GIVE
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A
CHANCE !

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CHALMERS UNIVERSITY OF TECHNOLOGY

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SE 412 96 GÖTEBORG, SWEDEN

2022

ISBN 978-91-88041-53-1

GIVE QUANTUM MECHANICS A CHANCE!

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To colleagues around the globe, who work with quantum mechanics on a daily basis.

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PREFACE

In a recent book [1], technology historian Julia Ravanis has shared her ideas about the development of physics, in particular quantum mechanics. She finds parallel connections between physics and human life. She regrets the lack of ambitions in physics to reach a better understanding of quantum mechanics. Physics students are trained to apply quantum theory without questioning, instead of being openly informed about remaining fundamental problems. At the same time, "in popular culture, interpretations of quantum mechanics are flourishing as sheer magic." Julia Ravanis was herself a physics student a few years ago, and she states her critical position in the book.

I started my own studies in quantum mechanics in Uppsala in 1956, and since that time, I have been carrying with me the measurement problem of quantum mechanics. (My choice was to consider it as an unsolved physical problem.) In later years, I have come to realize that the schooling of physics students that Ravanis criticized, has developed over a long time and is now an integrated part of the physics culture. This culture blocks the ways towards solving the measurement problem and it prevents the understanding of the important progress that has actually taken place. In particular, I am thinking about the progress in quantum diffusion which took place roughly during the period 1985-1995 [2].

In my own thinking, I have only slowly and stepwise been able to break blockings and see new possibilities and connections. Afterwards it has been difficult to understand how my blockings could have been so strong.

One physicist who kept himself to purely physical reasoning in his discussions about the measurement problem was John Bell [3]. He meant that also methods used in everyday physics research could be of value for a deeper understanding. Bell appreciated very much the work that was done in quantum diffusion. Unfortunately, his influence was not sufficient to inspire more physicists to go into research on measurement as a physical process. This little book is an attempt to continue the physical analysis in the tradition of John Bell.

A few months ago, I read quite carefully Erwin Schrödinger's famous article from 1935 with Schrödinger's cat [4]. As has been described quite recently by David Kaiser [5], the article was primarily intended to criticize the quantum mechanics of the time. Schrödinger, then a visitor in Oxford, had a frequent exchange of letters with Albert Einstein in Princeton. The fable about the cat does not take much space in the article. Most of the article is an attempt to analyze the interaction between a small quantum system and a measurement apparatus. The description given by Schrödinger is clear and well structured. His conclusions come from intelligent conjectures, not physical calculations. He probably felt very sure of being right in his guesses. If he had had access to relativistic quantum mechanics, everything would have looked different and it could have been possible to see how one definite measurement result can come out.

I mention Schrödinger's article [4], because it was an early confrontation of two opposite traditions in the same text, one based on scientific questioning, the other on ideology, tied to the author's conviction. While most readers now are drawn to the fable, written to show that quantum mechanics is absurd, I was fascinated by his early approach to analyze the measurement problem. It could almost have led to a solution but critically needed basic knowledge was not yet available to him and he did not like open questions.

Both traditions are present in Ravani's book [1]. The measurement problem is still an important arena for confrontations between these two traditions.

It can be tempting to connect oneself to a thrilling system of ideas, instead of analyzing a partial aspect of an unsolved physical problem.

Many such partial aspects were collected in John Bell's personal book Speakable and Unspeakable in Quantum Mechanics [3], and in Andrew Whitaker's rich book on the history of measurement theory, Einstein, Bohr and the Quantum Dilemma [6]. These books have given me a valuable basis to build on.

In this book, I have tried to continue in Bell's tradition, to do physical analysis, as it is conventionally done in everyday quantum mechanics. In the play in Chapter 2, I have also let Albert Einstein and Marie Curie join Bell as spokespersons for a realistic view.

Quantum Mechanics is not only a great theory with an enormous explanatory power. Contrary to what is usually expressed in comments on quantum mechanics, it is understandable. Also contrary to what is usually claimed, quantum measurement can be understood within the theory. Quantum Mechanics should be freed from the heavy burden of mysticism and be given its proper place in the modern scientific understanding of the world. We should finally give Quantum Mechanics a chance!

References

1. Julia Ravanis, Skönheten i kaos, ("The Beauty of Chaos" (in Swedish), Natur och kultur, Sweden 2021).

2. See the reference list of Chapter 1.

3. J.S. Bell, Speakable and Unspeakable in Quantum Mechanics (2nd ed., Cambridge, U.K. 2004).

4. E. Schrödinger, Naturwissenschaften 23, 807 (1935). English translation by John D. Trimmer in J.A. Wheeler and W.H. Zurek (eds), Quantum Theory of Measurement (Princeton Univ, Press, 1983).

5. D. Kaiser, The rise of fascism shaped Schrödinger's cat fable, Nautilus: science connected (October 13, 2016).

6. A. Whitaker, Einstein, Bohr and the Quantum Dilemma (2nd ed., Cambridge, U.K. 2006).

1. QUANTUM-MECHANICAL/STATISTICAL ANALYSIS OF MEASUREMENT

Background: new physics in early 20th century

Around 1900, several physical phenomena had been observed which did not fit into the traditional physical understanding of the 19th century. Among these were: a different kind of matter (radioactive) had been discovered; the speed of light seemed to be independent of the frame of inertia in which it was measured; the energy spectrum of heat radiation did not agree with the known thermodynamics; the interaction of electromagnetic radiation with atoms showed unexpected features.

One person was active in the study of several of these phenomena and made great contributions to the understanding of them: Albert Einstein. He was a pioneer in the two great theories of the century shift which led to a revolutionary change in physics: the special theory of relativity and quantum mechanics. About a decade later, he presented another new great theory: the general theory of relativity. Some predictions of this theory have been confirmed or reconfirmed in recent years, gravitational radiation and black holes.

The special theory of relativity and quantum mechanics now form the basis for the physical understanding of the structure and interaction of matter, These two theories have an enormous capacity to explain phenomena in physics, and due to their special role of physics, in the whole of science. In some instances, this includes a very accurate quantitative understanding. This situation is unique in the history of science.

To describe the special theory of relativity, it is quite straightforward to use geometric concepts, even though one must take into account the different nature of the fourth dimension, time. Therefore relativity is recognized as a theory that is fairly easy to comprehend. In contrast to this, quantum mechanics is usually described, even by physicists, as mysterious and difficult to understand. In relation to the capacity of quantum mechanics to explain a very broad range of phenomena, this situation is absurd. We shall soon return to the background of this situation.

The special theory of relativity and quantum mechanics are also the foundation of scientific applications and hence of all modern technology. Together with the general theory of relativity, these theories help us to understand our universe, to the extent that it can be understood. In this context, one should mention the difficulties to make general relativity and quantum mechanics fit together.

Determination of a measurement value in quantum mechanics

There is one reason behind the view of quantum mechanics as difficult and mysterious. One important aspect in the understanding of quantum mechanics is still incomplete. Physicists do not have a common understanding of what happens at the measurement of a physical quantity on a system, described by quantum mechanics. First, only certain measurement values can be obtained. What happens in a single measurement event can be predicted only in special cases where the result is unique. In general, more than one result is possible. If the state of the measured system is known, one can predict the probabilities for different results. This problem, the measurement problem of quantum mechanics, goes back to the 1920s.

In general, the quantity to be determined in the studied system, does not have a unique value. Instead, the value becomes determined in the process itself. In his book "Speakable" [1], John Bell described the situation as follows:

> This word [measurement] very strongly suggests the ascertaining of some preexisting property of some thing, any instrument involved playing a purely passive role. Quantum experiments are just not like that, as we learned especially from Bohr. The result has to be regarded as a joint product of 'system' and 'apparatus', the complete experimental set-up. ["Speakable", p. 166]

In line with this, we have decided to use the term 'determination', rather than 'measurement'. We shall limit our discussion to the determination of the value of a physical quantity for a system that is not destroyed in the process but remains afterwards. We choose a system with two possibilities: an electron (e^-) and the determination of the vertical component of its spin. This component can be directed up (we denote this state of e^- by $|+\rangle$) or it can be directed down (we denote this state of e^- by $|-\rangle$). When determining the vertical spin component, these are the two possible outcomes. If the electron, prior to the determination, is in the state $|+\rangle$ or in the state $|-\rangle$, the result is spin-up or spin-down, respectively.

Mathematically, the states $|+\rangle$ and $|-\rangle$ can be viewed as orthogonal basic vectors, spanning a two-dimensional space of quantum states. If e^- has been given another spin direction (than up or down) before the determination of the vertical spin component, its state $|\psi\rangle$ can be expressed as a linear combination, a superposition of $|+\rangle$ and $|-\rangle$ (See Box 1):

$$|\psi\rangle = \psi_+|+\rangle + \psi_-|-\rangle,$$

with $|\psi_+|^2 + |\psi_-|^2 = 1$, so that $|\psi\rangle$ is also a normalized vector.

In quantum mechanics, it is customary to use complex numbers ($u = a + bi$, where a and b are real numbers and $i = \sqrt{-1}$ is the imaginary unit, with the complex conjugate $u^* = a - bi$, and the squared norm (squared modulus) $|u|^2 = uu^* = a^2 + b^2$). Here we may assume that ψ_+ and ψ_- are real numbers (sufficient if we only consider spin directions in one plane through the vertical axis.).

If e^- is in a state $|\psi\rangle$ with both ψ_+ and ψ_- non-zero, and we have to determine its vertical spin component, the result can only be up (then after the determination, e^- will be in the state $|+\rangle$) or down (then after the determination, e^- will be in the state $|-\rangle$). For a single case, it is impossible to predict which result will be obtained. But taking a new e^-, again in the state $|\psi\rangle$, and making a new determination and repeating this many times, we will find the result 'up' ($|+\rangle$) in $|\psi_+|^2$ of

<u>Basis states</u>: $|+\rangle$ (spin up) and $|-\rangle$ (spin down).

(for these states, measurement/determination results are certain.)

<u>Superposition</u> of basis states: $|\psi\rangle = \psi_+|+\rangle + \psi_-|-\rangle$ $\quad (|\psi_+|^2 + |\psi_-|^2 = 1$

With e^- in the state $|\psi\rangle$, a determination of its vertical spin component, leads to:

(+) spin up and e^- in the final state $|+\rangle$, or
(−) spin down and e^- in the final state $|-\rangle$.

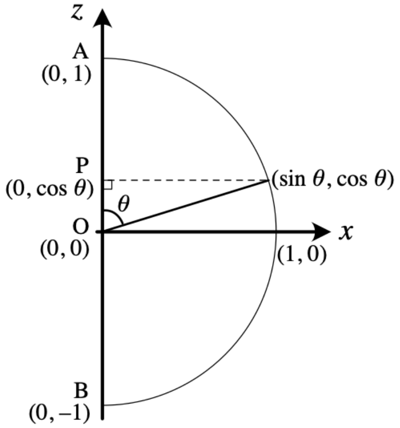
<u>Born's rule</u>: The probability for (+) is $|\psi_+|^2$,
and
the probability for (−) is $|\psi_-|^2$.

If the spin of e^- initially points in the direction $(\sin\theta, 0, \cos\theta)$, then the components of the state $|\psi\rangle$ are:

$$\psi_+ = \cos(\theta/2), \qquad |\psi_+|^2 = \frac{1+\cos\theta}{2} = \tfrac{1}{2}\,\mathrm{BP},$$

and

$$\psi_- = \sin(\theta/2); \qquad |\psi_-|^2 = \frac{1-\cos\theta}{2} = \tfrac{1}{2}\,\mathrm{PA}.$$



BOX 1. <u>Quantum states for the spin of an electron and determination of the vertical spin component</u>.

all cases, and 'down' ($|-\rangle$) in $|\psi_-|^2$ of all cases. This experimental fact is known as *Born's rule*.

Thus we can predict probabilities but not single results. *Among physicists, no common opinion exists on how a single result comes about*. This is *the measurement problem of quantum mechanics*. The description that we have just given here of a determination/measurement and of the measurement problem itself, however, are things that physicists agree on.

The measurement problem and the approach in the present work

The situation that there is something that should have been explained but which has not yet got its final explanation, has clearly influenced the situation in physics. Physicists have tried different ways to interpret what is already known. One has been open for the possibility that an unsolved problem can be a window into new important knowledge. Sometimes one has considered quantum mechanics to be only a theory about probabilities. Through this development, in the cultural context, physics has been given a mystical role; people from different schools of ideas in other fields have looked into physics for clues to their problems.

In "*Speakable*" [1], John Bell made a typology for different approaches to solve the measurement problem: in *unromantic* approaches, one seeks a solution in conventional research in physics; *romantic* approaches are also open to epistemological and metaphysical theories. Our approach is totally unromantic; in Bell's classification it would be called *pragmatic*. Determination of a measurement value is described completely within quantum mechanics, in our case meaning *relativistic quantum mechanics*. No special metatheories or generalizations are needed.

For everyday work with quantum mechanics, *the quantum-mechanical state* is a description of reality; this is a functioning *pragmatic ontology*. Now with determination (of a measurement value) also being possible to describe in quantum-mechanical theory, the pragmatic ontology of quantum mechanics can be considered as more generally valid. Thus the quantum-mechanical state can be more widely recognized as a description of reality.

John von Neumann's dilemma

Already around 1930, John von Neumann tried to solve the measurement problem but he found it necessary to use a special kind of dynamics for measurement [2]. As we have seen, the problem appears when the investigated system is in a state where the physical quantity to be determined does not have a predetermined value. One then gets one out of a set of possible values (in our example, one out of two values), and it is impossible to predict which one.

The interaction of e^- with the measurement apparatus should be such that the apparatus can register the vertical spin state of e^- without changing it. The components of e^- may interact with separate parts of the measurement apparatus. We have stayed with our example, but the discussion can be generalized from e^- to any system under study. In his attempt to analyze the determination process, von Neumann got entanglement between the studied system and the measurement apparatus (i.e., a state that is a superposition of product states), but he could not see any way for the interaction to change the relative proportions of the two components (+ and –). Therefore he could see no way for one component to take over completely with one single result obtaining. This situation has been called von Neumann's dilemma [3]. We describe it in Box 2.

