experimental procedures which allow of the unambiguous use of complementary classical concepts. In fact to measure the position of one of the particles can mean nothing else than to establish a correlation between its behavior and some instrument rigidly fixed to the support which defines the space frame of reference. Under the experimental conditions described such a measurement will therefore also provide us with the knowledge of the location, otherwise completely unknown, of the diaphragm with respect to this space frame when the particles passed through the slits. Indeed, only in this way we obtain a basis for conclusions about the initial position of the other particle relative to the rest of the apparatus. By allowing an essentially uncontrollable momentum to pass from the first particle into the mentioned support, however, we have by this procedure cut ourselves off from any future possibility of applying the law of conservation of momentum to the system consisting of the diaphragm and the two particles and therefore have lost our only basis for an unambiguous application of the idea of momentum in predictions regarding the behavior of the second particle. Conversely, if we choose to measure the momentum of one of the particles, we lose through the uncontrollable displacement inevitable in such a measurement any possibility of deducing from the behavior of this particle the position of the diaphragm relative to the rest of the apparatus, and have thus no basis whatever for predictions regarding the location of the other particle.

From our point of view we now see that the wording of the above-mentioned 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."

EPR was concerned about faster-than-light disturbances or influences between particles with pre-existing properties 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 behavior 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, Bohr denies the charge of "incompleteness" we see that the argumentation of the mentioned authors does not justify their conclusion that quantum-mechanical description is essentially incomplete. On the contrary this description, as appears from the preceding discussion, may be characterized as a rational utilization of all possibilities, of unambiguous interpretation of measurements, compatible with the finite and uncontrollable interaction between the object and the measuring instruments in the field of quantum theory. In fact, it is only the mutual exclusion of any two experimental procedures, permitting the unambiguous definition of complementary physical quantities, which provides room for new physical laws the coexistence of which might at first sight appear irreconcilable with the basic principles of science. It is just this entirely new situation as regards the description of physical phenomena that the notion of complementarity aims at characterizing.

(Physical Review, 48, 696, 1935))

In his long 1938 essay on "The Causality Problem in Atomic Physics" Bohr again emphasizes the "free choice" of an experimental procedure in his solution to the EPR paradox.

the paradox finds its complete solution within the frame of the quantum mechanical formalism, according to which no well defined use of the concept of "state" can be made as referring to the object separate from the body with which it has been in contact, until the external conditions involved in the definition of this concept are unambiguously fixed by a further suitable control of the auxiliary body. Instead of disclosing any incompleteness of the formalism, the argument outlined entails in fact an unambiguous prescription as to how this formalism is rationally applied under all conceivable manipulations of the measuring instruments. The complete freedom of the procedure in experiments common to all investigations of physical phenomena, is in itself of course contained in our free choice of the experimental arrangement, which again is only dictated by the particular kind of phenomena we wish to investigate.

(in "Causality and Complementarity," vol. IV of The Philosophical Writings of Niels Bohr, p. 102)

In all the recent EPR experiments to test Bell's Inequalities, "free choices" of the experimenters are needed when they select the angle of polarization. Note that what determines the second experimenter's results is these tests is simply the first experimenter's measurement, which instantaneously collapses the superposition of two-particle states into a particular state that is now a separable product of independent particle states.

Bell inequality investigators who try to recover the "elements of local reality" that Einstein wanted, and who hope to eliminate the irreducible randomness of quantum mechanics that follows from wave functions as probability amplitudes, often cite "loopholes" in EPR experiments. For example, the "detection loophole" claims that the efficiency of detectors is so low that they are missing many events that might prove Einstein was right.

Most all the loopholes have now been closed, but there is one loophole that can never be closed because of its metaphysical/philosophical nature. That is the "(pre-)determinism loophole."

If every event occurs for reasons that were established at the beginning of the universe, then the experimenters lack any free will or free choice and all the careful experimental results are meaningless. John Conway and Simon Kochen have formalized this loophole in what they call the Free Will Theorem.

Max Born

Max Born is nearly universally credited with the "statistical interpretation" of quantum mechanics that lies at the heart of Niels Bohr and Werner Heisenberg's principle of complementarity and the "*Copenhagen interpretation*."

Probability and statistics were very important in the two centuries before Born's work, but most physicists and philosophers saw the implied randomness to be the consequence of human ignorance. They denied any underlying absolute chance, with the exception of a few thinkers like Franz S.Exner and his student Erwin Schrödinger. The random distributions were thought to be completely deterministic at the particle level, with atoms following Newton's dynamical laws.

Albert Einstein explained the photoelectric effect with Planck's discrete units of light energy, later called photons. Since the momentum of a particle is the energy divided by velocity of a particle, the momentum p of a photon is $p = h\nu/c$, where c is the velocity of light. To make the dual aspect of light as both waves and particles (photons) more plausible, Einstein interpreted the square of the light wave amplitude as the probable density of photons.

Schrödinger's creation of his quantum mechanical wave function Ψ followed a suggestion by Louis De Broglie that a wave could be associated with a particle of matter - by analogy with the particle of energy that was associated with an optical wave. De Broglie predicted that the wavelength λ of a matter particle wave would be $\lambda = h/p$, since the wavelength of a photon is related to its frequency by $\lambda = c/\nu$.

Note that Born's interpretation of the quantum mechanical wave function of a material particle as the probability (amplitude) of finding the material particle somewhere is a direct extension of Einstein's interpretation of the connection between light waves and photons.

In the history of science it is hard to find ears more likely to be sympathetic to a new idea than these three great scientists should have been for Max Born's suggestion that the square of the amplitude of Schrödinger's wave function $|\Psi 2|$ should be interpreted statistically as the likelihood of finding the particle.

Yet they all objected strenuously, not so much to the probability and statistics as to the conviction of Born and his brilliant student Heisenberg that quantum phenomena, like quantum jumps between atomic energy levels, were only predictable statistically, and that there was a fundamental indeterminacy in the classical idea that particles have knowable positions and velocities (momenta). Born, Heisenberg, and Bohr had declared classical determinism untrue of the physical world.

Indeterminism and absolute chance had reappeared in the atomic world twenty-two centuries after Epicurus had called for atoms to swerve to provide room for free will.

Add material from Born-Einstein letters. And from his later book (date?)

From Part IX, Chance

> There is no doubt that the formalism of quantum mechanics and its statistical interpretation are extremely successful in ordering and predicting physical experiences. But can our desire of understanding, our wish to explain things, be satisfied by a theory which is frankly and shamelessly statistical and indeterministic? Can we be content with accepting chance, not cause, as the supreme law of the physical world?
>
> To this last question I answer that not causality, properly understood, is eliminated, but only a traditional interpretation of it,

consisting in its identification with determinism. I have taken pains to show that these two concepts are not identical. Causality in my definition is the postulate that one physical situation depends on the other, and causal research means the discovery of such dependence. This is still true in quantum physics, though the objects of observation for which a dependence is claimed are different: they are the probabilities of elementary events, not those single events themselves.

Part X, Metaphysical Conclusions

The statistical interpretation which I have presented in the last section is now generally accepted by physicists all over the world, with a few exceptions, amongst them a most remarkable one. As I have mentioned before, Einstein does not accept it, but still believes in and works on a return to a deterministic theory. To illustrate his opinion, let me quote passages from two letters. The first is dated 7 November 1944, and contains these lines:

`In unserer wissenschaftlichen Erwartung haben wir uns zu Antipoden entwickelt. Du glaubst an den würfelnden Gott und ich an volle Gesetzlichkeit in einer Welt von etwas objektiv Seiendem, das ich auf wild spekulativem Weg zu erhaschen suche. Ich hoffe, dass einer einen mehr realistischen Weg, bezw. eine mehr greifbare Unterlage für eine solche Auffassung finden wird, als es mir gegeben ist. Der grosse anfängliche Erfolg der Quantentheorie kann mich doch nicht zum Glauben an das fundamentale Würfelspiel bringen.

(In our scientific expectations we have progressed towards antipodes. You believe in the dice-playing god, and I in the perfect rule of law in a world of something objectively existing which I try to catch in a wildly speculative way. I hope that somebody will find a more realistic way, or a more tangible foundation for such a conception than that which is given to me. The great initial success of quantum theory cannot convert me to believe in that fundamental game of dice.)

The second letter, which arrived just when I was writing these pages (dated 3 December 1947), contains this passage:

`Meine physikalische Haltung kann ich Dir nicht so begründen, dass Du sie irgendwie vernünftig finden würdest. Ich sehe natürlich ein, dass die principiell statistische Behandlungsweise, deren Notwendigkeit im Rahmen des bestehenden Formalismus ja zuerst von Dir klar erkannt wurde, einen bedeutenden Wahrheitsgehalt hat. Ich kann aber deshalb nicht ernsthaft daran glauben, weil die Theorie mit dem Grundsatz unvereinbar ist, dass die Physik eine Wirklichkeit in Zeit und Raum darstellen soll, ohne spukhafte Fernwirkungen.... Davon bin ich fest überzeugt, dass man schliesslich bei einer Theorie landen wird, deren gesetzmässig verbundene Dinge nicht Wahrscheinlichkeiten, sondern gedachte Tatbestände sind, wie man es bis vor kurzem als selbstverständlich betrachtet hat. Zur Begründung dieser Überzeugung kann ich aber nicht logische Gründe, sondern nur meinen kleinen Finger als Zeugen beibringen, also keine Autorität, die ausserhalb meiner Haut irgendwelchen Respekt einflössen kann.

(I cannot substantiate my attitude to physics in such a manner that you would find it in any way rational. I see of course that the statistical interpretation (the necessity of which in the frame of the existing formalism has been first clearly recognized by yourself) has a considerable content of truth. Yet I cannot seriously believe it because the theory is inconsistent with the principle that physics has to represent a reality in space and time without phantom actions over distances.... I am absolutely convinced that one will eventually arrive at a theory in which the objects connected by laws are not probabilities, but conceived facts, as one took for granted only a short time ago. However, I cannot provide logical arguments for my conviction, but can only call on my little finger as a witness, which cannot claim any authority to be respected outside my own skin.)

I have quoted these letters because I think that the opinion of the greatest living physicist, who has done more than anybody else to establish modern ideas, must not be by-passed. Einstein does not share the opinion held by most of us that there is overwhelming evidence for quantum mechanics. Yet he concedes 'initial success' and 'a considerable degree of truth'. He obviously agrees that we have at present nothing better, but he hopes that this will be achieved later, for he rejects the 'dice-playing god'.