The famous article by Erwin Schrödinger about a cat in a cruel superposition state where one component is a living cat and the other one is a dead cat, was also published in the 1930s [4]. This is von Neumann's dilemma extended to a macroscopic, and even living, object. We show the situation in Box 3, extended with an extra component, an assistent known as "Wigner's Friend [5]. It should be mentioned immediately that a system of this kind would have an uncontrollable interacton with its environment that would make it totally unrealistic to discuss it as a closed quantum-mechanical system.

Consider a determination of the vertical spin component of e^- through an interaction between e^- and a measurement apparatus M initially in a state of preparedness $|0\rangle_M$.

First we assume e^- to be initially in a definite state of vertical spin, $|+\rangle_{e^-}$ or $|-\rangle_{e^-}$. The combined initial state then is

$$|+\rangle_{e^-} \otimes |0\rangle_M \quad \text{or} \quad |-\rangle_{e^-} \otimes |0\rangle_M .$$

Interaction between e^- and M gives a mark on M from the state of e^-. Thus, with simple notation, the interaction takes the initial state into a final state as follows:

$$|j\rangle_{e^-} \otimes |0\rangle_M \text{ is taken into } |j\rangle_{e^-} \otimes |(j)\rangle_M , \quad j = \pm .$$

We then take the case with e^- initially in the superposition

$$|\psi\rangle_{e^-} = \psi_+ |+\rangle_{e^-} + \psi_- |-\rangle_{e^-} ,$$

i.e, the combined initial and final states for e^- and M are

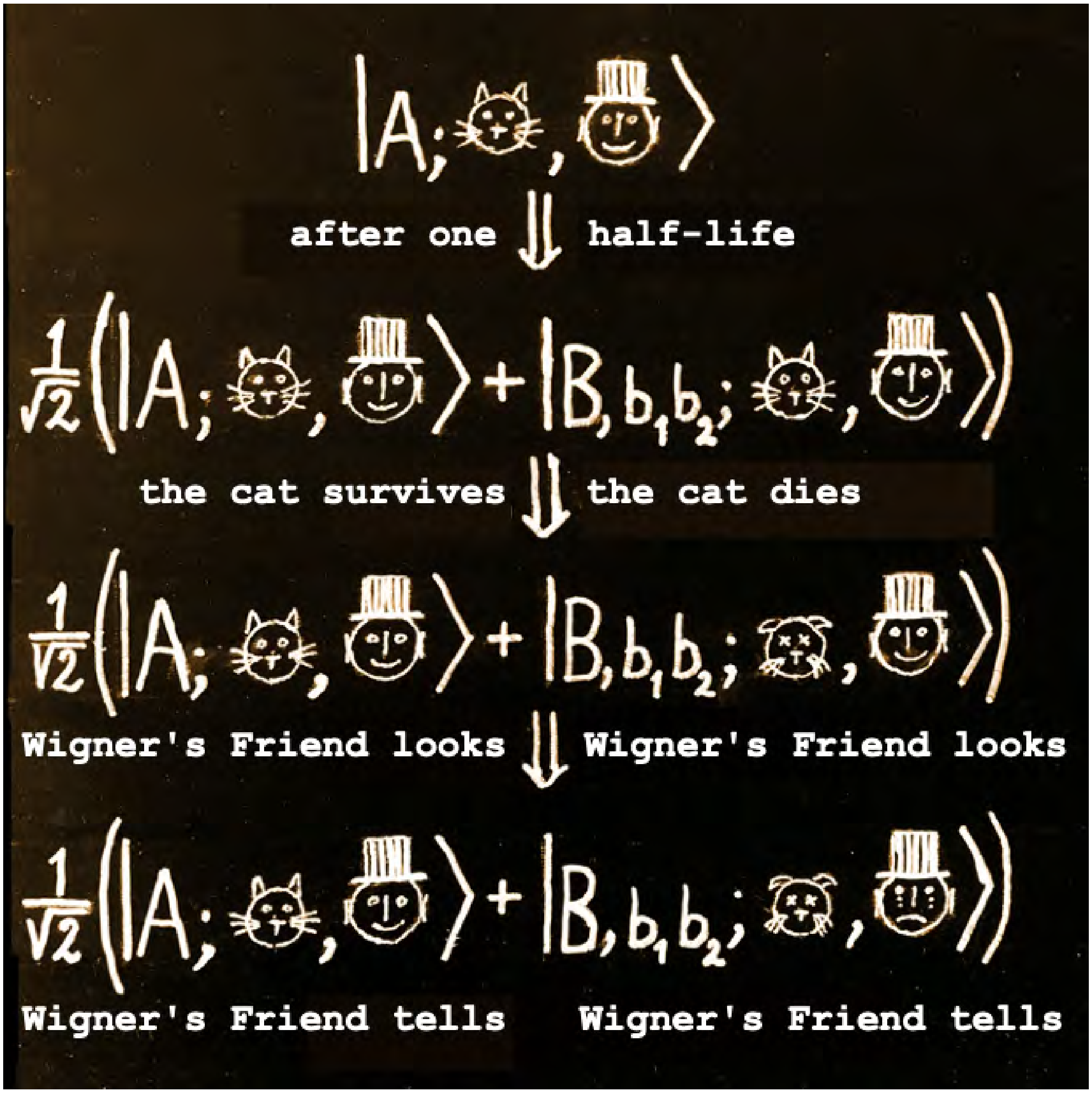
$$|\psi\rangle_{e^-} \otimes |0\rangle_M = \psi_+ |+\rangle_{e^-} \otimes |0\rangle_M + \psi_- |-\rangle_{e^-} \otimes |0\rangle_M \text{ (initial).}$$
$$\psi_+ |+\rangle_{e^-} \otimes |(+)\rangle_M + \psi_- |-\rangle_{e^-} \otimes |(-)\rangle_M \text{ (final).}$$

The final state of e^- and M is entangled, i.e., it is no longer a product of an e^- state and an M state.

We thus have entanglement but since the coefficients ψ_+ and ψ_- remain, no definite result (spin up or spin down) comes out. This is von Neumann's dilemma [3].

BOX 2. von Neumann's dilemma.

The implicit assumption of one given initial state for the measurement apparatus M leads to this dilemma. M has many degrees of freedom and a large ensemble of available initial states, that can cause very different interactions with e^-. Taking this into account and using relativistic quantum dynamics leads to an entirely different situation that opens for a solution of the measurement problem.



Box 3. Schrödinger’s Cat and Wigner’s Friend.

A radioactive nucleus A in a closed box can decay into another nucleus B and emitted particles b_1 and b_2. In the box there is also a cat. If A decays, this releases a mechanism that breaks a flask of hydrocyanic acid that kills the cat. After one half-life of A, Wigner’s Friend looks into the box to see if Schrödinger’s Cat is still alive. If the cat is dead, he becomes very sad...

Random walk in probabilities for spin-up och spin-down

Graphically we can represent the probabilities, p_+ and p_-, for the two possible outcomes, spin up (+) and spin down as a point (p_+,p_-), with $p_+ + p_- = 1$, on a line between $(0,1)$ to the left, representing spin down, and $(1,0)$ to the right, representing spin up (see Figure 1). Assuming for e^- the initial state $|\psi\rangle$, the corresponding position, $(|\psi_+|^2,|\psi_-|^2)$, on the probability interval, has also been marked.

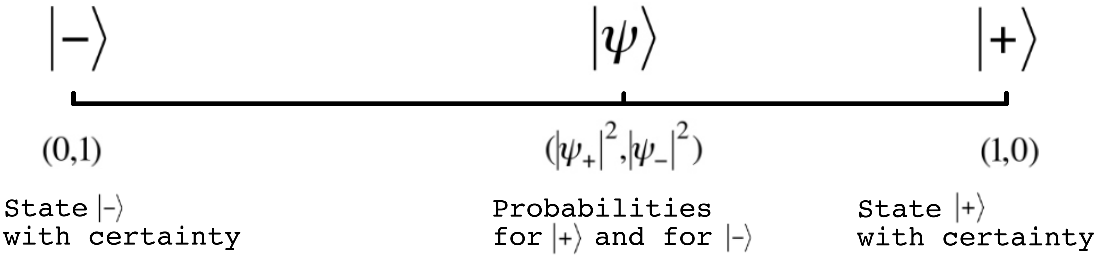


Figure 1. The probability interval for a two-level system. A random walk leads to one of the endpoints, corresponding to an eigenstate of the observable to be determined, in our case the vertical component of the spin, up (+) or down (−).

Giving the two endpoints $(0,1)$ and $(1,0)$, the weights suggested by their probabilities $|\psi_+|^2$ and $|\psi_-|^2$ of the Born rule, their resulting statistical center-of-mass is the starting point for our e^-, $(|\psi_+|^2,|\psi_-|^2)$.

The process to get from $(|\psi_+|^2,|\psi_-|^2)$ to the endpoints of the probability interval can therefore be a random walk without drift. Many random walks described simultaneously would be a diffusion process. A single determination is described by a random walk; the motion of an ensemble of many determinations is described by diffusion. Figure 2 illustrates such a diffusion process: the statistical distribution of positions after successively increasing the number of steps. Can this knowledge help us to find a process describing the determination of a value for the vertical spin component? First we comment on the diffusion process of Figure 2.

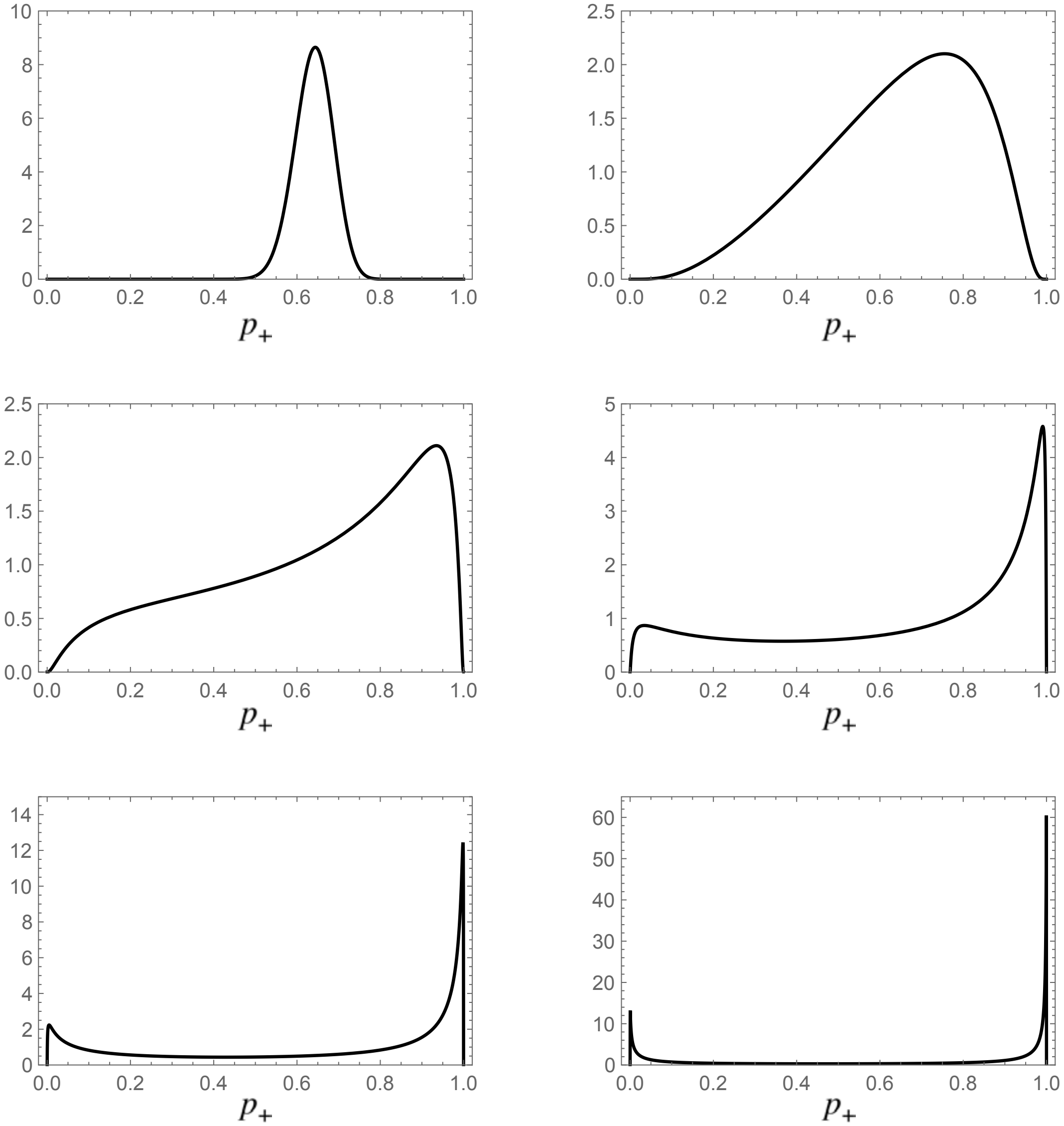


Figure 2. Diffusion on the probability interval. Distributions on the probability axis for increasing numbers of steps of the random walk.

The endpoints, $(0,1)$ and $(1,0)$, of the probability interval are special. Let us look at a random walk of a system on the probability interval. When it gets close to one endpoint, its next step has to be short. It cannot step outside the interval; also it cannot go very far towards the interior, since it has to keep the mean equal to zero. Only the endpoints have this kind of restriction. This leads to a slow-down near the endpoints. The result is that all diffusion, and hence all random walks on the probability interval, go towards one of the endpoints, as Figure 2 indicates. If the initial position is $(|\psi_+|^2, |\psi_-|^2)$, then $(1,0)$ is reached with probability $|\psi_+|^2$, and $(0,1)$ is reached with probability $|\psi_-|^2$, thus reproducing Born's rule.

This leads us to the question: Is there any physical process which mathematically could look like the described random walk? The answer is YES. But this does not take place with the dynamics as it was understood in the non-relativistic theory of the 1930s, resulting in von Neumann's dilemma.

Choosing the right theory of quantum mechanics

In the quantum mechanics of the 1930s, one had not yet taken the consequences of relativity theory into account. The necessary adaptation of quantum mechanics to special relativity had just started around 1930. With respect to the issue of this article, its completion can be dated to the early 1950s. Relativistic quantum mechanics has the form of Quantum Field Theory and it is fundamental for understanding the physics of elementary particles.

Relativistic quantum mechanics is very different from the quantum theory of the 1930s. One important detail is that von Neumann's dilemma is no more valid in quantum field theory. It is hard to understand why the discussion of the measurement problem has continued to take place within the undeveloped theory of the 1930s. Instead of a deep analysis of the measurement problem, an emerging theory was, for instance, Everett's [6] and DeWitt's Many-Worlds Interpretation [7]. In MWI, each measurement splits the universe into several worlds, one for each result. We shall return to this theory.

At present, also the view that the measurement problem is unsoluble seems to be fairly widespread. It was expressed with regret already in 1965 by Richard Feynman in his Lectures [8]:

> [P]hysics has given up on the problem of trying to predict exactly what will happen in a definite circumstance. Yes! physics has given up. *We do not know how to predict what would happen in a given circumstance*, and we believe now that it is impossible, that the only thing that can be predicted is the probability of different events. It must be recognized that this is a retrenchment in our earlier ideal of understanding nature. It may be a backward step, but no one has seen a way to avoid it.

Continued scientific development in physics has not been seriously hindered by the measurement problem. Physicists have been reluctant to present wild theories or take part in improductive discussions. Instead one has mostly followed David Mermin's rule [9]: "Shut up and calculate!" However, this rule has not helped to solve the measurement problem.

Random walk on the probability interval as a physical process

There exists a method to separate the two components of the state of e^-, the one with spin-up and the one with spin-down. If e^- passes an inhomogeneous magnetic field, one can separate these components into different paths (the Stern-Gerlach-effect). One can then make a determination of the vertical spin by letting one component, let us say spin-up, pass a detector. Then a positive reaction of the detector means spin-up and no detection means spin-down. In each step, it is equally likely that detection is supported as non-detection. (Of course, one can also have two detectors, one for each component.)

Here we shall sketch briefly what happens with our e^- in interaction with the part A of the measurement apparatus that it first meets. We can think of A as consisting of a row of subsystems $A_1, A_2, ..., A_n, ..., A_N$ along the path taken by the wavepacket describing e^- or one of its components. Each of these subsystems in its turn is interacting with e^- when e^- passes A. Figure 3 shows e^- interacting with $A_1, A_2, ..., A_n, ..., A_N$ leading in each step to new factors in the interaction strengths. We consider e^- to pass fast so that there is little time for the subsystems to interact with each other and this interaction can be neglected.

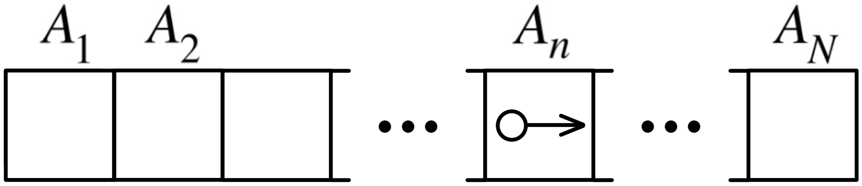


Figure 3. Defining the system A as a row of subsystems around the path taken by e^- or one of its components. e^- interacts with each of the subsystems of A, but we neglect the interaction of the subsystems with each other.

Each e^-A_n-interaction gives a new factor to each of the transition strengths, accidentally leading to enhancement of one transition and suppression of the other, but in the mean, leaving the transition strengths unchanged.

In relativistic quantum mechanics, what is important is the transition strength for transitions to different final states. What concerns us is the transition strength to the final state with e^- in $|+\rangle$ and A in a state with the subsystems marked +, and the transition strength to the final state with e^- in $|-\rangle$ and A in a correspondingly marked state. (I use 'transition strength', although it is not an established physical term; it suits my purpose here: a comparison between two transitions where one transition totally dominates over the other.)

For each subsystem A_n passed, each transition strength (for + and for –) is multiplied by an unknown factor as a result of the interaction between e^- and A_n. This factor depends on unknown details in the state of A_n.

To be a functioning part of a measurement apparatus, in the mean, A must be free from bias. Because of this, for each subsystem A_n, the means of the multiplying factors must be the same for spin-up and spin-down ($|+\rangle$ och $|-\rangle$). The probabilities for reaching the two endpoints, $(0,1)$ or $(1,0)$, can change in each step because of different new factors in the transition strengths for + and –. But since the means are the same in each step, the statistical centre-of-mass stays the same during the whole process.

Thus we have found a process which follows the random walk that we have been looking for. It starts in the point $(|\psi_+|^2,|\psi_-|^2)$ of the probability interval. For each subsystem A_n of A passed, the strengths for + and – get a new factor, meaning a new step. The factors have the same mean. The whole random walk has the probability $|\psi_+|^2$ to approach $(1,0)$, and the probability $|\psi_-|^2$ to approach $(0,1)$.

At the endpoints of the probability interval, the final state is a product state where e^- is in the state $|+\rangle$ or $|-\rangle$ with a definite vertical direction for its spin, and A is marked by this state of e^-. The state of e^- and A is a product state.

In this way, <u>we can understand the process of determining a definite result and why it follows Born's rule</u>. The determination takes e^- into the eigenstate of the observable that corresponds to the result.

We have assumed that A is free from systematic bias, but we have not carried out a physical analysis of this neutrality between + and –. This is an important question that needs to be analyzed before we have a complete theory.

Schrödinger's discussion of measurement in his cat article

In the preface of this book, I mentioned Schrödinger's article about the cat, who is now more famous than Schrödinger himself. I mentioned that for me, what was most important in Schrödinger's article was his attempt to analyze a measurement process, what here has been called a determination process. He described the interaction between the systems that we have called e^- and A and how it leads to entanglement which means that the combined state for e^- and A cannot be reduced to a product of independent states:

> When two systems interact, their ψ-functions [i.e., their states], as we have seen, do not come into interaction but rather they immediately cease to exist and a single one, for the combined system, takes their place. It consists, to mention this briefly, at first simply of the *product* of the two individual functions; which, since the one function depends on quite different variables from the other, is a function of all these variables, or "acts in a space of much higher dimension number" than the individual functions. As soon as the systems begin to influence each other, the combined function ceases to be a product and moreover does not again divide up, after they have again become separated, into factors that can be assigned individually to the systems. Thus one disposes provisionally (until the entanglement is resolved by an actual observation) of only a *common* description of the two in that space of higher dimension.

The crucial statement here is just something that Schrödinger was guessing, and it is wrong:

> [the combined function] does not again divide up, after they have again become separated, into factors that can be assigned individually to the systems.

Actually, such a separation does take place and, as we have seen, it can be understood as a random walk on the probability interval from $(|\psi_+|^2, |\psi_-|^2)$ to either $(0,1)$ or $(1,0)$. Thus the walk goes to an endpoint where e^- is in the state $|+\rangle$ or $|-\rangle$ and the state for e^- and A <u>is</u> a product state.

For Schrödinger, this was totally impossible to imagine. His conclusion is pessimistic:

> best possible knowledge of a whole does not include best possible knowledge of its parts—and that is what is keeping coming back to haunt us.

For Schrödinger, it was also impossible to see that relativistic theory could simplify everything. A couple of sentences later, he wrote that

> [t]he conceptual joining of two or more systems into *one* encounters great difficulty as soon as one attempts to introduce the principle of special relativity into QM.

Maybe one could have expected from later generations of physicists that they should have checked whether new knowledge could have helped them to complete the analysis of measurement that Schrödinger had attempted but not been able to carry out. This has not happened. Instead, the cat fable became a confused, and confusing, model. Unfortunately, it has been used as a foundation for the continued discussion.

After writing this and placing it in the general text, I could not resist going back to the question: Would it have been possible with Schrödinger's knowledge in 1935 to see a mechanism for measurement within quantum mechanics? My answer is YES! Here are my arguments:

First, von Neumann's dilemma was not at all necessary. It would have been very reasonable with deterministic dynamics and the initial state $|\psi\rangle$ of e^- given, to see the final result as an effect of the initial state of A. One question would remain however: How can transitions between spin-up and spin-down take place without any interaction generating it. A reasonable standpoint would then have been: "Let us wait and see. We have not yet taken relativity fully into account in quantum dynamics. If relativity has given the electron an antiparticle, the positron, it may also change quantum dynamics and make spin-up/spin-down transitions understandable."

Secondly, as often stressed by Bohr, A is macroscopic; it must have been reasonable to handle A statistically and to think of it as a source of the resulting statistics.

Thirdly, A should not introduce any systematic bias, i.e., in the mean, it should handle spin up and spin down in the same way. This points at an action on e^- that can be described on the probability interval as a random walk without drift.

Fourthly, such a process always leads towards one of the endpoints of the probability interval. For the initial state $|\psi\rangle$ for e^-, the resulting statistical frequencies are $|\psi_+|^2$ and $|\psi_-|^2$.

Let us look at p_+p_- which vanishes at the endpoints. One step, $(p_+,p_-)\to(p_+ + \Delta p, p_- - \Delta p)$, changes the mean of p_+p_- as follows:

$$\left\langle\left\langle (p_+ + \Delta p)(p_- - \Delta p) - p_+p_- \right\rangle\right\rangle = (p_- - p_+)\left\langle\left\langle \Delta p \right\rangle\right\rangle - \left\langle\left\langle \Delta p^2 \right\rangle\right\rangle = -\left\langle\left\langle \Delta p^2 \right\rangle\right\rangle < 0\,,$$

since $\left\langle\left\langle \Delta p \right\rangle\right\rangle = 0$. Thus in the random walk, p_+p_- steadily decreases and the walk gets arbitrarily close to one of the endpoints, $(1,0)$ or $(0,1)$. The frequencies for these approaches, $|\psi_+|^2$ and $|\psi_-|^2$, are determined by the statistical mean which stays at the starting point $(|\psi_+|^2,|\psi_-|^2)$.

Fifthly, the states at the ends of the probability interval are again product states without entanglement between e^- and A. Thus the final state of e^- is an eigenstate of the vertical spin component. This was excluded by Schrödinger as impossible.

The reasoning shown here, would not have been easy, but it would have been possible. Since relativistic influence on the theory still remained to be worked out, there was no reason to believe that one had the final version of quantum dynamics.

My conclusion is that the available knowledge was there for Schrödinger's cat paper to go in a totally different direction where the understanding would have resulted and where a cat in a superposition would have been totally irrelevant. Generations of physicists would have been guided towards understanding instead of confusion.

The irreversible part of the determination process

What we have called A, is only a small part of the measurement apparatus. The rest of the apparatus which we name E (see Figure 4), is then so large that it must be considered as an open system. Then E has an uncontrollable interaction with its environment and the interaction between A and E is irreversible. The determination (of the vertical spin component of e^-) that has already taken place in the e^-A-interaction is fixed in the AE-interaction.

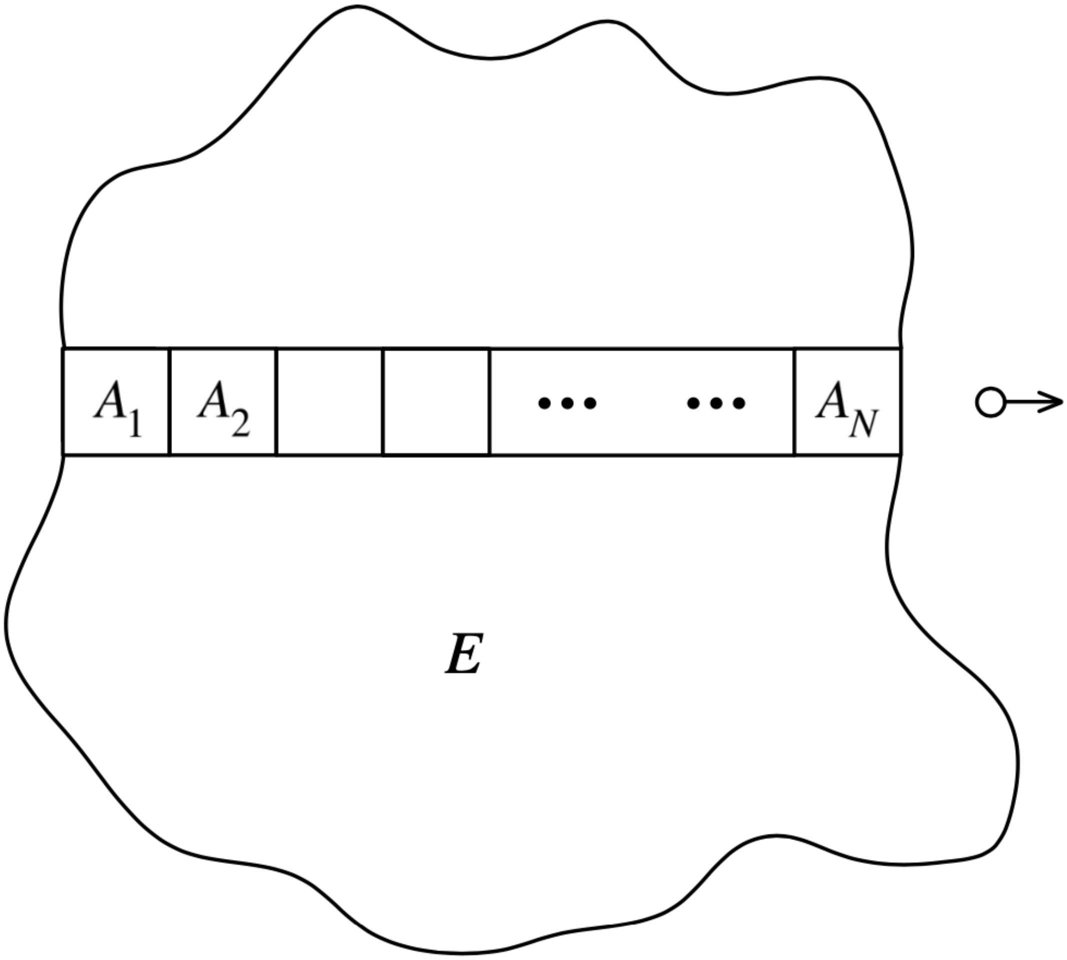


Figure 4. A as a subsystem of the whole measurement apparatus, $A \cup E$, where E is a large open system with irreversible interaction.