> I have discussed the chances of a return to determinism and found them slight. I have tried to show that classical physics is involved in no less formidable conceptional difficulties and had eventually to incorporate chance in its system. We mortals have to play dice anyhow if we wish to deal with atomic systems. Einstein's principle of the existence of an objective real world is therefore rather academic. On the other hand, his contention that quantum theory has given up this principle is not justified, if the conception of reality is properly understood. Of this I shall say more presently.
>
> Einstein's letters teach us impressively the fact that even an exact science like physics is based on fundamental beliefs. The words ich glaube appear repeatedly, and once they are underlined. I shall not further discuss the difference between Einstein's principles and those which I have tried to extract from the history of physics up to the present day. But I wish to collect some of the fundamental assumptions which cannot be further reduced but have to be accepted by an act of faith.

Arthur Holly Compton

In 1923, Compton discovered that radiation (high-energy X-rays) could collide with electrons, exchanging energy with them as they were scattered. This was the first solid evidence for Albert Einstein's "light-quantum hypothesis," proposed in 1905. Sadly, he did not think that his work supported Einstein's hypothesis, which was not fully accepted until after the "founders" of quantum mechanics reluctantly accepted it.

The "Compton effect" provided real support for the wave-particle duality of radiation (which Einstein had proposed as early as 1909) and matter (proposed by Louis de Broglie in 1924. Compton himself initially denied that his experiment supported Einstein's idea of light quanta (later called photons). Compton was awarded the Nobel Prize in Physics in 1927 for this "Compton effect," the year that Werner Heisenberg proclaimed his quantum indeterminacy.

Compton scattering is "inelastic," because the energy $h\nu$ (or hc / λ) of the incident photon is different from that of the scattered photon $h\nu'$ (or hc / λ').

Compton's experiments confirmed the relation

$$\lambda' - \lambda = (h / m_e c) (1 - \cos\theta)$$

The wavelength shift $\lambda' - \lambda$ varies from nothing to twice $h / m_e c$, which is known as the Compton wavelength. For a derivation, see Compton scattering on Wikipedia.

WOLFGANG PAULI objected to Compton's analysis. A "free" electron cannot scatter an electron, he argued. A proper analysis, confirmed by Einstein and Ehrenfest the same year (1923), is that scattering should be interpreted as a two-step process, the absorption of a photon of energy $h\nu$ followed by the emission of a directed photon hν', where the momentum of the photon $h\nu' / c$ balances the momentum of the scattered electron pv.

Paul Dirac

Paul (P. A. M.) Dirac formulated the most elegant version of the mathematical principles of quantum mechanics after hearing a lecture by Werner Heisenberg on his new ideas of "matrix mechanics." Shortly after matrix mechanics, Erwin Schrödinger developed his "wave mechanics" and showed it was equivalent to the Heisenberg picture.

Dirac then combined the matrix and wave formulations using abstract symbolic methods from classical mechanics called Poisson brackets and canonical transformations.

In his textbook *The Principles of Quantum Mechanics*, Paul Dirac introduced the concepts of superposition, projection, measurement, and indeterminacy using simple examples with polarized photons.

Dirac's examples suggest a very simple and inexpensive experiment that we call the *Dirac 3-polarizers* experiment to demonstrate the notions of quantum states, the preparation of quantum systems in states with known properties, the *principle of superposition* of states, the *axiom of measurement* of various properties, the *projection postulate* or *representation* of a state vector in another basis set of vectors, and the infamous "*collapse*" or "reduction" of the wave function and the resulting indeterminacy.

In their *Copenhagen interpretation* of quantum mechanics, Bohr and Heisenberg said that the results of quantum measurements must be expressible in classical concepts because it is the language that humans can understand. By contrast, Dirac argued that the non-intuitive concepts of quantum mechanics, though impossible to understand in terms of classical concepts, could be mastered through long familiarity with them.

> The new theories, if one looks apart from their mathematical setting, are built up from physical concepts which cannot be explained in terms of things previously known to the student, which cannot even be explained adequately in words at all. Like the fundamental concepts (e.g. proximity, identity) which every one must learn on his arrival into the world, the newer concepts of physics can be mastered only by long familiarity with their properties and uses.[5]

Information physics attempts to articulate some new concepts, albeit slightly modified versions of intuitive classical concepts. We associate quantum waves with possibilities and a quantum particle with actualization of a possibility. Quantum physics lets us calculate the probabilities for each possibility, to an extraordinary degree of accuracy. Although the calculation involves abstract complex quantities and the motion through space of immaterial information about those possibilities, the result is both understandable (if non-intuitive because never experienced) and visualizable.

The Information Interpretation of quantum mechanics is based on three simple premises:

When you hear or read that electrons are both waves and particles, think “either-or” -

first a wave of possibilities, then an actual particle.

Quantum systems evolve in two ways:

the first is the wave function deterministically exploring all the possibilities for interaction, interfering with itself as it travels,

the second is the particle randomly choosing one of those possibilities to become actual.

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[5] Preface to *The Principles of Quantum Mechanics*, First Edition, in the Fourth Edition, p.viii

No knowledge can be gained by a "conscious observer" unless new information has already been irreversibly recorded in the universe. That information can be created and recorded in three places:

in the target quantum system,

in the combined target system and measuring apparatus,

it can then become knowledge in the observer's mind.

In our two-stage model of free will, an agent first freely generates alternative possibilities, then evaluates them and chooses one, adequately determined by its motives, reasons, desires, etc. First come "free alternatives," then "willed actions." Just as with quantum processes - first possibilities, then actuality. The measuring apparatus is quantal, not deterministic or "classical." It need only be statistically determined and capable of recording the irreversible information about an interaction. The human mind is similarly only statistically determined.

We provide visualizations for some of these concepts, including Dirac's three polarizers, the two-slit experiment, and the Einstein-Podolsky-Rosen thought experiment.

Arthur Stanley Eddington

In the early 1920's, Eddington established himself as the leading interpreter of Einstein's new theories of relativity. First with a popular introduction to special relativity, and then with his astronomical measurements of light bending as it passes the sun he confirmed Einstein's general relativity theory. His popular interpretations of these difficult physical theories made Eddington widely known to the general public.

Both special and general relativity are deterministic theories. Special relativity is especially so, with some interpretations saying that the fourth dimension of time is like the other three, already there, so the future already exists. In his Gifford Lectures of 1927, Eddington had described himself as unable "to form a satisfactory conception of any kind of law or causal sequence which shall be other than deterministic."

A year later, in response to Heisenberg's uncertainty principle, Eddington revised his lectures for publication as *The Nature of the Physical World*. There he dramatically announced "physics is no longer pledged to a scheme of deterministic law." He went even farther and enthusiastically identified indeterminism with freedom of the will.

> "It is a consequence of the advent of the quantum theory that physics is no longer pledged to a scheme of deterministic law... we may note that science thereby withdraws its moral opposition to freewill."[6]
>
> "The indeterminacy recognised in modern quantum theory is only a partial step towards freeing our actions from deterministic control."[7]

In the mid-thirties, Eddington was a bit more circumspect, no doubt because some philosophers, led by L.Susan Stebbing, had been quick to attack him. She argued in her book Philosophy and the Physicists that a "free electron" has nothing to do with human freedom.

Eddington defended his views more cautiously,

> "The revolution of theory which has expelled determinism from present-day physics has therefore the important consequence that it is no longer necessary to suppose that human actions are completely predetermined. Although the door of human freedom is opened, it is not flung wide open; only a chink of daylight appears."[8]
>
> "I would even say that in the present indeterministic theory of the physical universe we have reached something which a reasonable man might almost believe."[9]

Eddington was apparently unaware of the work of William James or Henri Poincaré to make deliberation a two-stage process - first random possibilities, then a de-liberate decision, first chance, then choice.

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[6] *The Nature of the Physical World*, 1928, pp.294-5)

[7] *ibid.*,, p.313

[8] *New Pathways in Science*, 1935, p.87

[9] *ibid.*, p.91

A decade after embracing indeterminism and just a few years before his death, Eddington in his 1939 book *The Philosophy of Physical Science* reluctantly concluded there is no "halfway house" between randomness and determinism - an echo of David Hume's "no medium betwixt chance and an absolute necessity."

> "There is no half-way house between random and correlated behavior. Either the behavior is wholly a matter of chance, in which case the precise behavior within the Heisenberg limits of uncertainty depends on chance and not volition. Or it is not wholly a matter of chance, in which case the Heisenberg limits... are irrelevant."[10]

The Cogito two-stage model of human freedom is in many ways the "halfway house" that Eddington could not see, combining limited forms of determinism and indeterminism.

Eddington succumbed to the standard logical argument against free will. He thus left himself open to the charge since Epicurus' time, that chance could not be identified with freedom. He was apparently unaware of the work of William James or Henri Poincaré to make deliberation a two-stage process - first the random generation of alternative possibilities, then an adequately determined (by reasons, motives, etc.) choice.

In the end, Eddington may have considered some sort of dualistic transcendent (metaphysical) explanation.

"There is in a human being some portion of the brain, perhaps a mere speck of brain-matter, perhaps an extensive region, in which the physical effects of his volitions begin,."[11]

This sounds too much like the pineal gland of Descartes' dualistic mind-body distinction. Such metaphysics is unnecessary, as basic quantum physics is all that is needed for liberty and creativity, and statistical regularity all that is needed for adequate determinism

Hugh Everett III

Everett was one of John Wheeler's most famous graduate students. Others included Richard Feynman. Wheeler supervised more Ph.D. theses than any Princeton physics professor.

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[10] *The Philosophy of Physical Science*, 1938, p.182

[11] *ibid.*

Everett took mathematical physics classes with Eugene Wigner, who argued that human consciousness (and perhaps some form of cosmic consciousness) was essential to the collapse of the wave function.

Everett was the inventor of the “universal wave function” and the “relative state” formulation of quantum mechanics, later known as the “many-worlds interpretation.”

The first draft of Everett’s thesis was called “Wave Mechanics Without Probability.” Like Einstein and Schrödinger, Everett was appalled at the idea of *indeterministic* events. For him, it was much more logical that the world was entirely deterministic.