The measurement problem and relativistic quantum mechanics

For some reason, it has been taken for granted that the development within relativistic quantum mechanics is without relevance for the measurement problem; the discussion has continued within the old tradition. It has been overlooked that the changes in the perspective of quantum mechanics brought in by the theory of relativity, are crucial for the understanding of the measurement problem.

Relativistic quantum mechanics, i.e., Quantum Field Theory, is totally different from the non-relativistic theory. As already mentioned, without relativity, one cannot understand why the electron has an antiparticle, the positron. Space-time has a different structure in relativistic theory. One consequence is that for any elementary process included in a larger process, also its inverse process has to be included. This is crucial for the measurement process.

In spite of these differences, the non-relativistic theory has been allowed to prevent progress. von Neumann's dilemma has hindered the search for a solution of the measurement problem. Why it has been like this, is a mystery in the history of science.

The Many-Worlds Interpretation [7]

When the first article pointing in the direction of Many Worlds was published [6] in 1957, good textbooks/handbooks in relativistic quantum mechanics were already available. For instance, The Theory of Photons and Electrons by J.M. Jauch and F. Rohrlich [10] had been published already in 1955. For John Wheeler in Princeton, Everett's supervisor, it was still somehow natural to base the thesis work on the incorrect and obsolete non-relativistic version of quantum mechanics. Looking back, this choice can seem strange; it is part of the mentioned mystery in the history of science.

The idea in Everett's paper is an interpretation of von Neumann's dilemma: Let us accept that the proportions of different state components cannot change and no measurement result can outweigh the others. The main thing is the agreement between the measured system and the apparatus (Box 2). In each term of the resulting entangled superposition, there is agreement. Everett's idea was then to continue and accept all terms in the superposition as representing realities, later interpreted as realities in different worlds, with the actual observation occuring just in one of these worlds.

The person who has become best known as spokesperson for the Many-Worlds Interpretation is Bryce DeWitt with an article in Physics Today in 1970. DeWitt's article follows quite closely the fable in Schrödinger's cat article. DeWitt described the consequence of the Many-Worlds Interpretation like this:

> [E]very quantum transition taking place on every star, in every galaxy, in every remote corner of the universe is splitting our local world on earth into myriads of copies of itself.

This made him immediately hesitate:

> I still recall vividly the shock I experienced on first encountering this multiworld concept. The idea of 10^{100+} slightly imperfect copies of oneself all constantly splitting into further copies, which ultimately become unrecognizable, is not easy to reconcile with common sense.

Still DeWitt continued to speak for this theory. It is not unusual that physicists still today understand measurement in this way.

Vitalism and the measurement problem

There are important differences in the development of life sciences and physics, but still it is tempting to compare the measurement problem with the biological thinking around 1900. One had believed that life, including the metabolism of cells, was dependent on a special '<u>vital force</u>'. This view was called vitalism. But Eduard Buchner (1860-1917, Nobel Prize in chemistry 1907) had ground yeast cells and showed that the resulting material, no longer alive, could still ferment sugar into alcohol and carbon dioxide, with the sum reaction,

$$C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2 .$$

This was a clear sign that the metabolic reactions could simply be understood by the chemical knowledge which one already had. No hypothesis about a 'vital force' was needed and vitalism came to an end.

Magdalena Eriksson showed me how this was described in the Lehninger Biochemistry textbook [11] (my underlining):

> Through the discovery of Buchner, Biology was relieved of another fragment of mysticism. The splitting up of sugar into CO_2 and alcohol is no more the effect of a vital principle than the splitting up of cane sugar by invertase. The history of this problem is instructive, as it warns us against considering problems to be beyond our reach because they have not yet found their solution.

Quantum mechanics has the knowledge needed to solve the measurement problem. The Many-Worlds Interpretation or similar speculative ideas are simply not needed. I think it is correct to say that more than a century after the abandoning of vitalism by biologists and chemists, the physics society is still stuck in an unnecessary vitalism syndrom of its own.

There are now good reasons to free quantum mechanics of its mystical load and appreciate it for its enormous explanatory power.

History of the measurement problem: a personal perspective

As I argue several times in this book, it is reasonable to consider the progress made in quantum diffusion during the decade around 1990, as containing also the solution to the measurement problem. The equation of motion for quantum diffusion in a work by Gisin and Percival [12], can be derived within our description of the interaction of e^- with an extended system A [13]. Other authors in the field of quantum diffusion are P. Pearle who was very early to consider random walk [14], and L. Diósi [15]. I shall not review this field here.

It is not always clear how to interpret quantum diffusion. In the Gisin-Percival treatment, entanglement between the system corresponding to e^- and A seems to be implicit. When entanglement is only intermediate, the final state is again a product state.

In 1986, John Bell described the development of quantum diffusion as follows ("Speakable", p. 190):

> The necessary technical development involves introducing what is called 'nonlinearity' and perhaps what is called 'stochasticity' into the basic 'Schrödinger equation'. There have been interesting pioneer efforts in this

direction, but not yet a breakthrough. This possible way ahead is unromantic in that it requires mathematical work by theoretical physicists, rather than interpretation by philosophers, and does not promise lessons in philosophy for philosophers.

In his book, Andrew Whitaker ([2] pp. 319-322] also refers to the work of Gisin and Percival. He interprets the work as providing a valuable phenomenological description but no direct connection to fundamental quantum mechanics. In a recent paper mentioned already [13], I have shown, however, that quantum diffusion can be seen as a consequence of linear quantum mechanics.

The random-walk idea [14, 16] presented in this chapter came at the same time as several ideas in quantum diffusion. Mathematical details of our work have then been published in different papers [17]. For a more complete work on the theory, Kristian Lindgren and I collaborated with Erik Sjöqvist and Martin Cederwall [18]. A paper on our common work was then published by Kristian Lindgren and myself [19].

I think of John Bell as the most careful and consistent physicist in the analysis of quantum mechanics. In 1960, John Bell came to CERN to join the permanent staff of the Theory Division. At that time, I had a fellowship there and he got a room very close to mine. One day when we met and discussed our research projects, John Bell said: "It would be nice to derive what should be on page 25 in any textbook in quantum mechanics." I understood immediately that he meant measurement in quantum mechanics and Born's rule. After this, I have always had Bell's words with me as a challenge. (I apologize for repeating here what I also tell in Chapter 4 on the background of ideas.) I have been thinking a lot about this, but for long periods, progress was held up by my poor understanding and lack of insight. In this way, my difficulties have been very similar to those of many of my physics colleagues.

John Bell did not allow himself to be confused. He kept a consistently analytical attitude towards quantum mechanics. This attitude is very clearly manifested in "Speakable".

My ambition in this chapter has been to present work in the analytical tradition of John Bell.

John Bell (1928-1990) lecturing 1982. (Photo: CERN PhotoLab.) (https://commons.wikimedia.org/wiki/File:Physicist_John_Bell_at_CERN,_June_1982.png)

In the quotation from "Speakable" by John Bell, he says that "work by theoretical physicists [...] does not promise lessons in philosophy for philosophers." But even if not promised, I think the pragmatic view of the quantum-mechanical state as describing reality can now be a valuable lesson also to philosophers who have been lacking a proper ontology.

In this chapter, I have presented our theory of measurement together with comments on the history of the measurement problem. For clarity, I now give a summary of the major steps of the measurement theory that I have tried to communicate.

In the play of Chapter 2, I have tried to show steps of understanding or possible understanding during the history of the measurement problem. In my view, the knowledge basis, but not the physics culture itself, was ready for a solution of the measurement problem in the late 1950s.

Summary of the present analysis of measurement

1. We describe quantum measurement, or the determination process as we call it, as an interaction between the chosen system e^-, subject to measurement (of its vertical spin component) and the part A of the measurement apparatus first met by e^-. Describing e^- as a wavepacket, or two wavepacket components, A is the part of the apparatus immediately surrounding the e^- wavepacket or wavepackets.

For a more detailed analysis, we look upon A as consisting of a row of subsystems, $A_1, A_2, ..., A_n, ..., A_N$, which interact, one by one, with e^-, as e^- passes them, but not appreciably with each other during the short time of passage.

The description of the process is given within relativistic quantum mechanics. The interaction of e^- with A_n then contributes a factor to each of the transition amplitudes of the e^-A-interactions and hence also to the strengths of these transitions.

2. In the single case, each interaction step can accidentally favour spin up ($|+\rangle$) or spin down ($|-\rangle$). But as part of a measuring equipment, in the mean, each A_n should stay neutral with respect to + or –. Described on the probability interval between $(0,1)$ and $(1,0)$, we have a random walk but no drift.

3. Thus the result is that an incoming e^- in the superposition $|\psi\rangle = \psi_+|+\rangle + \psi_-|-\rangle$, starting its random walk from $\left(|\psi_+|^2, |\psi_-|^2\right)$,

approaches $(1,0)$ in $|\psi_+|^2$ of all cases and approaches $(0,1)$ in $|\psi_-|^2$ of all cases. Thus a result is obtained and the probabilities agree with Born's rule.

4. The pragmatic ontology that has been used by physicists working with quantum mechanics, with the quantum-mechanical state describing reality, can be recognized as more generally valid.

References

1. J.S. Bell, Speakable and Unspeakable in Quantum Mechanics (Cambridge Univ. Press, 2004), here referred to as "Speakable".

2. A. Whitaker, Einstein, Bohr and the Quantum Dilemma (2nd ed., Cambridge, U.K. 2006).

3. M. Nauenberg, J. Cosmol. 14 (2011).

4. E. Schrödinger, Naturwissenschaften 23, 807 (1935). English translation by John D. Trimmer in J.A. Wheeler and W.H. Zurek (eds), Quantum Theory of Measurement (Princeton Univ, Press, 1983).

5. Wigner's Friend in Wikipedia (https://en.wikipedia.org/wiki/Wigner%27s_friend).

6. H. Everett, Rev. Mod. Phys. 29, 454 (1957).

7. B.S. DeWitt, Phys. Today 23, 30 (1970).

8. R.P. Feynman, R.B. Leighton and M. Sands, The Feynman Lectures on Physics (Addison-Wesley 1965), Ch. 37, p. 37-10.

9. D. Mermin, Physics Today 42, 4, 9 (1989).

10. J.M. Jauch and F. Rohrlich, Theory of Photons and Electrons (Addison-Wesley, 1955).

11. D.L. Nelson and M.M. Cox, Lehninger - Principles of Biochemistry, 6th edition (2013), Section 14.1 Glycolysis, p. 544.

12. N. Gisin and I.C. Percival, J. Phys. A 25, 5677 (1992).

13. K.E. Eriksson, arXiv 2203.00586 (2022).

14. P. Pearle, Found. Phys. 12, 249 (1982).

15. L. Diósi, J. Phys. A. Math. Gen. 21, 2885 (1988).

16. K.E. Eriksson, Phys. Scr. 32, 277 (1985).

17. K.E. Eriksson, J. Phys. B 42, 085001 (2009).

18. K.E. Eriksson, M. Cederwall, K. Lindgren and E. Sjöqvist, arXiv 1708.01552v2 (2017).

19. K.E. Eriksson and K. Lindgren, Entropy 21, 834 (2019).

2. ALICE AND MR TOMPKINS BACK IN WONDERLAND — A DRAMA IN THREE ACTS ABOUT QUANTUM MECHANICS

The situation is modelled after Lewis Carroll, George Gamow and Michael Frayn.

Prelude: Planning the new visit
Act 1: The new tea party
Interlude: Talking to Marie Curie
First intermission
Act 2: Seminar on quantum measurement
Second intermission
Act 3: Seminar continued: consequences of the new theory of measurement

Characters, in order of appearance:

Alice
Mr Tompkins
Melanie Bayley
The Hatter
The March Hare
The Dormouse
Paul Dirac
Schrödinger's Cat
Wigner's Friend
Sankofa
Marie Curie
Albert Lehninger
Albert Einstein
Niels Bohr
John Bell
Bryce DeWitt
Richard Feynman

[The first appearance of each character is marked by * below.]

Prelude: Planning the new visit

[*Over the stage, there is a screen on which pictures can be projected. The entrance of the town library is to the right of the stage.* Alice* *is standing and waiting outside the library.* Mr Tompkins* *comes walking with a stopwatch, a pen and a notebook and with a folded meter stick visible in one of his pockets*.]

Mr Tompkins [*noticing* Alice*, slowing down, walking up to her and greeting her politely*]: Good afternoon, Alice. I know you from John Tenniel's portraits of you in 'Alice in Wonderland'. Very happy to meet you. I am Mr Tompkins. I have also visited Wonderland. I was taken there by George Gamow, the man with the Big Bang. Are you going into the library?

Alice: Good afternoon, Mr Tompkins. No, I agreed to meet a person here. My grandpa showed me an article in the New Scientist by Melanie Bayley. She is a scholar in literature and she has written about Lewis Carroll and my visit to Wonderland, including the mad tea party. Dr Bayley has agreed to meet me here, but I am a bit early.

Mr Tompkins: After returning from Wonderland, I have continued my studies. I have also read Dr Bayley's article. I would also like to see her.

Alice: Then wait with me and join us in our discussion.

Mr Tompkins: Very kind of you; do you think she will accept that.

Alice: Of course, she will, and you can tell us about your physics experience.

Melanie Bayley* [*arriving in fast walk*]: Hello Alice, am I late?

Alice: Nice to meet you Melanie; no I was early. I guess you have heard of Mr Tompkins who has also been to Wonderland.

Melanie: Yes, I have. When I read the books. I think relativity was well described but I had difficulties to appreciate the quantum mechanics descriptions.

Mr Tompkins: Gamow and myself tried our best but it is very difficult.

Alice: When I heard about you, Melanie, I got the idea to ask you to come with me to Wonderland to find out more. Would you like to do that? I would like to have a more peaceful visit this time than the one that Lewis Carroll gave me.

Melanie: There are many things to find out about literature as well as science.

Mr Tompkins: If I could come along, I would be curious to find out more about quantum mechanics. It could even be constructive to go there.

Melanie: How could you expect yourself or us to find out? So many people have tried their best and failed.

Alice: I think the three of us would be a good team. We do not get stuck as easily as physicists do.

Melanie: It might be a good idea. I can look back on history and try to understand. But...

Mr Tompkins: I was fascinated by the play Copenhagen with Niels and Margrethe Bohr and Werner Heisenberg meeting after death to look back on history.

Alice: My grandpa told me about that play. We can go inside the library to sit down and talk about our trip.

[*All three of them enter the library*.]

End of Prelude.

Act 1: The new tea party

[The Hatter*'s house is to the left; in front of the house is a tea table with a few chairs. The tea table is under a big tree. On the tree trunk, a pendulum clock is hanging; it has stopped at six o'clock. The right side of the stage looks like a park.*

Alice *is approaching the tea table.* The Hatter*, The March Hare* *and* The Dormouse* *sit at the table. Tea is served.*]

The Hatter [*rising to greet her*]: Welcome to another tea party, Alice. Nice to have you here again. Please, sit down!

The March Hare: This time, we do not have to be rude to each other.

[The Hatter *starts to serve the tea.*]

The Dormouse: ... since we have no script from Lewis Carroll to follow. [*To* The Hatter *and* The March Hare:] In particular, the two of you must not try to put me into the tea pot.

The Hatter: I am sorry about last time. And also you do not have to be sleepy all the time. It is so nice to have you back, Alice.

Alice: It is really nice to be back and to see you again. Mr Hatter, do you have more tea cups? The thing is, I am here with two new friends. But I wanted to greet you before I bring them here... if I may?

The Hatter: Of course, you may. Your friends are our friends.

Alice: My friends have some facts to tell the three of you. It is about Lewis Carroll's intention with you and your relevance as characters.

The March Hare: I will be very interested to listen to them.

The Dormouse: As for me, I am curious by nature. I am happy if they do not plan to put me to sleep too much, like Carroll did.

[The Hatter *brings the additional tea cups*.]

Alice: My friend, Mr Tompkins, is a British gentleman and a character from the literature just like the four of us. My other friend Melanie Bayley comes from the real world. But do not worry, she is a scholar of literature and science. [*Calling out*]: My friends, please come and join us!

Melanie [*hesitating*]: I am not sure I dare come, thinking of the previous tea party here.

Alice: This one will be decent and serious. Please come!

[Melanie *comes and approaches the table*. Mr Tompkins *comes walking with a wheelbarrow with some equipment. He sits down at the table*.]

The Hatter: Very welcome, indeed. Alice's friends are our friends. Nice to meet you Dr Bayley.

Melanie: Call me Melanie.

The Hatter: Come and sit down, Melanie. Nice to meet you Mr Tompkins.

[*Introductions and exchange of greetings.* The Hatter *serves the tea*.]

The March Hare: Alice said that you, Mr Tompkins, and you, Dr Bayley...

Melanie: Melanie!

The March Hare: ... yes, Melanie, that you may have something to say about us as characters. We are curious.

Mr Tompkins: The physicist George Gamow took me here to demonstrate the ideas of relativity and atomic physics, including quantum mechanics. But what I may have to say should come after Melanie's more direct information on your mathematical relevance. Let me contribute this sculpture to your room. [*Hangs a sculpture, probability graph for a two-level system, on a tree branch.*]

The Hatter: Thank you.

The Dormouse: Are we relevant persons? The Hatter, the March Hare and myself?

The March Hare: So we are not just crazy or mean figures, only making trouble to Alice and to each other?

Melanie: You represent the three imaginary units of a number system called quaternions. This system was new in Lewis Carroll's time. It had been introduced by William Rowan Hamilton. It could be connected to spatial orientation.

Mr Tompkins: Hamilton's notion of this was made more concrete much later by Wolfgang Pauli who used the quaternions in matrix form to describe the magnetic orientation of an electron. The imaginary units are then directly related to rotations around three perpendicular axes. I must confess, I have studied quite a bit. No one is too old to learn.

Let me show you now. [*Shows his cubic (green, red, yellow) box with three cranks.*] This is for all of you. There is also one crank for each of you. You see where you can connect the cranks.

Please, Dormouse, come here. You will handle rotations around the vertical axis. March Hare, you will handle rotations around an axis in the front direction, and you Mr Hatter, the side direction will be left to you to rotate around.

[*Brings two very big dices of different coulors and puts them in equal positions beside each other.*] Before we use the box, let the Dormouse rotate this one by 90° and then the March Hare by 90°. [*They do so.*] Let us now start with the same situation with the other dice but take the March Hare's rotation first followed by that of the Dormouse. [*They do so.*] Now you see that the result is different. The order in which you do things is important.

[Mr Tompkins *prepares the box and the cranks.* The Dormouse, The March Hare *and* The Hatter *takes turns to use their cranks.*]

Mr Tompkins: Sorry to tie you up with this. I hope you are not angry.

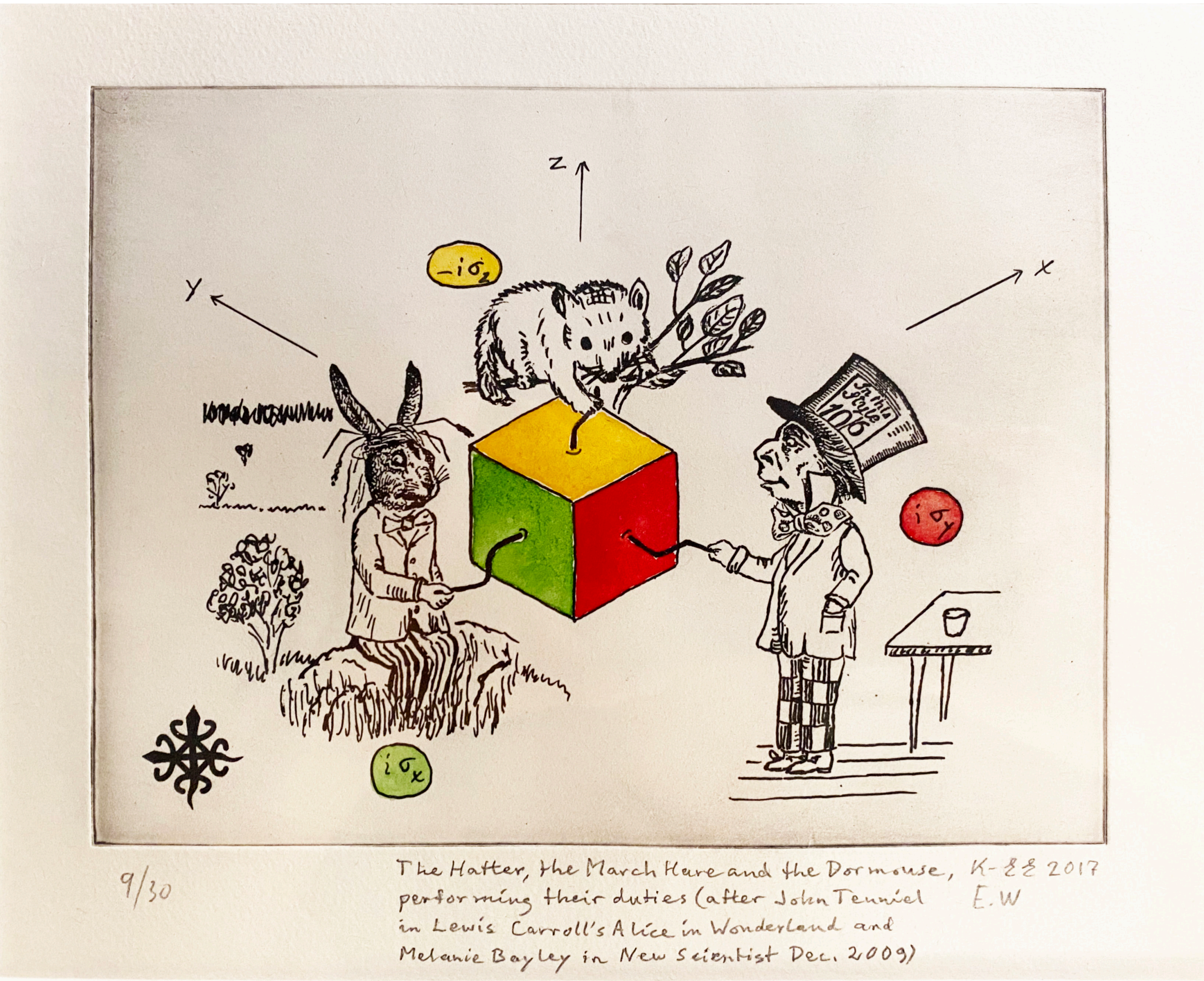


Figure 5. The tea-party persons of Alice in Wonderland, representing Hamiltons imaginary units and hence Pauli's spin matrices which are perpendicular generators of rotations.

The Hatter: It is nice exercise. We will play with this when we feel like it. Thank you, Mr Tompkins.

Melanie: So you guys, I mean the Hatter, the March Hare and the Dormouse, represent rotations around perpendicular axes. Hamilton would have liked to have time included, but he could not make it. Lewis Carroll was true to Hamilton but very critical of his ideas. Mr Time was missing in the party that carried his name: t(ea) for time.

The Hatter: Yes, the time stopped at six o'clock, and the clock refused to move.

Melanie: The fourth character in the tea party, you Alice, you are an ordinary person and represent the ordinary unit (1) in the quaternions.

Alice: So what do you and Mr Tompkins represent?

Melanie: We are not part of this. But let me tell you what happened. The orientation in space for the electron was generalized by Paul Dirac into a description of space-time orientation. Pauli had three basic matrices, one for each of you,... [The Dormouse *who has fallen asleep, starts to snore and* The March Hare *pushes him awake*.] ...and Dirac had four basic matrices. Dirac's description includes time and relativity theory.

Dirac* [*walking by but stopping, listening and coming to join the party*]: Hello everybody. I happened to come walking by and heard your discussion. Yes, it is true, I was lucky to be able to extend Pauli's matrices to four 4x4-matrices, the γ-matrices, for relativistic quantum mechanics. Then time is included! [*The clock hanging on the trunk, starts to move. They look at it in surprise*.]

The Hatter: Concepts are important. You see Melanie, your little lecture went beyond Hamilton and included time, Professor Dirac joined us and our clock was liberated from Lewis Carroll's restriction.

Mr Tompkins: I know relativity and I know simple quantum mechanics, but I never got to know relativistic quantum mechanics.

Melanie: Professor Dirac, you constructed a dynamical equation for the electron.

Dirac: Yes, I did. Time is included and the theory is relativistic.

Some laws of nature are similar to laws from legislation in a parliament. But a few general laws are more like the constitution describing the basic principles of how laws should be made. We can still view the special theory of relativity and quantum mechanics as such laws, forming the constitution of the physics of the material world. Relativity and quantum mechanics together form Quantum Field Theory.

Elementary particle physics is based on Quantum Field Theory. It goes beyond the dynamics of Schrödinger. I was very lucky to take part in this development.

Now, let me continue my walk and come back. [*Goes.*]

The Dormouse: That fellow Schrödinger, didn’t he have a cat?

Mr Tompkins: The cat was part of a thought experiment. Schrödinger considered a radioactive atomic nucleus in a box. After one half-life, the nucleus in the box is in a "both-and" state of remaining and of having decayed into other particles. The box also contains a detector that can register the decay. In the box there is also a cat and if a decay is registered, this triggers a little hammer to hit a small flask of hydrogen cyanide...

Schrödinger's Cat* [*who has been listening at the entrance*]: ...and the poison then kills the cat. I am that cat.

The Hatter [*turning towards the entrance*]: Please, come in! There is tea for you too. [Scrödinger’s Cat *enters. They all look at him/her with surprise*. The Dormouse *immediately climbs one high cupboard.*]

Mr Tompkins: Hello Schrödinger's Cat. Please, join us! Yes, and you become part of this both-and state: in the component where the nucleus remains undecayed, you are alive, and in the other component where it has decayed, you are dead.

Schrödinger's Cat [*looking at* The Dormouse]: Don't worry, I do not eat friends. As you heard, I am the one who is really threatened. I was conceived just to be under threat.

Mr Tompkins: But in one state component you are still alive.

Schrödinger's Cat [*grabs the hanging sculpture in the right hand and puts himself/herself in a Hamlet posture, then speaks in a deep voice*]: To be and not to be, that is the answer!

The Hatter: No, no, wrong! To be or not to be!

Schrödinger's Cat: Not in my case! Schrödinger wanted me to be both dead and alive just to show the absurdity of quantum mechanics.

Melanie: But still it is a question, not an answer, isn't it?

Schrödinger's Cat: To try to point out an absurdity was Schrödinger's answer; he was clever but not curious enough to ask the questions. [*Hangs the sculpture back in the tree.*]

Mr Tompkins: But nothing has happened to you yet. They just talk and talk but the experiment will never be done.

Schrödinger's Cat: For me the constant threat is cruel enough. I would like to be as clever as your famous friend, the Cheshire Cat, who knows how to disappear, leaving only his ironic smile behind.