Everett began his thesis by describing John von Neumann’s “two processes.”

Process 1 is the sudden collapse of the wave function from a superposition of quantum states into a single state, with the probability of collapsing into a given state proportional to the overlap of the wave functions of new state with each of the superposition states. (See von Neumann Process 1.)

Process 2 is the unitary time evolution of the wave function deterministically generated by the Schrödinger wave equation. (See von Neumann Process 2.)

Everett then presents the internal contradictions of observer-dependent collapses of wave functions with examples of “Wigner’s Friend,” an observer who observes another observer. For whom does the wave function collapse?

Everett considers several alternative explanations for Wigner’s paradox, the fourth of which is the standard statistical interpretation of quantum mechanics, which was criticized by Einstein as not being a complete description.

> Alternative 4: To abandon the position that the state function is a complete description of a system. The state function is to be regarded not as a description of a single system, but of an ensemble of systems, so that the probabilistic assertions arise naturally from the incompleteness of the description.[12]

In order to be “complete, “hidden variables” would be necessary.

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[12] “*The Many-Worlds Interpretation of Quantum Mechanics*,” p.8

His "theory of the universal wave function" is the last alternative:

> Alternative 5: To assume the universal validity of the quantum description, by the complete abandonment of Process 1. The general validity of pure wave mechanics, without any statistical assertions, is assumed for all physical systems, including observers and measuring apparata. Observation processes are to be described completely by the state function of the composite system which includes the observer and his object-system, and which at all times obeys the wave equation (Process 2).

Everett says this alternative has many advantages.

> It has logical simplicity and it is complete in the sense that it is applicable to the entire universe. All processes are considered equally (there are no "measurement processes" which play any preferred role), and the principle of psycho-physical parallelism is fully maintained. Since the universal validity of the state function description is asserted, one can regard the state functions themselves as the fundamental entities, and one can even consider the state function of the whole universe. In this sense this theory can be called the theory of the "universal wave function, " since all of physics is presumed to follow from this function.[13]

Information and Entropy

In a lengthy chapter, Everett develops the concept of information - despite the fact that his deterministic view of physics allows no possibilities. For Claude Shannon, the developer of the theory of communication of information, there can be no information transmitted without possibilities. Everett correctly observes that in classical mechanics information is a conserved property, a constant of the motion. No new information can be created in the universe.

> As a second illustrative example we consider briefly the classical mechanics of a group of particles. The system at any instant is represented by a point...in the phase space of all position and momentum coordinates. The natural motion of the system then carries each point into another, defining a continuous transformation of the phase space into itself. According to Liouville's theorem the measure of a set of points of the phase space is invariant under this transformation. This invariance of measure implies that if we begin with a probability distribution over the

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[13] *ibid.*, p.8

> phase space, rather than a single point, the total information,... which is the information of the joint distribution for all positions and momenta, remains constant in time.[14]

Everett correctly notes that if total information is constant, the total entropy is also constant.

> if one were to define the total entropy to be the negative of the total information, one could replace the usual second law of thermodynamics by a law of conservation of total entropy, where the increase in the standard (marginal) entropy is exactly compensated by a (negative) correlation entropy. The usual second law then results simply from our renunciation of all correlation knowledge (stosszahlansatz), and not from any intrinsic behavior of classical systems. The situation for classical mechanics is thus in sharp contrast to that of stochastic processes, which are intrinsically irreversible.[15]

The Appearance of Irreversibility in a Measurement

> There is another way of looking at this apparent irreversibility within our theory which recognizes only Process 2. When an observer performs an observation the result is a superposition, each element of which describes an observer who has perceived a particular value. From this time forward there is no interaction between the separate elements of the superposition (which describe the observer as having perceived different results), since each element separately continues to obey the wave equation. Each observer described by a particular element of the superposition behaves in the future completely independently of any events in the remaining elements, and he can no longer obtain any information whatsoever concerning these other elements (they are completely unobservable to him).
>
> The irreversibility of the measuring process is therefore, within our framework, simply a subjective manifestation reflecting the fact that in observation processes the state of the observer is transformed into a superposition of observer states, each element of which describes an observer who is irrevocably cut off from the remaining elements. While it is conceivable that some outside agency could reverse the total wave function, such a change cannot be brought about by any observer which is repre-

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[14] *ibid.*, p.31.

[15] *ibid.*, pp.31-32

> sented by a single element of a superposition, since he is entirely powerless to have any influence on any other elements.
>
> There are, therefore, fundamental restrictions to the knowledge that an observer can obtain about the state of the universe. It is impossible for any observer to discover the total state function of any physical system, since the process of observation itself leaves no independent state for the system or the observer, but only a composite system state in which the object-system states are inextricably bound up with the observer states.
>
> Here is Everett's radical thesis that the observation "splits" the single observer into a superposition of multiple observers, each one of which has knowledge only of the new object-system state (interpreted later by Bryce DeWitt as different "universes") As soon as the observation is performed, the composite state is split into a superposition for which each element describes a different object-system state and an observer with (different) knowledge of it. Only the totality of these observer states, with their diverse knowledge, contains complete information about the original object-system state - but there is no possible communication between the observers described by these separate states. Any single observer can therefore possess knowledge only of the relative state function (relative to his state) of any systems, which is in any case all that is of any importance to him.[16]

In the final chapter of his thesis, Everett gives five possible "interpretations, the "popular", the "Copenhagen", the "hidden variables", the "stochastic process", and the "wave" interpretations.

> a. The "popular" interpretation. This is the scheme alluded to in the introduction, where ψ is regarded as objectively characterizing the single system, obeying a deterministic wave equation when the system is isolated but changing probabilistically and discontinuously under observation.[17]
>
> b. The Copenhagen interpretation. This is the interpretation developed by Bohr. The ψ function is not regarded as an objective description of a physical system (i.e., it is in no sense a conceptual model), but is regarded as merely a mathematical artifice which enables one to make statistical predictions, albeit the best

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[16] *ibid.*, pp.97-98.

[17] *ibid.*, p.110.

> predictions which it is possible to make. This interpretation in fact denies the very possibility of a single conceptual model applicable to the quantum realm, and asserts that the totality of phenomena can only be understood by the use of different, mutually exclusive (i.e., "complementary") models in different situations. All statements about microscopic phenomena are regarded as meaningless unless accompanied by a complete description (classical) of an experimental arrangement.[18]
>
> c. The "hidden variables" interpretation. This is the position (Alternative 4 of the Introduction) that ψ is not a complete description of a single system. It is assumed that the correct complete description, which would involve further (hidden) parameters, would lead to a deterministic theory, from which the probabilistic aspects arise as a result of our ignorance of these extra parameters in the same manner as in classical statistical mechanics.[19]

Everett says that here the ψ-function is regarded as a description of an ensemble of systems rather than a single system. Proponents of this interpretation include Einstein and Bohm.

> The stochastic process interpretation. This is the point of view which holds that the fundamental processes of nature are stochastic (i.e., probabilistic) processes. According to this picture physical systems are supposed to exist at all times in definite states, but the states are continually undergoing probabilistic changes. The discontinuous probabilistic "quantum-jumps" are not associated with acts of observation, but are fundamental to the systems themselves.[20]

This is close to our information interpretation of quantum mechanics, which claims that collapses of the wave function result from interactions between quantum systems, independent of any observers or measurement processes.

The wave interpretation. This is the position proposed in the present thesis, in which the wave function itself is held to be the fundamental entity, obeying at all times a deterministic wave equation.[21]

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[18] *ibid.*, p.110.

[19] *ibid.*, p.111.

[20] *ibid.*, p.114.

[21] *ibid.*, p.115.

Everett says that this is his thesis, that it follows most closely the view held by Erwin Schrödinger, who denied the existence of "quantum jumps" and collapses of the wave function. See Schrödinger's Are There Quantum Jumps?, Part I and Part II (and, years after Everett, John Bell (1987) and H. Dieter Zeh (1993) who wrote articles with similar titles).

On the "Conscious Observer"

Everett proposed that the complicated problem of "conscious observers" can be greatly simplified by noting that the most important element in an observation is the recorded information about the measurement outcome in the memory of the observer. He proposed that human observers could be replaced by automatic measurement equipment that would achieve the same result. A measurement would occur when information is recorded by the measuring instrument.

> It will suffice for our purposes to consider the observers to possess memories (i.e., parts of a relatively permanent nature whose states are in correspondence with past experience of the observers). In order to make deductions about the past experience of an observer it is sufficient to deduce the present contents of the memory as it appears within the mathematical model.
>
> As models for observers we can, if we wish, consider automatically functioning machines, possessing sensory apparatus and coupled to recording devices capable of registering past sensory data and machine configurations.
>
> We can further suppose that the machine is so constructed that its present actions shall be determined not only by its present sensory data, but by the contents of its memory as well. Such a machine will then be capable of performing a sequence of observations (measurements), and furthermore of deciding upon its future experiments on the basis of past results. If we consider that current sensory data, as well as machine configuration, is immediately recorded in the memory, then the actions of the machine at a given instant can be regarded as a function of the memory contents only, and all relevant experience of the machine is contained in the memory.

Everett's observer model has what might be called artificial

> consciousness. For such machines we are justified in using such phrases as "the machine has perceived A" or "the machine is aware of A" if the occurrence of A is represented in the memory, since the future behavior of the machine will be based upon the occurrence of A. In fact, all of the customary language of subjective experience is quite applicable to such machines, and forms the most natural and useful mode of expression when dealing with their behavior, as is well known to individuals who work with complex automata.[22]

Everett's observer model is a classic example of artificial intelligence.

And his model of machine memory completely solves the problem of "Wigner's Friend." As in the information interpretation of quantum mechanics, it is the recording of information in a "measurement" that makes a subsequent "observation" by a human observer possible.

Summary of Everett's Ideas

Everett's idea for the "universal validity of the quantum description" can be read as saying that quantum mechanics applies to all physical systems, not merely microscopic systems. Then "classical" mechanics emerges in the limit of the Planck quantum of action h → 0, or more importantly, h / m → 0, so that classical physics appears in large massive objects (like human beings) because the indeterminacy is too small to measure.

Everett says that the ψ-function is a description of an ensemble of systems rather than a single system. It is true that the phenomenon of wave interference is only inferred from the results of many single particle experiments. We do not "see" interference directly. Probabilistic assertions arise naturally from the incompleteness of the description.