Alice: My grandpa is a physicist. He thinks that the box experiment is useless, even as a thought experiment. If that were right, you would be safe.

Schrödinger's Cat: Yes and I would become a purely mythical character. But theoretical physics and its followers in culture are going in another direction. Heard of my friend known as 'Wigner's Friend'? Wigner was a physicist, but his Friend was introduced as a person to check the experimental result for Wigner. Oh, let me call Wigner's Friend. [*Calls on his mobile phone*...] Yes, he is free to join us.

The Hatter [*to himself*]: Some more cups. Better make some new tea. [*He does so. The conversation goes on for a short while*.]

Wigner's Friend* [*arriving*]: Good afternoon!

The Hatter: Good afternoon and welcome! A cup of tea?

Wigner's Friend: Would be refreshing.

Alice: Our new friend, Wigner's Friend! Please, let me know how it was in Wigner's days. Did you know a fixed and ready result of the measurement that you could tell to Wigner. Or were you in a superposition, entangled – is that the word? [Mr Tompkins *nods*.] – entangled with the quantum system, or you do not remember?

Wigner's Friend: Honestly, I do not remember. But Wigner used to say that human consciousness is the ultimate reality.

Schrödinger's Cat: So human consciousness was considered superior to cat consciousness. This is not science; it is simply racism.

The March Hare and The Dormouse: We animal characters are as real and human as the Hatter or Mr Tompkins or Wigner's Friend or even Alice.

Schrödinger's Cat: I do not like to be dead or entangled. I must look up that Cheshire Cat and learn the art of escaping.

Alice: So, Mr Wigner's Friend! If Schrödinger's Cat can be entangled (but I do not believe so), you could be entangled too, and maybe Wigner himself got entangled. But Wigner was not a made-up figure; he was really real, I guess.

Melanie and Mr Tompkins: Yes, he was.

Alice: Was he two different characters then, one for each experimental result?

Mr Tompkins: With this question you have just rediscovered Hugh Everett’s interpretation of quantum mechanics as entanglement in parallel universes. Everybody is like Schrödinger’s Cat. If you continue beyond Wigner himself, you may finally involve the whole universe. Then it becomes a multiverse of different parallel universes. With different possibilities and more entanglement, there will be new splitting into more parallel universes.

Alice: My grandpa told me about this, but I was not quite sure what he meant. But he does not believe in an entangled cat or a multiverse. He says that he is childish and believes in one world.

Schrödinger’s Cat: Either dead or alive but not both. Anyway, since your grandpa wants me to live, he must be a nicer guy than that man Schrödinger.

Mr Tompkins [*to* Alice *and* Melanie]: Let us take a small walk. We have a few things to discuss.

[Wigner’s Friend *gets ready to leave*.]

The Hatter, The March Hare and The Dormouse: We are quite happy to know that we are relevant. We now have equipment related to our roles. It is all very exciting. Thanks for informing us, Dr Melanie, and thanks Mr Tompkins, and goodbye.

Melanie and Mr Tompkins: Good luck and goodbye.

[Melanie, Mr Tompkins, Schrödinger’s Cat *and* Wigner’s Friend *wave good-bye and turn to go*.]

Wigner’s Friend: Thanks for the refreshing tea. [*Goes*.]

The Hatter: Thank you for coming.

Schrödinger's Cat [*to* Alice]: I have to go and find that Cheshire Cat and learn some good tricks. Good-bye. [*Goes*.]

Alice: Bye, bye. [*Stands up*.] My friends, I am happy that we met again and that we could find out who you really are. Good luck and goodbye.

[*They part and wave happily*. Alice *catches up with* Melanie *and* Mr Tompkins.]

Mr Tompkins: In Wonderland we are also wondering. We are wondering about physicists, how they came to think the way they did.

Alice: Yes, why do physicists have so crazy ideas about looking at things, decayed and not decayed, dead and alive?

Mr Tompkins: Yes, physicists have a fairly good idea what happens to a physical system when it is left by itself. But what happens in a measurement is not well understood.

Dirac [*having just returned*]: No, but we know what happens. The electron has a spin. If we measure the spin component in the vertical direction we find that it is either completely 'up' or completely 'down'; the probabilities for these outcomes depend on its original orientation, but the specific result in a single measurement ('up' or 'down') cannot be predicted. After the measurement, the electron is in the state that agrees with the measurement result.

Alice: But physicists do not agree about what happens just when somebody measures?

Dirac: That is right.

Mr Tompkins: And most people even think that it is not possible to understand.

Alice: This does not make sense. If you have such a good theory, and you use it to describe measurement, then you must get some understanding.

Dirac: Maybe Alice is right, maybe we have not tried hard enough.

Alice: We are in Wonderland where many things are possible. We could collect people to discuss what happened in history and what could have happened, like in the play Copenhagen.

Melanie: Yes, Michael Frayn made Werner Heisenberg meet Niels and Margrethe Bohr after death for a penetrating discussion on what had happened when Heisenberg visited Copenhagen in 1941.

Dirac: This is a very good idea. Alice, come with me! [Dirac *and* Alice *go*.]

End of Act 1.

The Solvay Conference of 1927. (Photo: Benjamin Couprie.) https://commons.wikimedia.org/wiki/File:Solvay_conference_1927_restored.jpg

Interlude: Talking to Marie Curie

[Dirac *and* Alice *walk together. They are followed by a person,* Sankofa*, but they *do not take much notice. They come to a park area with lawns and flowers and walking paths.* Marie Curie* *sits on a bench writing in a notebook.* Dirac *and* Alice *approach her.* Sankofa *stops a few steps behind.*]

Dirac: Good afternoon, Professor Curie. Sorry to disturb you. [*To* Alice]: As you know, Professor Marie Curie is the grand old person of modern science.

Marie Curie [*looks up and smiles*]: Good afternoon, Paul; nice to see you. Good afternoon, young lady!

Dirac: Alice is a literary character that you know from Lewis Carroll's book. [Alice *and* Marie Curie *shake hands*.] She is a critical young person; she is very dissatisfied with the present understanding of quantum measurement. She wants to look back to find out if science could have followed another path. I was thinking of the 1927 Solvay Conference where we discussed this issue.

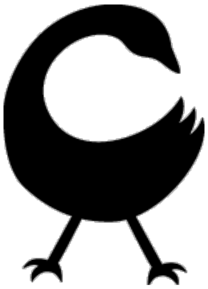


Figure 6. An Adinkra symbol: Sankofa.
Among the philosophical/religious Adinkra symbols of the Akan people in West Africa, one of the most well-known symbols is Sankofa, "return and get it", symbol of the importance of learning from the past.

Sankofa [*after coming closer, greeting with a bow*]: Sorry to disturb you, I am Sankofa. I think this is a very good idea. One should always learn from the past.

Marie Curie [*looking at Sankofa with kind curiosity*]: Sorry Sankofa, I do not know who you are but I understand you are supporting Professor Dirac and Alice.

Sankofa: I am supporting. I am one of the Adinkra symbols, a whole set of symbols for proverbs and thinking, from the traditions of the Akan people in West Africa. [*A whole chart of* *symbols is shown*.] I often meet persons who wonder why I turn around and look behind, but that is my message: 'Look back and learn from the past!'.

Marie Curie: Alice, it is good to be critical; that takes science forward. Paul, it is good to support a young curious person, although Alice has been around longer than both of us. Sankofa, thanks for supporting us with your Akan proverb.

Paul, what I and you have to do is to organize a small hearing or seminar with some of our colleagues from the development of physics. Clearly, Bohr and Einstein have to be with us.

End of Interlude.

First intermission

Act 2: Seminar on quantum measurement

[*The stage is a seminar room with a blackboard on the wall.* Marie Curie *is in place as chairperson. Other persons present*: Alice, Melanie, Mr Tompkins, Dirac, Sankofa, Lehninger, Einstein, Niels Bohr, Bell, DeWitt, Feynman.]

Marie Curie: We are gathered here to reconsider the measurement problem of quantum mechanics. The first Wonderland traveller, Alice, has come here with Mr Tompkins and she thinks the problem has not been properly handled. She came to me with Paul Dirac to ask if we could look back on the development in physics to see if things could have followed another path. So together with Paul, I have called you to this seminar. Let me introduce you briefly to each other.

Alice, Mr Tompkins and Sankofa from West Africa are literary persons; Dr. Melanie Bailey, also travelling with Alice, is a scholar in literature and science from the real world. The rest of us are 20th-century scientists, mostly from the area of physics: Niels Bohr, Albert Einstein, Paul Dirac, Richard Feynman, John Bell, Bryce DeWitt, but Professor Albert Lehninger comes from biochemistry. Thank you all for joining us. I am Marie Curie.

Before we discuss quantum mechanics, I would like to go back to my own time as a young scientist. Around 1900, the life sciences went through a paradigm shift. I call on Professor Albert Lehninger to tell us about this.

Lehninger*: It may be good for the physics community to recall the situation in the life sciences around 1900. To understand the nature of life had been a problem. Vitalism was the widespread idea that a special vital force is necessary to explain how organic matter is functioning in metabolic processes in living cells. Then Eduard Buchner showed in an experiment that non-living extract from yeast cells can ferment sugar; living cells are not needed for the process. From this, one could draw the conclusion that no vital force is needed; the metabolic process of fermentation can be completely understood as a chemical process. This made vitalism come to an end.

Marie Curie: So what do we learn from this?

Lehninger: The history of cell metabolism is instructive. It warns us against considering problems to be beyond our reach because they have not yet found their solution.

So I encourage you physicists to carry on and continue to solve your problem!

Marie Curie: Thank you, Professor Lehninger for sharing this with us. Melanie, I see your hand.

Melanie: Here I think it is proper to use Daniel Dennett's notion of 'cranes' and 'skyhooks'. Ordinarily, one tries to build science on a firm basis. 'Cranes' can stand on what has already been constructed and be used to lift new elements to be put in place in the construction. When there is no firm level to stand on or when no crane is available, it is tempting to invent an imaginary 'skyhook' hanging down from heaven, a doctrine, and to use this instead of a crane to lift in new elements. We know this very well from the content of folklore or religion, but skyhooks should have no place in science.

Around 1900, the 'vital force' of vitalism was such a skyhook till Buchner removed it.

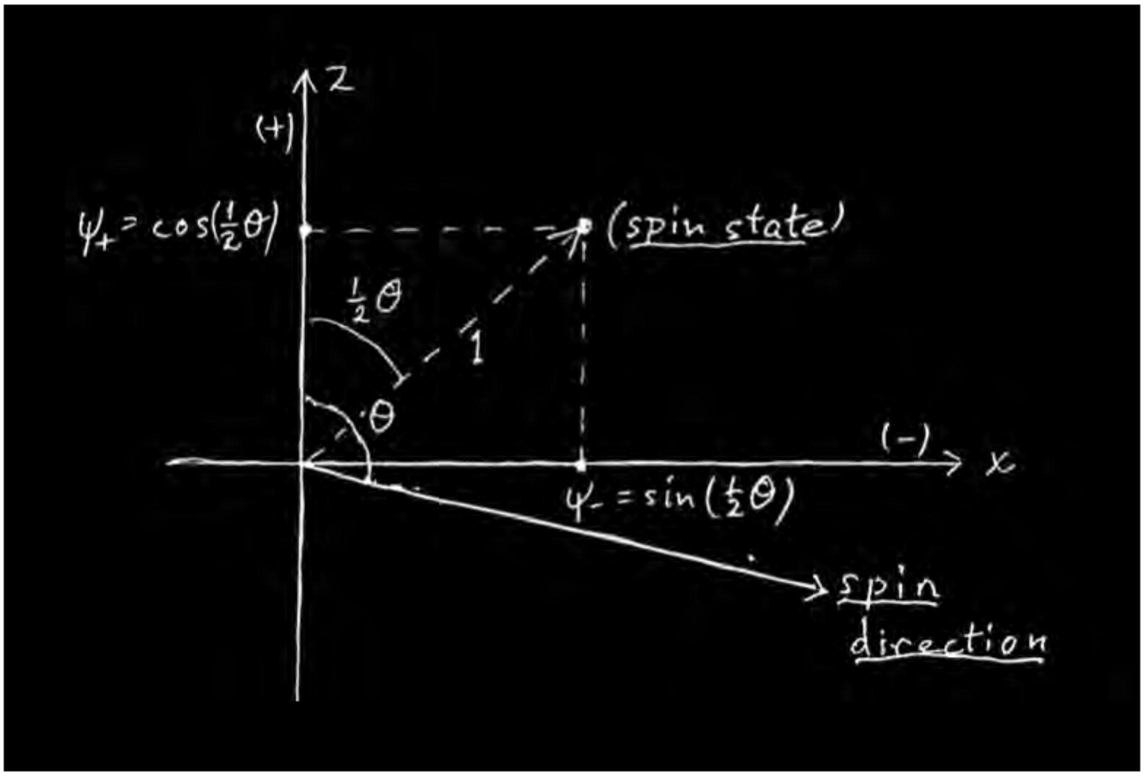
Marie Curie: Some of us can date the measurement problem of quantum mechanics back to the discussions of the 1920s. Bohr, Einstein, Dirac and myself took part in the Solvay meeting in 1927. Paul, can you state the problem?

Dirac: Let us think of a two-level system, such as the spin of a spin-$\frac{1}{2}$ particle and a measurement of the vertical spin component. The result of a measurement will either be up or down. [*Starts to draw and write on the blackboard.*] If the initial state has been prepared so that the electron spin forms an angle θ with the up-direction, it is a superposition of spin-up ($|+\rangle$) and spin-down ($|-\rangle$),

$$|\psi\rangle = \cos\tfrac{\theta}{2}|+\rangle + \sin\tfrac{\theta}{2}|-\rangle .$$

Then 'Born's rule' states that the probability for getting the measurement result 'up' is $\left(\cos\frac{\theta}{2}\right)^2$, and the probability to get the result 'down' is $\left(\sin\frac{\theta}{2}\right)^2$.

After measurement, the spin will point in the direction that agrees with the result of measurement.



Dirac's blackboard.

To predict the result for a single measurement is impossible unless the spin is already pointing up or down. In the interaction between the electron and the measurement apparatus, there is no force for changing the up state into the down state or vice versa.

There is no common understanding for how the spin changes from the original direction to point either up or down. This is the measurement problem.

Marie Curie: I think, we all agree with your description. Alice, you came to me with Professor Dirac. What do you say?

Alice: If quantum mechanics is a good theory about everything, it should also be true for the measurement apparatus. It is made of the same kind of matter as the small thing that is being measured. We should use quantum mechanics to understand better what the two things do to each other.

Marie Curie: In the old discussion, Professors Bohr and Einstein were very active with very diverging ideas. Albert, the experimental development in physics has continued to go your way with respect to general relativity with many observations of black holes and with detection of gravitational radiation. But it has not gone your way with respect to quantum mechanics. What do you say?

Einstein*: It is true that observations of quantum phenomena have disproved some of my ideas. I have to admit that spatially separated systems can be entangled. Maybe reality then lies in the entangled state.

But quantum mechanics, the way it is used now, is not yet a theory. In a proper theory, one should be able to derive Born's rule and the change of state that Dirac described.

Marie Curie: Thank you, Albert. What about you, Niels? Can we have your comments?

Niels Bohr*: Einstein is never satisfied. I like to think of quantum mechanics as a statistical theory. Natural laws are still laws, even if they are given in statistical form.

Bell*: But Professor Bohr, you have also said that measurement is the joint result of an interaction between two systems, the measured system, let us call it μ and the part of the apparatus first met by μ; let us call this system A.

Niels Bohr: Yes, you are right. If μ is initially in a superposition, there is no unique measurement value available; it is somehow determined in the interaction between μ and A.

Marie Curie: Thank you, Niels. Any comment? Yes, Albert.

Einstein: Niels, the system A, interacting with μ, must have many degrees of freedom; it cannot be known. Then the unknown initial state of A could be the source of statistics; we do not have to blame the dynamics.

[Bohr *looks ready to say something but he stays quiet.*]

Marie Curie: We learnt from von Neumann that each state of μ gets entangled with A, but the proportions of the two channels stay the same. Neither spin up nor spin down can take over from the other. This dilemma led to the stories about Schrödinger's Cat and Wigner's Friend. The dilemma was turned into a formal theory by Everett in 1957. I now call upon Bryce DeWitt. You developed Everett's theory into a whole world view.

DeWitt*: Thank you. The understanding is that in a measurement, entanglement extends further and further, but all possibilities remain with the same proportions. The quantum-mechanical state contains all possibilities even after measurement. Extending the Schrödinger's Cat idea to everything, one gets a multiverse split in parallel worlds. Similar things may happen all over the universe. I once described it like this:

"... every quantum transition taking place on every star, in every galaxy, in every remote corner of the universe is splitting our local world on earth into myriads of copies of itself."

Mr Tompkins: And then you continued:

"I still recall vividly the shock I experienced on first encountering this multiworld concept. The idea of 10^{100+} slightly imperfect copies of oneself all constantly splitting into further copies, which ultimately become unrecognizable, is not easy to reconcile with common sense."

Marie Curie: Melanie, I see that you would you like to comment on this.

Melanie: The Many-Worlds Interpretation also looks to me like a skyhook. To solve one problem in our world, one assumes any number of unknown worlds.

Marie Curie: Thank you, Melanie. John Bell, you have also criticized the Everett-DeWitt theory.

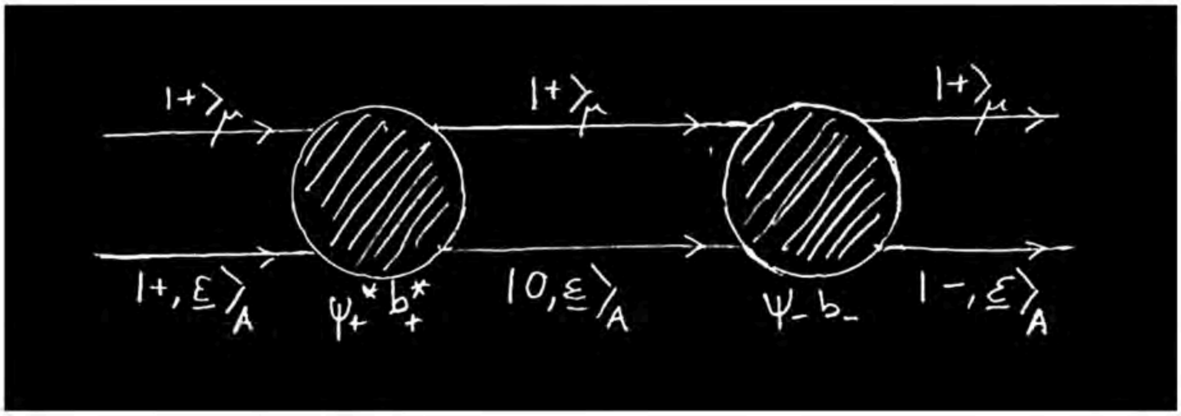
Bell*: Yes, the multi-world idea involves branching of the world but not debranching. That way, the theory brings in an asymmetry in time that seems foreign to quantum mechanics. We have to look for a description that keeps reversibility.

Marie Curie: Maybe the quantum mechanics of the 1930s was not adequate. If we follow the physics development, does quantum field theory have the reversibility that you are asking for. [*Niels Bohr shows that he would like to speak.*] Please Niels, let us wait with the discussion.

Bell: Quantum Field Theory is reversible. One can see this when using Feynman diagrams to calculate. Actually, we have the diagram architect with us here. But Richard, contrary to what Professor Lehninger said, you have stated that we may have to accept giving up our ambitions to solve the measurement problem. What do you think now?

Marie Curie [*after giving* Niels Bohr *the opportunity to speak, but* Niels Bohr *only shakes his head*]: Yes, Professor Feynman, what do you think?

Feynman* [*thoughtfully*]: Right now, I think John opened a possible path by stressing the importance of reversibility. Let us think again of measuring the vertical spin component of an electron! The state of the electron has two components, one for spin up and one for spin down. In the interaction with the measuring apparatus, these components get increasingly entangled with the apparatus. In the 1930s, one did not see any way back. [*Drawing on the blackboard while he speaks more thoughtfully*:] But with reversibility, the apparatus and the electron can return to their initial state. So returning and then taking the other way is a possibility. In this way, there is a connecting path between spin up and spin down. Sorry, I have not thought of this before. [*With increasing excitement*]: I see now! We can simply refute the von Neumann dilemma! It is an obsolete product of the 1930's; it is not valid.

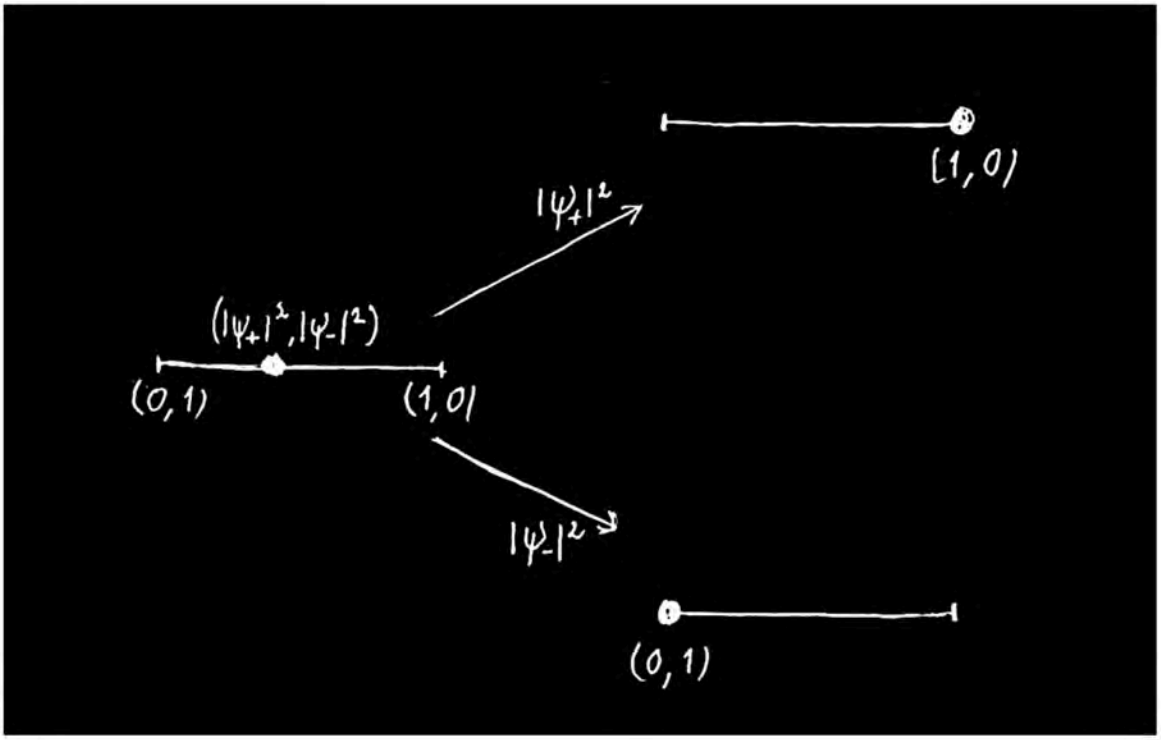


Feynman's blackboard.

Generally, the measurement apparatus should be unbiased. But that must hold statistically, in the mean. Depending on the state of A, a single process can accidentally favour one outcome rather than the other one. But in the mean, an unbiased A should be equally open to be marked by μ with spin up as with spin down.

Marie Curie: To lead to a definite result, one of them must totally dominate over the other. How can that come about? [*Makes an inviting sign to* Einstein *who has raised his hand.*]

Einstein: We saw before that through the μA-interaction, A could be a source of statistics. Let us think of the probability interval with certainty for 'spin down', $(0,1)$, to the left, certainty for 'spin up', $(1,0)$, to the right and fifty/fifty, horizontal spin direction, in the middle. From our starting point, $\left(\left(\cos\frac{\theta}{2}\right)^2, \left(\sin\frac{\theta}{2}\right)^2\right)$, Born's rule gives probability $\left(\cos\frac{\theta}{2}\right)^2$ for going to $(1,0)$ and probability $\left(\sin\frac{\theta}{2}\right)^2$ for going to $(0,1)$. Then we map the influence of interaction as motion on the probability interval.



Einstein's blackboard,

We can think of μ as passing through the system A and interacting stepwise. As Feynman said, in each step, we can expect accidental support of spin up or spin down, but in the mean, there should be strict neutrality.

Recording these steps on the probability interval, we get a random walk: small steps are taken, supporting spin up or spin down, but for each step, the mean is zero.

Each walk ends up in one of the endpoints, $(1,0)$ or $(0,1)$, that is in either spin up or spin down. But since the mean does not change, the frequencies for getting spin up or spin down are $\left(\cos\frac{\theta}{2}\right)^2$ and $\left(\sin\frac{\theta}{2}\right)^2$, respectively. So Born's rule is confirmed.

Maybe I should explain why a random walk ends up in an endpoint. Simply because the mobilitiy is the same in both directions, and the system must not move outside the interval; therefore approaching an endpoint decreases mobility. Random walks stop there.

Marie Curie: Thank you, Albert.[*Looks around and* Bell *gives a sign.*] Yes, Professor Bell.

Bell*: Professor Einstein mentioned the steps along the probability interval with 'spin up' at one end and 'spin down' at the other. In the early 1990s, Gisin and Percival studied quantum diffusion with a non-linear stochastic Schrödinger equation. Like Professor Einstein, they got a definite value of the measured quantity. They claimed to describe an open quantum-mechanical system and that has later been supported. Their results can be derived within traditional quantum mechanics.

Actually, I think that it is fair to say that Gisin and Percival, together with Lajos Diósi and Philip Pearle, solved the measurement problem around 1990 with the theory of quantum diffusion, analyzing the system μ in interaction with the unknown system A, although not very explicitly described.

Their theory is now known to be a consequence of linear quantum dynamics, and it should be recognized as a solution of the measurement problem.

Marie Curie: Thank you, John Bell. This may be the most elegant way of looking at measurement. [Bell *raises his hand.*] Maybe you have something to add.

Bell: After the interaction between μ and A, there is interaction between A and the rest of the apparatus. This is irreversible and the mark by μ on A gets irreversibly fixed.

Marie Curie: Thank you, Professor Bell. To me it seems that we are close to having solved the whole problem. Any comment? Alice!

Alice: Then it is not God who plays dice but the physicist with unknown details in the system A of her apparatus.

Sankofa [*after approval from* Marie Curie]: It seems like the system is moving forward in time to check various ways, then reversing back to make the best choice. I am preaching 'learning from the past' but this looks like learning from the future! Maybe we should have a new Adinkra symbol for that? Very thrilling!

Bell [*commenting to himself*]: Yes, just like Feynman's integral over histories!

Feynman [*looks up with a smile*]: Let me mention a small technical thing. In all this, reversibility is important, but very often it is not explicitly visible.

Alice [*eagerly waving her hand and allowed by* Marie Curie *to speak*]: I understand that Schrödinger's experiment with a cat is meaningless and Everett's description of measurement is wrong.

Melanie [*also waving and allowed to spe*ak]: ... and Professor DeWitt! Your skyhook is gone, so you can return to common sense.

[DeWitt *smiles quietly but says nothing*.]

Schrödinger's Cat [*enters, very upset*]: He is impossible to talk to, disappears and disappears, always leaving that stupid smile behind.

Marie Curie: Order! Order!

Alice [*after requesting the floor, goes to* Schrödinger's Cat *and takes him/her in front of everybody*]: This is Schrödinger's Cat. All since (s)he was conceived by Schrödinger, (s)he has been threatened by the poison that could kill him/her or one component of him/her. [*To* Schrödinger's Cat]: The idea of putting you in that box is no more valid. You are now a historical figure; you have been brave to stand all that suffering, but now you are free. Go and tell your friends!