Everett correctly observes that in classical mechanics information is a conserved property, a constant of the motion. No new information can be created in a classical universe.

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[22] "The "Relative State Formulation of Quantum Mechanics," *Rev. Mod. Phys*, 29, 3, p.457

Everett's automatic measuring equipment that stores information about measurements in its "memory" nicely solves von Neumann's problem of "psycho-physical parallelism" in "conscious-observer"-dependent quantum mechanics, like the Bohr-Heisenberg "Copenhagen interpretation."

The Everett theory preserves the "appearance" of possibilities as well as all the results of standard quantum mechanics. It is an "interpretation" after all. So even wave functions "appear" to collapse. Note that if there are many possibilities, whenever one becomes actual, the others disappear instantly.

Richard Feynman

Feynman won a Nobel Prize for his work on quantum electrodynamics (QED) but he also developed simple yet insightful explanations of quantum mechanics.

In his famous *Lectures on Physics*, and in some of the more accessible material re-published as *Six Easy Pieces*, Feynman argued that the most important scientific knowledge - from physics to biology - is the simple fact that all things are made of atoms.

> If, in some cataclysm, all of scientific knowledge were to be destroyed, and only one sentence passed on to the next generations of creatures, what statement would contain the most information in the fewest words? I believe it is the atomic hypothesis (or the atomic fact, or whatever you wish to call it) that all things are made of atoms—little particles that move around in perpetual motion, attracting each other when they are a little distance apart, but repelling upon being squeezed into one another. In that one sentence, you will see, there is an enormous amount of information about the world, if just a little imagination and thinking are applied... [23]
>
> Everything is made of atoms. That is the key hypothesis. The most important hypothesis in all of biology, for example, is that everything that animals do, atoms do. In other words, there is nothing that living things do that cannot be understood from the point of view that they are made of atoms acting according to the laws of physics. This was not known from the beginning: it took some experimenting and theorizing to suggest this hypoth-

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[23] *Six Easy Pieces*, p.4

> esis, but now it is accepted, and it is the most useful theory for producing new ideas in the field of biology. [24]

Feynman is quite right that everything is made up of discrete particles. We might rewrite his advice to the future this way:

The universe consists of discrete, discontinuous, and in some sense "digital," particles. There is no "classical" world, only a quantum world. The "classical" world emerges from the quantum world when a large enough number of particles get together. The continuous space (and time) in which we locate the particles is but a mathematical construct that allows us to describe the world.There are no continuous "fields" in which particles of matter (electrons, atoms, etc.) are thought to be singularities. The continuous, causal "forces" like gravity that we postulate are useful fictions. They are only statistical averages over other types of particles (photons, bosons, gravitons) that look continuous when very many such particles are present. At the microscopic level, quantum events are discontinuous and acausal. The analytic integral and differential equations that we assume deterministically govern the motions of material particles are idealizations only accurate for very large bodies.

Feynman imagined a scenario like that Arthur Holly Compton used as a model for free will based on quantum uncertainty.

> ...we could cook up — we'd better not, but we could — a scheme by which we set up a photo cell, and one electron to go through, and if we see it behind hole No. 1 we set off the atomic bomb and start World War III, whereas if we see it behind hole No. 2 we make peace feelers and delay the war a little longer.

Werner Heisenberg

In 1925 Max Born, Heisenberg, and PASCUAL JORDAN, formulated their matrix mechanics version of quantum mechanics as a superior formulation of Niels Bohr's old quantum theory. The matrix mechanics confirmed discrete states and "quantum jumps" of electrons between the energy levels, with emission or absorption of radiation. But they did not yet accept today's standard textbook

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[24] *ibid.*, p.20.

view that the radiation is also discrete and in the form of Albert Einstein's light quanta, about to be renamed "photons" by Gilbert Lewis in late 1926.

In early 1926, Erwin Schrödinger developed wave mechanics as an alternative formulation of quantum mechanics. Schrödinger disliked the idea of discontinuous quantum jumps. His wave mechanics was a continuous theory, but it predicted the same energy levels and was otherwise identical to the discrete theory in its predictions. Indeed, Schrödinger proved that matrix mechanics and his wave mechanics were isomorphic theories.

Within months of the new wave mechanics, Max Born showed that while Schrödinger's wave function evolved over time deterministically, it only predicted the positions and velocities of atomic particles probabilistically. Born applied to matter Einstein's view that the waves of radiation could be interpreted as probabilities for finding light quanta, which was described as public knowledge as early as in 1921 by H. A. Lorentz.

Heisenberg used Schrödinger's wave functions to calculate the "transition probabilities" for electrons to jump from one energy level to another. Schrödinger's wave mechanics was easier to visualize and much easier to calculate than Heisenberg's own matrix mechanics.

In early 1927, Heisenberg announced his indeterminacy principle limiting our knowledge of the simultaneous position and velocity of atomic particles, and declared that the new quantum theory disproved causality. "We cannot - and here is where the causal law breaks down - explain why a particular atom will decay at one moment and not the next, or what causes it to emit an electron in this direction rather than that." Albert Einstein had shown this in his 1917 paper on the emission and absorption of light by matter.

More popularly known as the Uncertainty Principle in quantum mechanics, it states that the exact position and momentum of an atomic particle can only be known within certain (sic) limits. The product of the position error and the momentum error is greater than or equal to Planck's constant h divided by 2π.

$$\Delta p \Delta x \geq \hbar = h/2\pi \qquad (1)$$

Indeterminacy (Unbestimmtheit) was Heisenberg's original name for his principle. It is a better name than the more popular uncertainty, which connotes lack of knowledge. The Heisenberg principle is an ontological as well as epistemic lack of information.

Causality

Heisenberg was convinced that quantum mechanics had put an end to classical ideas of causality and strict determinism.

In his classic paper introducing the principle of indeterminacy, he concluded with remarks about causality.

If one assumes that the interpretation of quantum mechanics is already correct in its essential points, it may be permissible to outline briefly its consequences of principle. We have not assumed that quantum theory — in opposition to classical theory — is an essentially statistical theory in the sense that only statistical conclusions can be drawn from precise initial data. The well-known experiments of Geiger and Bothe, for example, speak directly against such an assumption. Rather, in all cases in which relations exist in classical theory between quantities which are really all exactly measurable, the corresponding exact relations also hold in quantum theory (laws of conservation of momentum and energy). Even in classical mechanics we could never practically know the present exactly, vitiating Laplace's demon But what is wrong in the sharp formulation of the law of causality, "When we know the present precisely, we can predict the future," is not the conclusion but the assumption. Even in principle we cannot know the present in all detail. For that reason everything observed is a selection from a plenitude of possibilities and a limitation on what is possible in the future. As the statistical character of quantum theory is so closely linked to the inexactness of all perceptions, one might be led to the presumption that behind the perceived statistical world there still hides a "real" world in which causality holds. But such speculations seem to us, to say it explicitly, fruitless and senseless. Physics ought to describe only the correlation of observations. One can express the true state of affairs better in this way : Because all experiments are subject to the laws of quantum mechanics, and therefore to equation (1), it follows that quantum mechanics establishes the final failure of causality.

But Heisenberg was not convinced that the lack of causality helped with the problem of human freedom. He reportedly said, “We no longer have any sympathy today for the concept of ‘free will.’” On the other hand, his close colleague, Carl von Weizsäcker, said that Heisenberg thought about the problem of free will “all the time.” (Owen Gingerich, personal communication)

On Einstein’s Light Quanta

Heisenberg must have known that Einstein had introduced probability and causality into physics in his 1916 work on the emission and absorption of light quanta, with his explanation of transition probabilities and discovery of stimulated emission.

But Heisenberg gives little credit to Einstein. In his letters to Einstein, he acknowledges that Einstein’s work is relevant to indeterminacy, but does not follow through on exactly how it is relevant. And as late as the Spring of 1926, perhaps following Niels Bohr, he is not convinced of the reality of light quanta. “Whether or not I should believe in light quanta, I cannot say at this stage,” he says. After Heisenberg’s talk on matrix mechanics at the University of Berlin, Einstein invited him to take a walk and discuss some basic questions:

I apparently managed to arouse Einstein’s interest/for he invited me to walk home with him so that we might discuss the new ideas at greater length. On the way, he asked about my studies and previous research. As soon as we were indoors, he opened the conversation with a question that bore on the philosophical background of my recent work. “What you have told us sounds extremely strange. You assume the existence of electrons inside the atom, and you are probably quite right to do so. But you refuse to consider their orbits, even though we can observe electron tracks in a cloud chamber. I should very much like to hear more about your reasons for making such strange assumptions.”

“We cannot observe electron orbits inside the atom,” I must have replied, “but the radiation which an atom emits during discharges enables us to deduce the frequencies and corresponding amplitudes of its electrons. After all, even in the older physics wave numbers and amplitudes could be considered substitutes for electron orbits. Now, since a good theory must be based on directly observable magnitudes, I thought it more fitting to restrict myself to these, treating them, as it were, as representatives of the electron orbits."

"But you don't seriously believe," Einstein protested, "that none but observable magnitudes must go into a physical theory?"

"Isn't that precisely what you have done with relativity?" I asked in some surprise. "After all, you did stress the fact that it is impermissible to speak of absolute time, simply because absolute time cannot be observed; that only clock readings, be it in the moving reference system or the system at rest, are relevant to the determination of time."

"Possibly I did use this kind of reasoning," Einstein admitted, "but it is nonsense all the same. Perhaps I could put it more diplomatically by saying that it may be heuristically useful to keep in mind what one has actually observed. But on principle, it is quite wrong to try founding a theory on observable magnitudes alone. In reality the very opposite happens. It is the theory which decides what we can observe. You must appreciate that observation is a very complicated process. The phenomenon under observation produces certain events in our measuring apparatus. As a result, further processes take place in the apparatus, which eventually and by complicated paths produce sense impressions and help us to fix the effects in our consciousness. Along this whole path - from the phenomenon to its fixation in our consciousness — we must be able to tell how nature functions, must know the natural laws at least in practical terms, before we can claim to have observed anything at all. Only theory, that is, knowledge of natural laws, enables us to deduce the underlying phenomena from our sense impressions. When we claim that we can observe something new, we ought really to be saying that, although we are about to formulate new natural laws that do not agree with the old ones, we nevertheless assume that the existing laws — covering the whole path from the phenomenon to our consciousness—function in such a way that we can rely upon them and hence speak of 'observations'...

"We shall talk about it again in a few years' time. But perhaps I may put another question to you. Quantum theory as you have expounded it in your lecture has two distinct faces. On the one hand, as Bohr himself has rightly stressed, it explains the stability of the atom; it causes the same forms to reappear time and again. On the other hand, it explains that strange discontinuity or inconstancy of nature which we observe quite clearly when we watch flashes of light on a scintillation screen. These two aspects are obviously connected. In your quantum mechanics you will have to take both into account, for instance when you speak of the emission of light by atoms. You can calculate the discrete energy values of the stationary states. Your theory can thus account for the stability of certain forms that cannot merge continuously into one another, but must differ by finite amounts and seem capable of permanent re-formation. But what happens during the emission of light?

It is astonishing that Einstein has to remind Heisenberg of what is now the standard textbook view, that quantum jumps of electrons are accompanied by emission and absorption of light quanta (photons) As you know, I suggested that, when an atom drops suddenly from one stationary energy value to the next, it emits the energy difference as an energy packet, a so-called light quantum. In that case, we have a particularly clear example of discontinuity. Do you think that my conception is correct? Or can you describe the transition from one stationary state to another in a more precise way?"

In my reply, I must have said something like this: "Bohr has taught me that one cannot describe this process by means of the traditional concepts, i.e., as a process in time and space. With that, of course, we have said very little, no more, in fact, than that we do not know. Whether or not I should believe in light quanta, I cannot say at this stage. Radiation quite obviously involves the discontinuous elements to which you refer as light quanta. On the other hand, there is a continuous element, which appears, for instance, in interference phenomena, and which is much more simply described by the wave theory of light. But you are of course quite right to ask whether quantum mechanics has anything new to say on these terribly difficult problems. I believe that we may at least hope that it will one day.

“I could, for instance, imagine that we should obtain an interesting answer if we considered the energy fluctuations of an atom during reactions with other atoms or with the radiation field. If the energy should change discontinuously, as we expect from your theory of light quanta, then the fluctuation, or, in more precise mathematical terms, the mean square fluctuation, would be greater than if the energy changed continuously. I am inclined to believe that quantum mechanics would lead to the greater value, and so establish the discontinuity. On the other hand, the continuous element, which appears in interference experiments, must also be taken into account. Perhaps one must imagine the transitions from one stationary state to the next as so many fade-outs in a film. The change is not sudden—one picture gradually fades while the next comes into focus so that, for a time, both pictures become confused and one does not know which is which. Similarly, there may well be an intermediate state in which we cannot tell whether an atom is in the upper or the lower state.”

“You are moving on very thin ice,” Einstein warned me. “For you are suddenly speaking of what we know about nature and no longer about what nature really does. In science we ought to be concerned solely with what nature does. It might very well be that you and I know quite different things about nature. But who would be interested in that? Perhaps you and I alone. To everyone else it is a matter of complete indifference. In other words, if your theory is right, you will have to tell me sooner or later what the atom does when it passes from one stationary state to the next”

“Perhaps,” I may have answered. “But it seems to me that you are using language a little too strictly. Still, I do admit that everything that I might now say may sound like a cheap excuse. So let’s wait and see how atomic theory develops.”

Einstein gave me a skeptical look. “How can you really have so much faith in your theory when so many crucial problems remain completely unsolved?”[25]

Pascual Jordan

With Born and Heisenberg, Jordan contributed to the mathematical formulation of matrix mechanics, the first form of quantum mechanics.

At Göttingen, Jordan was an assistant to mathematician Richard Courant and later to Born.

According to Max Jammer[26], Jordan declared, with emphasis, that observations not only disturb what has to be measured, they produce it! In a measurement of position, for example, as performed with the gamma-ray microscope,

> “the electron is forced to a decision. We compel it to assume a definite position; previously it was, in general, neither here nor there; it had not yet made its decision for a definite position.... If by another experiment the velocity of the electron is being measured, this means: the electron is compelled to decide itself for some exactly defined value of the velocity; and we observe which value it has chosen. In such a decision the decision made in the preceding experiment concerning position is completely obliterated.” According to Jordan, every observation is not only a disturbance, it is an incisive enchroachment into the field of observation: “we ourselves produce the results of measurement” [Wir selber rufen die Tatbestände hervor][27]

Jordan went further, arguing that there were times when a quantum system effectively observed itself, by collapsing into a specific state rather than remaining in a superposition of states. This does not need any “conscious observer,” as had been argued by John von Neumann and Eugene Wigner, but it does need decoherence (and collapse) of the wave function that prevents further interference of various possibilities.

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[25] *Physics and Beyond*, p. 67

[26] *The Philosophy of Quantum Mechanics*, p. 161

[27] *Erkenntinis*, 4, 215-252, 1934

Jordan connected the decoherence with thermodynamic increase in the entropy (it is also connected with the increase of information in the measurement that will be recognized by the conscious observer). He noted that every microphysical observation leaves some sort of macrophysical record (containing information). Indeed, if it did not, there would be nothing to be observed by the conscious observer.

In more orthodox formulations of quantum mechanics one is accustomed to say that the process of observation (or measurement) makes the photon decide between the two possibilities-or makes any other observable take one of its different eigenvalues. But I think that what is here called "observation," must not be interpreted as any mental process, but as a purely physical one; we may better call it, following Margenau (3), the preparation of a state, chosen from those which correspond to a certain operator or observable. The essential point seems to me to be that this process must be a macrophysical one. Macrophysics by definition deals with objects or processes which allow an application of the traditional concept of reality. It is essential that we may think of a macrophysical object as existing independently of any process of observation. Certainly we know of the planet Pluto only because we possess astronomical observatories; but we believe Pluto to have existed already in the time of homo neandertalensis. This is what we call, in the German literature, "Objektivierung," to think of objects as existing independently of the processes of observation. Or to put it otherwise: It belongs to the definition of macrophysics that we are here never faced with the characteristic microphysical features of complementarity.

Now we have indeed in each case of microphysical observation and measurement a situation in which the microphysical object of observation makes a track of macrophysical dimensions. Usually this is made possible by an avalanche process set off by the microphysical object of observation. To induce this track (giving a macrophysical record of the microphysical decision), is - I think - in some cases identical with the decision itself...

Let us first consider what might appear to be a difficulty. A silver grain in a photographic plate - or any other object suited to allow a macrophysical track to be produced by a microphysical decision - is nothing other than an accumulation of microphysical individuals. If we try to give a complete description of the silver grain, then we have to mention its atoms and their wave functions - and we are faced again with those difficulties which we tried to avoid by emphasising the macrophysical character of the silver grain.

This leads us to acknowledge that it is both possible and necessary to formulate a physical axiom not formulated hitherto. Above we held it to be part of the definition of macrophysics, to show no complications in the manner of complementarity, but to allow a complete "objectivation" of phenomena in space and time. But usually one defines macrophysics only by stating that it deals with great numbers of microphysical individuals - and this is another and a different definition. We need therefore a special axiom to express the empirical fact that these two definitions define the same thing - that really each large accumulation of microphysical individuals always shows a well defined state in space and time that a stone never, unlike an electron, has indeterminate coordinates. One often vaguely believes this to be guaranteed already by Heisenberg's $\Delta p \, \Delta q > h$; but in fact this relation only provides a possibility and not a necessity for the validity of our axiom. Let us assume that, in our experiment involving the photon, the photographic plate be removed, but that we have an arrangement whereby a macrophysical stone will fall according to the decision of the photon. Then, if we strictly assume v. Neumann's view, the stone comes to possess a wave function which makes it undecided whether it does fall or does not, and an observer has the opportunity to compel the stone to a decision by the mental process of forgetting that interference between the two wave functions of the falling stone would be possible. Schrödinger's famous cat is another illustration of this point.

I think we can summarize the situation by saying that indeed a new feature - to be formulated by a new axiom - lies in the fact that such things do not happen; all formulations of quantum mechanics hitherto given do not suffice to exclude them. We are unable to make a clock with a hand which does not always point to a definite figure on the dial. This is a well known fact, but a fact of which present theory gives no sufficient account.

It seems possible to give a still more precise meaning to our new axiom. Let us look at a special case. The emission of an alpha particle by a nucleus (this nucleus may be assumed to be infinitely heavy and to be located at a definite point) is regulated by a spherical wave. Now it is doubtless possible that by some suitable arrangement we could cause interference between alpha emissions in widely different directions, as in the case of photon emission by an atom. But if we let this emission take place in a Wilson-chamber, we always get the picture of a Wilson track showing the particle to have taken a well defined direction. Why is that?

One will scarcely doubt that the thermal motion of the gas molecules must play a decisive role in this instance. I will not discuss here the application of v. Neumann's and v. Weizsäcker's ideas to this case. My own opinion is this. We have to see the cause of the phenomenon not in any "perception," nor any mental process, nor in the fact that drops of water are formed - for surely in the absence of water (though then any direct observation would be difficult) the particle would have a definite direction of emission and we would have tracks of ionisation in the gas. The decisive point seems to be that in consequence of the gas temperature all possibilities of interference between wave functions of different atoms are destroyed. For if we were to fill the chamber not with ordinary gas but with liquid helium at the temperature T = 0, I do not see why interference of alpha emission over wide angles should not remain possible.

Returning again to our photon, we may say that the Nicoll itself would be able to make the two waves φ and ψ incoherent, provided the Nicoll had a sufficient degree of Brownian movement. Generally we can regard Brownian movement as that factor which is suited to create incoherence and to destroy every possibility of interference.

An irreversible event (wave-function collapse) followed by entropy radiated away are the two essential steps in any measurement If this idea is correct, then we see that thermodynamics is involved in quantum mechanical observation; and this is in harmony with a fact showing irreversibility to be connected with observation: We draw from an observation consequences about the probabilities of experiments to be made afterwards; we cannot reverse this relation.

But while thermodynamics is essential for the concept of observation and measurement, this concept itself seems to me to be indispensable in thermodynamics and in the notion of entropy. The relation of thermodynamics and quantum mechanics - especially thermodynamical statistics and quantum mechanics - has been the object of much discussion. Let us mention here only the first and the last stages of the subject.