Schrödinger's Cat: Is it true?

Marie Curie: Yes, go and tell your friends!

Before we celebrate our achievements, I think we should hear the views of Albert Einstein and Niels Bohr. What do you say?

Einstein: My main concern is always the possibility to understand and I think we have reached a good understanding now.

The quantum-mechanical state represents a reality that develops according to a deterministic dynamics. As Bell helped me to clarify, the probabilistic features come from details of the apparatus that are unknown and even not knowable, like in statistical mechanics. Subtle is the Lord, but malicious He is not.

Together we have been very constructive? What do you say Niels?

Niels Bohr: All the time I have believed in Quantum Mechanics. When others were not satisfied with it, I liked to step in to defend it. What I see now is, of course, that it is even better than I could dream of. So I am very satisfied. Marie, you were right in taking us into Quantum Field Theory. We have been able to develop this together.

Marie Curie: Thank you, Albert and Niels! We are now free from von Neumann's dilemma and we have more or less solved the problem. Richard Feynman, you took the first step! This is an occasion when it would be proper to listen to your drumming.

DeWitt [*while* Feynman *is putting up his drums*]: It is fine to go back to common sense and to one world.

[*When* Feynman *is ready, he starts drumming with a big smile.* The Dormouse *comes and dances with* Schrödinger's Cat. The Hatter, The March Hare, *and* The Doormouse *come and dance together.* Wigner's Friend *and* Sankofa *join in the dancing.* Marie Curie *is resting*. Lehninger *and* DeWitt *sit quietly together*. Melanie, Alice and Mr Tompkins *have a small quiet meeting.* Bell *and* Dirac *sit together.* Niels Bohr *and* Einstein *comment to each other (not audible) and nod quietly. When* Feynman *stops drumming, dancing stops and everybody claps*. Feynman *recieves the appreciation smiling.*

End of Act 2.

Second intermission

Act 3. Continued seminar: Looking forward and looking out

[*The same room with* Marie Curie *in place as chairperson. Persons present are again*: Alice, Melanie, Mr Tompkins, Dirac, Sankofa, Lehninger, Einstein, Niels Bohr, Bell, DeWitt, Feynman.]

Marie Curie [*clapping her hands to bring order*]: Let us continue! [*When people are seated*]: Any comment? Melanie!

Melanie: In our discussion, Quantum Mechanics has shown its strength. Measurement is a quantum-mechanical process that we can understand. Congratulations to all of us, in particular to Professor Bohr, the strongest supporter of quantum theory.

Marie Curie: Could we now have a comment from Professor Lehninger?

Lehninger: I have looked at you physicists from the outside. In everyday practice, you have very much followed David Mermin’s rule: ’Shut up and calculate!’ You have not disturbed each other with dogmatic quarrel. So physics has evolved peacefully and efficiently with the measurement problem remaining unsolved.

To listen today has been a remarkable experience. Congratulations to physics for catching up with biochemistry!

Marie Curie: Thank you, Professor Lehninger. Paul, at the beginning, you stated the problem. What do you say now?

Dirac: We now understand how a non-destructive measurement leads to one of the possible results. The measured system goes to the state related to the result. But still we need to develop more realistic models of actual measurement processes. Without this, our young colleagues will consider our result as simply talking, talking.

Marie Curie: After nearly 100 years with the problem, our talking here has not been bad. But I agree, of course. Realistic models of measurement processes are needed. What about consequences of what we have achieved? What do you say, Feynman?

Feynman: Physical reality is hard to guess. Therefore it is almost impossible to anticipate physical knowledge through philosophical discussions. But progress in physics can give knowledge that must be analyzed in philosophy and incorporated in our general scientific and philosophical understanding.

Let us continue our discussion and ask Dr Bayley to take notes of what could be of importance to her and her friends in philosophy. [Melanie *immediately opens a new page in her notebook and takes up her pen*.]

Marie Curie: Thank you, good idea! Let me say something about one consequence of our new insights. The understanding of measurement means that we now have a better description of the interaction between the instruments used in science and the object systems studied. This means that we have given an important contribution to epistemology, the part of philosophy that deals with the gaining of human knowledge.

Professor Bell, I see that you would like to say something.

Bell: In the everyday work with quantum mechanics, when we study some quantum-mechanical system, we have a pragmatic way of describing reality for practical use: the quantum-mechanical state of the system studied. Up till now, this description has only been pragmatic for most of us, representing a potentiality rather than a reality. Now we can describe measurement in the same scheme. [*To* Feynman]: What do you say, Richard?

Feynman: Yes, we should follow Professor Einstein’s idea and consider the pragmatic concept of the quantum-mechanical state as representing or even being reality, the whole way.

[Marie Curie *gives the floor to* Melanie.]

Melanie: So what has been only a pragmatic ontology for physicists, can now be promoted to a more general ontology. [*Slowly and thoughtfully*:] The quantum-mechanical state is recognized as real rather than a potentiality. Very interesting! [*Eagerly writing in her notebook*.]

DeWitt [*after raising his hand and getting a sign from* Marie Curie]: I could say with some pride that this has been our ontology all the time in the multi-world picture. But being stuck with von Neumann's dilemma, our reality became so extremely complicated. Now without the dilemma and with the statistical reduction mechanism shown to us by Professors Einstein and Bell, it all comes out very nicely.

Marie Curie: Thank you, Professor DeWitt. Yes, first Alice, then you, Niels!

Alice: We have seen how one component wins in a measurement. We get only one out of the two possible results. The other one has disappeared. Doesn't that mean end of entanglement? Finally, it becomes very simple.

Niels Bohr: Just what I wanted to comment. In our everyday life, the world appears classical; we do not witness strange superpositions. Maybe the random-walk or quantum diffusion mechanism shown to us by Einstein and Bell, is more generally active. It can remove entanglement and make our every-day world classical, as we experience it.

Marie Curie: Thank you Niels. And what about causality, about cause and effect? The ontology that Paul described to us was about small systems. For them we often know the dynamics. But what about bigger systems? Albert.

Einstein: Most of you know my 1935 paper with Boris Podolsky and Nathan Rosen. We showed that, in quantum mechanics, pairs of particles could become entangled and correlated over large space-like separations. We wanted to show that quantum mechanics is paradoxical. Now we have to accept such entangled particles as reality.

Bell [*after receiving approval from Marie Curie*]: All the time and all over the universe, fast pairs of entangled particles may be created; they can tie systems together over space-like distances. This means that almost any localized system can have small but far-reaching entanglement. Then such a localized system cannot be described by a pure quantum-mechanical state; it must be described statistically. Even if we view the quantum-mechanical state as fundamental in ontology, a statistical description has to be the rule for systems in general. Only very limited systems can be considered as isolated.

Marie Curie: Thank you Albert, and thank you, John Bell, for these clarifications. Melanie!

Melanie: I think that in this seminar, we have found a quantum-mechanical basis for a new understanding of the world as we meet it in our every-day experiences. It seems that science and common sense can work closely together to achieve a consistent description of the same reality.

Alice: Sometimes physicists have had a loose connection to reality. What Lewis Carroll wrote about me after my first visit in Wonderland became true about physicists of the 20th century: "So many out-of-the-way things had happened in science that maybe the physicists had begun to believe that very few things indeed are really impossible."

Melanie: Yes, in the evolution of physics, strange ideas appeared. Probably some physicists were hoping to make discoveries similar to relativity and quantum mechanics.

Lehninger: In biology we have examples of extreme evolution processes such as the development of the peacock’s tail. Cultural evolution is based on ideas instead of genes. The postmodern denial of reality can be viewed as an example of extreme cultural evolution. The notion that quantum mechanics is incomprehensible may be an example of extreme evolution in the physics culture.

Throughout history there have been developments of extremism in religion and in political thinking. We know all too well the dangers inherent in such phenomena.

Dirac: Are we moving away from physics now?

Marie Curie: Yes maybe. But physics is everywhere. For me, the physical substances that I was studying, finally killed me. Some of you took an active part in developing nuclear arms, based on the understanding of atomic nuclei. That turned out to be the beginning of an irresponsible game. Now almost 80 years later, such arms are still a serious threat to the human society and to higher life forms on Earth. Physics is far from innocent.

It is also difficult to predict how tools based on sophisticated science can be used. Communication technology is of this kind. It is now widely used to spread threats and lies, to misrepresent science, to support stupidity and to undermine democracy.

Scientists should follow science-and-society issues very closely and develop the ability to take responsible action when it is needed.

Sankofa: In our minds and together we should move into the future to see the outcome of different ways of acting or non-acting, then return to the present to make good decisions and agreements. [*To this, participants react with restrained surprise and approval.*]

Marie Curie: Good suggestion, Sankofa. Let us end our meeting here. Thanks everybody. Is Alice satisfied?

Alice: Oh yes!

Marie Curie: Thanks everybody! Thank you, Alice and Mr Tompkins! Thank you Dr Bayley! Thanks for your coming here to study quantum mechanics more deeply with us. What about you, Niels and Albert? Are you satisfied?

Niels Bohr: Here we have met in a world of fiction to help people in the real world get a better grip of their reality. This is a paradoxical situation of a kind that I like... [*laughing*] ... in contrast to Albert.

Einstein [*first smiling, then becoming serious*]: Confusion is lethal. We have to be realists and to combat confusion.

Bell [*after looking at* Marie Curie *and getting approval*]: Yes, we have to. But we must remain humble. Remember, we used to think that we know what our world consists of. Now we know that we know only a small fraction of the stuff making up our world.

[The Hatter, The March Hare *and* The Dormouse *come with their box and their cranks and start turning*. Feynman *starts drumming*. Marie Curie, Bell *and* Melanie *begin a small discussion*.]

Melanie: Where could we publish the proceedings of this meeting?

THE END

Tradition, characters and story of the play

Charles Lutwidge Dodgson (1832-88) published in 1865, under the pseudonym Lewis Carroll, Alice's Adventures in Wonderland with illustrations of John Tenniel. The Hatter, The March Hare and The Dormouse are the persons of the tea party in the book.

With Alice, I have introduced an ambiguity based on the fact that I have a grandchild named Alice.

George Gamow (1904-1968) was a Russian/Ukrainian-American theoretical physicist and cosmologist. Further reading about the book series in http://en.wikipedia.org/wiki/Mr_Tompkins.

George Gamow's Mr Tompkins in Wonderland was first published in 1940, and Mr Tompkins explores the atom was first published in 1944.

Michael Frayn (born 1933) is an English playwright and novelist. His play Copenhagen deals with a meeting in 1941 in Copenhagen between Niels Bohr and the German physicist Werner Heisenberg. In the play they meet, together with Niels' wife Margrethe Bohr, after death and try to reconstruct what happened in 1941. The focus is on Heisenberg's responsibility to develop a nuclear weapon for Nazi Germany.

In Alice's adventures in Wonderland solved (New Scientist 16 December 2009), Melanie Bayley shows that the tea party in Lewis Carroll's book (with The Hatter, The March Hare and The Dormouse) is a parodic allegory of W.R. Hamilton's theory of quaternions, later used by Wolfgang Pauli in matrix form to describe electron spin.

Melanie Bayley (born 1959) is a literary scholar with a background in mathematics and science and experience in science journalism. One of her research interests is the impact of mathematics on nineteenth century fiction.

Paul Dirac (1902-1984, Nobel prize in physics 1933) was an English theoretical physicist. He made fundamental work in quantum mechanics and quantum electrodynamics. He formulated the Dirac equation for particles with spin 1/2. From this the existence of antimatter could be predicted. Dirac was known to be an eccentric person. Because of the importance of his ideas, I have chosen to portray him as more social than he was known to be. Eugene Wigner (see below) and Dirac were the only early physicists in the play that I got to know a bit.

Schrödinger's Cat is a thought experiment, sometimes described as a paradox, devised by Erwin Schrödinger in 1935. It illustrates what he saw as the problem of the Copenhagen interpretation of quantum mechanics applied to everyday objects. The scenario presents a cat in a state of being both alive and dead, this state being tied to an atomic system. (Wikipedia's description.)

Erwin Schrödinger (1887-1961, Nobel prize in physics 1933) was an Austrian physicist. He made important contributions to quantum theory but was not willing to accept it.

Wigner's Friend: The Wigner's Friend thought experiment posits a friend of Wigner who performs the Schrödinger's cat experiment after Wigner has left the laboratory. Only when he returns does Wigner learn the result of the experiment from his friend, that is, whether the cat is alive or dead. The question is raised: was the state of the system a superposition of "dead cat/sad friend" and "live cat/happy friend," reduced only when Wigner learned the result of the experiment, or was it determined at some previous point? (Wikipedia's description.)

Eugene P. Wigner (1902-95, Nobel prize in physics 1963) was a Hungarian-American theoretical physicist. He believed that human consciousness was a necessary component in the analysis of quantum measurement.

Sankofa is one of the Adinkra symbols, a religious and philosophical set of symbols from the Akan people of West Africa. Sankofa's message is: Look back, and learn from the past!

Marie Curie (1867-1934, Nobel prize in physics 1903, in chemistry 1911) was a Polish-French physicist and chemist who studied radioactivity. She was a pioneer who opened the field of atomic and nuclear science and thus the whole of modern physics.

I have tried to describe Marie Curie as an openminded person and as a grand old lady of science. I have not made any attempt to learn about her as a person to have a model for my character.

Albert L. Lehninger (1917-86) was an American biochemist, who wrote a very widely used textbook in biochemistry, still in use, regularly updated. (When Magdalena Eriksson showed me what Lehninger had written about the development in the life sciences 110+ years ago, it changed my view on physics.)

Albert Einstein (1879-1955, Nobel prize for 1921 in physics) was a German-born theoretical physicist, founder of relativity theory and cofounder of quantum mechanics, but also very critical against the common interpretations of quantum mechanics. He played a crucial role both in the development of nuclear arms and in the efforts to prevent a nuclear-arms