1) Pauli (5) emphasised that even in quantum theory there remains the necessity of an "hypothesis of elementary disorder," which has to be acknowledged as an additional axiom besides the "pure" quantum mechanics as formulated by the Schrödinger equation. Our macrophysical axiom mentioned above stands in close connection with this axiom of elementary disorder, governing each thermodynamic system; indeed, we may also say each macrophysical system.

2) During the last years Born (1) and Green, in a series of papers, developed a fascinating account of thermodynamical statistics based upon quantum mechanics. Those results of their endeavour which are related intimately to our question here may be formulated in two theses:

A) Quantum mechanics in its full content implies irreversibility as a necessary consequence.

B) But "pure" or "restricted" quantum mechanics, which applies only the Schrödinger equation without the concepts of preparation of states, observation., measurement or "decision", would not do so.

Point A) has been emphasised by Born himself.

Point B) requires some comment in order to show that it is really in accord with Born's statement and not in any contradiction with it. Born's exposition allows us to see with great clarity where the concept of "decision" comes to play its role: The notion of transition probabilities is used - they are given by his formula [23], (1) which is derived from [21]. This is exactly the point in which we are interested here: It was the whole purpose of our discussion to show the inadequacy of the statement that the intensities of the photon waves φ and ψ are probabilities (of transition or of decision - this is only a verbal difference), and to look

> for the physical process which makes these waves incoherent.[28]

Wolfgang Pauli

Wolfgang Pauli was one of the handful of theoretical physicists who formulated the quantum theory. Like Werner Heisenberg, Paul Dirac, and Pascual Jordan, Pauli was still in his twenties in the 1920's. The other great founders, Neils Bohr, Max Born, Erwin Schrödinger, and Albert Einstein, averaged twenty years older. Max Planck, who invented the quantum of action in 1900, the year Pauli was born, was forty years older.

Pauli's name is on the *exclusion principle* which limits to two the number of fermions that can be in the same volume of phase space.

With the principal quantum number n, the angular momentum quantum number l, and the magnetic quantum number m, the electron spin s (limited to values of +1/2 and -1/2) completes the four quantum numbers needed to explain the electronic structure of all the atoms. These four numbers account for the periodic table of the elements. Pauli discovered the fourth quantum number before Goudschmidt and Uhlenbeck discovered the spin itself (just as Bohr found the principal quantum number n without a physical derivation).

While still a student, Pauli was encouraged by Arnold Sommerfeld to write an article on the theory of relativity for the Mathematical Encyclopedia that remains today one of the most important accounts of both special and general relativity. In his preface to a second edition shortly after Einstein's death in 1955, Pauli wrote of Einstein clinging to the dream of a unified field theory:

> I do not conceal to the reader my scepticism concerning all attempts of this kind which have been made until now, and also about the future chances of success of theories with such aims. These questions are closely connected with the problem of the range of validity of the classical field concept in its application to the atomic features of Nature. The critical view, which I uttered in the last section of the original text with respect to any solu-

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[28] "On the process of measurement in quantum mechanics," *Philosophy of Science*, 16, 1949, pp. 269-278

tion on these classical lines, has since been very much deepened by the epistemological analysis of quantum mechanics, or wave mechanics, which was formulated in 1927. On the other hand Einstein maintained the hope for a total solution on the lines of a classical field theory until the end of his life. These differences of opinion are merging into the great open problem of the relation of relativity theory to quantum theory, which will presumably occupy physicists for a long while to come. In particular, a clear connection between the general theory of relativity and quantum mechanics is not yet in sight.

Just because I emphasize in the last of the notes a certain contrast between the views on problems beyond the original frame of special and general relativity held by Einstein himself on the one hand, and by most of the physicists, including myself, on the other, I wish to conclude this preface with some conciliatory remarks on the position of relativity theory in the development of physics.

There is a point of view according to which relativity theory is the end-point of "classical physics", which means physics in the style of Newton-Faraday-Maxwell, governed by the "deterministic" form of causality in space and time, while afterwards the new quantum-mechanical style of the laws of Nature came into play. This point of view seems to me only partly true, and does not sufficiently do justice to the great influence of Einstein, the creator of the theory of relativity, on the general way of thinking of the physicists of today. By its epistemological analysis of the consequences of the finiteness of the velocity of light (and with it, of all signal-velocities), the theory of special relativity was the first step away from naive visualization. The concept of the state of motion of the "luminiferous aether", as the hypothetical medium was called earlier, had to be given up, not only because it turned out to be unobservable, but because it became superfluous as an element of a mathematical formalism, the group-theoretical properties of which would only be disturbed by it.

By the widening of the transformation group in general relativity the idea of distinguished inertial coordinate systems could also be eliminated by Einstein as inconsistent with the group-theoretical properties of the theory. Without this general critical attitude, which abandoned naive visualizations in favour of a con-

> ceptual analysis of the correspondence between observational data and the mathematical quantities in a theoretical formalism, the establishment of the modern form of quantum theory would not have been possible. In the "complementary" quantum theory, the epistemological analysis of the finiteness of the quantum of action led to further steps away from naive visualizations. In this case it was both the classical field concept, and the concept of orbits of particles (electrons) in space and time, which had to be given up in favour of rational generalizations. Again, these concepts were rejected, not only because the orbits are unobservable, but also because they became superfluous and would disturb the symmetry inherent in the general transformation group underlying the mathematical formalism of the theory.
>
> I consider the theory of relativity to be an example showing how a fundamental scientific discovery, sometimes even against the resistance of its creator, gives birth to further fruitful developments, following its own autonomous course.[29]

In 1930, Pauli predicted the existence of another particle, electrically neutral, but carrying the needed to conserve the total spin in the beta decay of a radioactive nucleus or a neutron (n) decaying to become a proton (p). It was called the neutrino ("little neutron") by Enrico Fermi.

$$n_0 \rightarrow p+ + e- + \nu_e$$

The neutrino was not discovered until a quarter-century after Pauli's prediction.

Pauli on Measurements

Pauli distinguished two kinds of measurements. The first is when we measure a system in a known state ψ. (It has been prepared in that state by a prior measurement.) If we again use a measurement apparatus with eigenvalues whose states include the known state, the result is that we again find the system in the known state ψ. No new information is created, since we knew what the state of the system was before the measurement. This Pauli called a measurement of the *first kind*.

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[29] *Theory of Relativity*, Pergamon Press, 1958, p.v

In the second case, the eigenstates of the system plus apparatus do not include the state of the prepared system. Dirac's transformation theory tells us to use a basis set of eigenstates appropriate to the new measurement, say the set φ_n.

In this case, the original wave function ψ can be expanded as a linear superposition of states φn with coefficients cn,

$\psi = \Sigma_n \, c_n \varphi_n$,

where $c_n^{\,2} = | < \psi \,|\, \varphi_n > |^2$ is the probability that the measurement will find the system in state φ*n*.

Pauli calls this a measurement of the *second kind*. It corresponds to von Neumann's **Process 1**, interpreted as a "collapse" or "reduction" of the wave function.

In this measurement, all the unrealized possibilities are eliminated, and the one possibility that is actualized produces new information (following von shannon's mathematical theory of the communication of information. We do not know which of the possible states becomes actual. That is a matter of ontological chance. If we did know, there would be no new information.

There is a fundamental and deeply philosophical connection between multiple possibilities and information. When one possibility is actualized, where do all the other possibilities go? For Hugh Everett, III, they go into other universes.

Pauli and the Compton Effect

When, in 1923, the discovery of the Compton effect provided evidence for Albert Einstein's "light-quantum hypothesis, Pauli objected to the explanation that a free electron had scattered the photon (a high energy x-ray). An isolated "free" electron cannot scatter a photon, he maintained.

Pauli was one of the few scientists to take Einstein's light-quantum hypothesis of 1905 seriously. Einstein's 1917 paper on the emission and absorption of radiation by matter had not convinced many physicists of the reality of light quanta before Compton's experimental evidence. No one was prepared to renounce the wave theory of light, with its well-established interference properties. Moreover, there was almost universal unhappiness with the irreducible and ontological chance that Einstein found in the direction and timing of emitted radiation.

Pauli's biographer, Charles Enz, described the work

> Shortly after Pauli's paper [1], Einstein and Ehrenfest published a different interpretation of Eq. (4.22) [2]. By writing $F = b\rho\nu (a1 + b1\rho\nu1)$ scattering may be understood as a composite process consisting of the absorption of a quantum ν followed by the emission of a quantum $\nu1$. Pauli has given a beautiful account of this entire subject in Section. 5 of his 'Quantentheorie' [3].
>
> There he concludes: "In order to maintain the connection between emission and absorption on the one hand and scattering on the other hand also in quantum theory it seems therefore natural in quantum theory to assume always scattering processes as consisting of two partial processes. . . . Although in the case of free electrons there is no case of emission and absorption we will have to hold on to the decomposition of the scattering processes into two partial processes" (translated from Ref. [3], p. 28).
>
> 1 W. Pauli, "Über das thermische Gleichgewicht zwischen Strahlung und freien Electronen," Zeitschrift für Physik, 18, 227 (1923), reprinted in R. Kronig and V. F. Weisskopf (eds.) Collected Scientific Papers by Wolfgang Pauli, In Two Volumes (Wiley Interscience, New York, 1964), vol.2, pp.161-175
>
> 2 A. Einstein and P. Ehrenfest, "Zur Quantentheorie des Strahlungsgleichgewichts," Zeitschrift für Physik, 19, 301 (1923)
>
> 3 W. Pauli, "Quantentheorie," in H. Geiger and K. Scheel (eds.), Handbuch der Physik, vol.23, 226, pp.1-278 (1926), repr. in Collected Scientific Papers, vol.1, pp.271-548

Max Planck

In 1900, Planck hypothesized a quantum of action h and restricted the energy in oscillators radiating electromagnetic energy to integer multiples of $h\nu$, where ν is the radiant frequency. He then discovered a formula for the distribution of radiant energy in a black body at any temperature.

$$B_\nu (\nu, T) = (2h\nu^3 / c^2) (1 / (e^{h\nu / kT} - 1))$$

Planck solved the great problem of blackbody radiation by applying the statistical mechanics of the Maxwell-Boltzmann velocity distribution law for particles to the distribution of energy in a radiation field. Planck did not suggest that light actually came in quantized (discrete) bundles of energy. That was the work of Albert Einstein five years later in his photo-electric effect paper (for which he won the Nobel Prize), in which he proposed his "light-quantum hypothesis." For Einstein, the particle equivalent of light (later called a "photon") contains $h\nu$ units of energy, where h is Planck's constant and ν is the frequency of the light wave.

Planck did not actually believe that light radiation itself existed as light quanta. His quantization assumption was for an ensemble of "oscillators" or "resonators" that were emitting and absorbing the radiation. Although the Lorentz theory of the electron was already complete, Planck did not accept electrons and instead described "the energy flowing across a spherical surface of a certain radius containing the resonator." He assumed the resonators could be described as having energy values limited to multiples of $h\nu$.

Note the resemblance to the Bohr theory of the atom thirteen years later, where Bohr postulated stationary states of the electron and transitions between those states with the emission or absorption of continuous waves of energy equal to $h\nu$!

Planck's assumption was simply a mathematical device to make the distribution of light as a function of frequency (and thus energy) resemble the Maxwell-Boltzmann distribution of molecular velocities in a gas as a function of velocity (and thus energy). In 1925, he called his work "a fortunate guess at an interpolation formula" and "the quantum of action a fictitious quantity... nothing more than mathematical juggling."

Note the striking resemblance between the distribution of blackbody radiation as a function of temperature and the Maxwell-Boltzmann distribution of velocities.

Planck in 1900 explained the spectral distribution of colors (wavelengths) in blackbody electromagnetic radiation by using Boltzmann's principle that the entropy *S* of a gas is related to the probabilities W for the possible random distributions of molecules in different places in its container and with different velocities. $S = k \log W$, where k is Boltzmann's constant (so named by Planck. Boltzmann and Einstein used R/N)). Boltzmann's calculations of probabilities used the number of ways that particles can be distributed in various volumes of phase space. Planck used the same combinatorial analysis, but now for the number of ways that discrete elements of energy could be distributed among a number of radiation oscillators.

To simplify calculations, both Boltzmann and Planck assumed that energies could be considered multiples of a unit of energy, $E = \varepsilon, 2\varepsilon, 3\varepsilon \ldots$ Plank regarded this quantum hypothesis as a mathematically convenient device, but not representing reality. He found the density of radiation with frequency ν to be

$$\rho_\nu = (8\pi h\nu^3/c^2) / (e^{h\nu/kT} - 1).$$

Planck's "blackbody" radiation law was the first known connection between the mechanical laws of matter and the laws of electromagnetic energy. Planck realized that he had made a great step in physical understanding, "the greatest discovery in physics since Newton," he reportedly told his seven-year-old son in 1900.

In particular, Planck found that Boltzmann's statistical mechanics constant $k = R/N$, derived from the distribution of velocities of material gas particles, appears in his new law for the distribution of electromagnetic radiation energy. Boltzmann himself had never described this constant k as such. It was Planck who gave it a symbol and a name, although it is inscribed on Boltzmann's tomb in his famous formula relating entropy to probability, $S = k \log W$

Planck established an independent and very accurate value for Boltzmann's constant. His blackbody radiation distribution law of course also includes the new Planck constant h. He called it the "quantum of action" because it had the units of position times momentum. Planck's formula led him to a value for Avogadro's number of molecules in a mole (the gram molecular weight) of a gas and an estimate of the fundamental unit of electrical charge. These gave Planck great confidence that his "fictitious" formula must be correct.

Five years later, Albert Einstein explained the photoelectric effect using "light quanta," discrete units of light energy, later called photons. Since the momentum of a particle is the energy divided by velocity of a particle, the momentum p of a photon is $p = h\nu/c$, where c is the velocity of light. To make the dual aspect of light as both waves and particles (photons) more plausible, Einstein interpreted the square of the light wave amplitude as the probable density of photons.

In fact, Planck fundamentally disliked the idea that physical quantities might be discrete and not continuous. He did not truly accept quanta of light until many years after Einstein had shown the quantization of light in his 1905 explanation of the photoelectric effect. Nevertheless, Planck's constant h lies at the heart of quantum mechanics, which introduced an irreducible and ontological randomness or indeterminacy into physics, first recognized by Einstein in his 1916 work on transition probabilities for the emission and absorption of light quanta.

Planck, along with Einstein, Erwin Schrödinger and others, opposed such indeterminism. Einstein called chance a "weakness in the theory." Planck remained convinced that determinism and strict causality were essential requirements for physical science and so must be true.

> "Just as no physicist will in the last resort acknowledge the play of chance in human nature, so no physiologist will admit the play of chance in the absolute sense."
>
> "the assumption of chance in inorganic nature is incompatible with the working principle of natural science."
>
> "We must admit that the mind of each one of our greatest geniuses — Aristotle, Kant or Leonardo, Goethe or Beethoven, Dante or Shakespeare — even at the moment of its highest flights of thought or in the most profound inner workings of the soul, was subject to the causal fiat and was a instrument in the hands of an almighty law which governs the world."[30]

In 1925, a few years before the development of quantum mechanics, Planck republished a series of articles as the book *A Survey*

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[30] *Where Is Science Going?*, pp.147, 154, 156

of Physical Theory. In an article on “The Nature of Light,” Planck describes Einstein’s insight in 1905 that led to Einstein’s “light-quantum hypothesis.” But Planck does not mention Einstein!

> When ultra-violet rays fall on a piece of metal in a vacuum, a large number of electrons are shot off from the metal at a high velocity, and since the magnitude of this velocity does not essentially depend on the state of the metal, certainly not on its temperature, it is concluded that the energy of the electrons is not derived from the metal, but from the light rays which fall on the metal. This would not be strange in itself; it would even be assumed that the electro-magnetic energy of light waves, is transformed into the kinetic energy of electronic movements. An apparently insuperable difficulty from the view of Huygens’s wave theory is the fact (which was discovered by Philipp Lenard and others), that the velocity of the electrons does not depend on the intensity of the beam, but only on the wavelength, i.e. on the colour of light used. The velocity increases as the wave-length diminishes. If the distance between the metal and the source of light is continuously increased, using, for example, an electric spark as the source of light, the electrons continue to be flung off with the same velocity, in spite of the weakening of the illumination; the only difference is that the number of electrons thrown off per second decreases with the intensity of the light.
>
> The only possible explanation for these peculiar facts appears to be that the energy radiated from the source of light remains, not only for all time, but also throughout all space, concentrated in certain bundles, or, in other words, that light energy does not spread out quite uniformly in all directions, becoming continuously less intense, but always remains concentrated in certain definite quanta, depending only on the colour, and that these quanta move in all directions with the velocity of light. Such a light-quantum, striking the metal, communicates its energy to an electron, and the energy always remains the same, however great the distance from the source of light. Here we have Newton’s emanation theory resurrected in another and modified

Planck here describes Einstein’s “light-quantum hypothesis,” his 1905 explanation for the photoelectric effect for which Einstein won the Nobel Prize. But Planck does not mention Einstein!

> form. But interference, which was a bar to the further development of Newton's emanation theory, is also an enormous difficulty in the quantum theory of light, for it is difficult at present to see how two exactly similar light quanta, moving independently in space, and meeting on a common path, can neutralize each other, without violating the principle of energy..
>
> So the present lecture on our knowledge of the physical nature of light ends, not in a proud proclamation, but in a modest question. In fact, this question, whether light rays themselves consist of quanta, or whether the quanta exist only in matter, is the chief and most difficult dilemma before which the whole quantum theory, halts, and the answer to this question will be the first step towards further development.[31]

Erwin Schrödinger

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.

In his early career, Schrödinger was a great exponent of fundamental chance in the universe. He followed his teacher Franz S. Exner, who was himself a colleague of the great Ludwig Boltzmann at the University of Vienna. Boltzmann used intrinsic randomness in molecular collisions (molecular chaos) to derive the increasing entropy of the Second Law of Thermodynamics.

Most physicists, mathematicians, and philosophers believed that the chance described by the calculus of probabilities was actually completely determined. The "bell curve" or "normal distribution" of random outcomes was itself so consistent that they argued for underlying deterministic laws governing individual events. They thought that we simply lack the knowledge necessary to make exact predictions for these individual events. Pierre-Simon Laplace was first to see in his "calculus of probabilities" a universal law that determined the motions of everything from the largest astronomical objects to the smallest particles.

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[31] *A Survey of Physical Theory*, pp.96-101

On the other hand, in his inaugural lecture at Zurich in 1922, Schrödinger argued that the evidence did not justify our assumptions that physical laws were deterministic and strictly causal. His inaugural lecture was modeled on that of Franz Serafin Exner in Vienna in 1908.

> "Exner's assertion amounts to this: It is quite possible that Nature's laws are of thoroughly statistical character. The demand for an absolute law in the background of the statistical law — a demand which at the present day almost everybody considers imperative — goes beyond the reach of experience. Such a dual foundation for the orderly course of events in Nature is in itself improbable. The burden of proof falls on those who champion absolute causality, and not on those who question it. For a doubtful attitude in this respect is to-day by far the more natural."

Several years later Schrödinger wrote

> "Fifty years ago it was simply a matter of taste or philosophic prejudice whether the preference was given to determinism or indeterminism. The former was favored by ancient custom, or possibly by an a priori belief. In favor of the latter it could be urged that this ancient habit demonstrably rested on the actual laws which we observe functioning in our surroundings. As soon, however, as the great majority or possibly all of these laws are seen to be of a statistical nature, they cease to provide a rational argument for the retention of determinism.
>
> "If nature is more complicated than a game of chess, a belief to which one tends to incline, then a physical system cannot be determined by a finite number of observations. But in practice a finite number of observations is all that we can make. All that is left to determinism is to believe that an infinite accumulation of observations would in principle enable it completely to determine the system. Such was the standpoint and view of classical physics, which latter certainly had a right to see what it could make of it. But the opposite standpoint has an equal justification: we are not compelled to assume that an infinite number of observations, which cannot in any case be carried out in practice, would suffice to give us a complete determination."

Despite these strong arguments against determinism, just after he completed the wave mechanical formulation of quantum mechanics in June 1926 (the year Exner died), Schrödinger began to side with the determinists, including especially Max Planck and Albert Einstein (who ironically had in 1916 showed that ontological chance s involved in the emission of radiation).

Schrödinger's wave equation is a continuous function that evolves smoothly in time, in sharp contrast to the discrete, discontinuous, and indeterministic "quantum jumps" of the Born-Heisenberg matrix mechanics. His wave equation seemed to Schrödinger to restore the continuous and deterministic nature of classical mechanics and dynamics. And it allows us to visualize particles as wave packets moving in spacetime, which was very important to Schrödinger. By contrast, Bohr and Heisenberg and their Copenhagen Interpretation of quantum mechanics insisted that visualization of quantum events is not possible.

Max Born, Werner Heisenberg's mentor and the senior partner in the team that created matrix mechanics, shocked Schrödinger with the interpretation of the wave function as a "probability amplitude." The motions of particles are indeterministic and probabilistic, even if the equation of motion for the probability is deterministic. It is true, said Born, that the wave function itself evolves deterministically, but its significance is that it predicts only the probability of finding an atomic particle somewhere. When and where particles would appear - to an observer or to an observing system like a photographic plate - was completely and irreducibly random, he said.

Einstein had seen clearly for many years that quantum transitions involve chance, that quantum jumps are random, but he could not believe it. Although the Schrödinger equation of motion is itself continuous and deterministic, it is impossible to restore continuous deterministic behavior to material particles and return physics to strict causality. Schrödinger did not like this idea and never accepted it, despite the great success of quantum mechanics, which uses Schrödinger's wave functions to calculate Heisenberg's matrix elements for atomic transition probabilities.

Discouraged, Schrödinger wrote to his friend Willie Wien in August 1926

> “[That discontinuous quantum jumps]...offer the greatest conceptual difficulty for the achievement of a classical theory is gradually becoming even more evident to me.”...[yet] today I no longer like to assume with Born that an individual process of this kind is “absolutely random.” i.e., completely undetermined. I no longer believe today that this conception (which I championed so enthusiastically four years ago) accomplishes much. From an offprint of Born’s work in the Zeitsch f. Physik I know more or less how he thinks of things: the waves must be strictly causally determined through field laws, the wavefunctions on the other hand have only the meaning of probabilities for the actual motions of light- or material-particles.”

Why did Schrödinger not welcome Born’s absolute chance? It was strong evidence that Boltzmann’s assumption of chance in atomic collisions was completely justified. Exner thought chance was absolute, but did not live to see how fundamental it was to physics. And the early Epicurean idea that atoms sometimes “swerve” could be replaced by the insight that atoms are always swerving randomly - when near other atoms.

Could it be that senior scientists like Max Planck and Albert Einstein were so delighted with Schrödinger’s work that it turned his head? Planck, universally revered as the elder statesman of physics, invited Schrödinger to Berlin to take Planck’s chair as the most important lecturer in physics at a German university. And Schrödinger shared Einstein’s goal to develop a unified (continuous and deterministic) field theory. Schrödinger won the Nobel prize in 1933. But how different our thinking about absolute chance would be if perhaps the greatest theoretician of quantum mechanics had accepted random quantum jumps in 1926?

In his vigorous debates with Neils Bohr and Werner Heisenberg, Schrödinger attacked the probabilistic Copenhagen interpretation of his wave function with a famous thought experiment (based on an Einstein suggestion) called Schrödinger’s Cat.

In 1952, Schrödinger wrote two influential articles in the British Journal for the Philosophy of Science denying quantum jumping. They influenced generations of quantum collapse deniers, including John Bell, John Wheeler, Wojciech Zurek, and H. Dieter Zeh.

The Einstein-Podolsky-Rosen Paradox

Schrödinger was very pleased to read the Einstein-Podolsky-Rosen paper in 1935. He immediately wrote to Einstein in support of an attack on Bohr, Born, and Heisenberg and their "dogmatic" quantum mechanics.

> "I was very happy that in the paper just published in P.R. you have evidently caught dogmatic q.m. by the coat-tails...My interpretation is that we do not have a q.m. that is consistent with relativity theory, i.e., with a finite transmission speed of all influences. We have only the analogy of the old absolute mechanics . . . The separation process is not at all encompassed by the orthodox scheme."[32]

Einstein had said in 1927 at the Solvay conference that nonlocality (faster-than-light signaling between particles in a space-like separation) seemed to violate relativity in the case of a single-particle wave function with non-zero probabilities of finding the particle at more than one place. What instantaneous "action-at-a-distance" prevents particles from appearing at more than one place, Einstein oddly asked. [The answer, one particle becoming two particles never appears in nature. That would violate the most fundamental conservation laws.]

In his 1935 EPR paper, Einstein cleverly introduced two particles instead of one, and a two-particle wave function that describes both particles. The particles are identical, indistinguishable, and with indeterminate positions, although EPR wanted to describe them as widely separated, one "here" and measurable "now" and the other distant and to be measured "later."

Schrödinger challenged Einstein's idea that two systems that had previously interacted can be treated as separated systems, and that a two-particle wave function ψ12 can be factored into a product of separated wave functions for each system, ψ1 and ψ2. They cannot,

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[32] *Schrödinger*, Walter Moore, p.304

until another quantum event separates them. Schrödinger published a famous paper defining his idea of "entanglement" in August of 1935. 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. 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...[33]

In the following year, Schrödinger looked more carefully at Einstein's assumption that the entangled system could be separated enough to be regarded as two systems with independent wave functions:

> Years ago I pointed out that when two systems separate far enough to make it possible to experiment on one of them without interfering with the other, they are bound to pass, during the process of separation, through stages which were beyond the range of quantum mechanics as it stood then. For it seems hard to-imagine a complete separation, whilst the systems are still so close to each other, that, from the classical point of view, their interaction could still be described as an unretarded actio in distans. And ordinary quantum mechanics, on account of its thoroughly unrelativistic character, really only deals with the actio in distans case. The whole system (comprising in our

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[33] "Discussion of Probability between Separated Systems", *Proceedings of the Cambridge Physical Society* 1935, 31, issue 4, p.555

> case both systems) has to be small enough to be able to neglect the time that light takes to travel across the system, compared with such periods of the system as are essentially involved in the changes that take place...
>
> It seems worth noticing that the paradox could be avoided by a very simple assumption, namely if the situation after separating were described by the expansion [$\psi (x,y) = \Sigma ak\, gk(x) fk(y)$, as assumed in EPR], but with the additional statement that the knowledge of the phase relations between the complex constants ak has been entirely lost in consequence of the process of separation.
>
> This would mean that not only the parts, but the whole system, would be in the situation of a mixture, not of a pure state. It would not preclude the possibility of determining the state of the first system by suitable measurements in the second one or vice versa. But it would utterly eliminate the experimenters influence on the state of that system which he does not touch.[34]

During separation, if the two-particle wave function collapses, the system decoheres, there is no more interference, and we have a mixed state rather than a pure state.

Schrödinger says that the entangled system may become *disentangled* long before any measurements and that perfect correlations between the measurements would remain. Note that the entangled system could simply decohere as a result of interactions with the environment, as proposed by decoherence theorists. All the perfectly correlated results of Bell-inequality experiments would be preserved.

John von Neumann

In his 1932 *Mathematical Foundations of Quantum Mechanics*, von Neumann explained that two fundamentally different processes are going on in quantum mechanics (in a temporal sequence for a given particle - not at the same time).

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[34] "Probability Relations between Separated Systems," *Proceedings of the Cambridge Physical Society* 1936, 32, issue 2, p.446-452

Process 1. A non-causal process, in which the measured electron winds up randomly in one of the possible physical states (eigenstates) of the measuring apparatus plus electron.

The probability for each eigenstate is given by the square of the coefficients cn of the expansion of the original system state (wave function *ψ*) in an infinite set of wave functions φ that represent the eigenfunctions of the measuring apparatus plus electron.

$c_n = < \varphi_n \mid \psi >$

This is as close as we get to a description of the motion of the particle aspect of a quantum system. According to von Neumann, the particle simply shows up somewhere as a result of a measurement.

Information physics says that the particle shows up whenever a new stable information structure is created, information that can be observed.

Process 2. A causal process, in which the electron wave function ψ evolves deterministically according to Erwin Schrödinger's equation of motion for the wavelike aspect. This evolution describes the motion of the probability amplitude wave *ψ* between measurements. The wave function exhibits interference effects. But interference is destroyed if the particle has a definite position or momentum. The particle path itself can not be observed.

$(ih/2\pi)\ \partial\psi/\partial t = H\psi$

Von Neumann claimed there is another major difference between these two processes. **Process 1** is thermodynamically irreversible. **Process 2** is reversible. This confirms the fundamental connection between quantum mechanics and thermodynamics that is explainable by information physics and the information interpretation of quantum mechanics.

Information physics establishes that **process 1** may create information. It is always involved when information is created. It is irreversible when stable information is recorded.

Process 2 is deterministic and information preserving or conserving. It is reversible.

The first of these processes has come to be called the *collapse* of the wave function.

It gave rise to the so-called problem of measurement, because its randomness prevents it from being a part of the deterministic mathematics of process 2.

Information physics has solved the problem of measurement by identifying the moment and place of the collapse of the wave function with the creation of an observable information structure. There are interactions which create collapses but do not create stable information structures. These can never be the basis of measurements.

The presence of a conscious observer is not necessary. It is enough that the new information created is observable, should a human observer try to look at it in the future. Information physics is thus subtly involved in the question of what humans can know (epistemology).

The Schnitt

Von Neumann described the collapse of the wave function as requiring a “cut” (Schnitt in German) between the microscopic quantum system and the observer. He said it did not matter where this cut was placed, because the mathematics would produce the same experimental results.

There has been a lot of controversy and confusion about this cut. Eugene Wigner placed it outside a room which includes the measuring apparatus and an observer A, and just before observer B makes a measurement of the physical state of the room, which is imagined to evolve deterministically according to process 2 and the Schrödinger equation.

The case of Schrödinger’s Cat is thought to present a similar paradoxical problem.

von Neumann contributed a lot to this confusion in his discussion of subjective perceptions and “psycho-physical parallelism,” which was encouraged by Neils Bohr. Bohr interpreted his “complementarity principle” as explaining the difference between subjectivity and objectivity (as well as several other dualisms). von Neumann wrote: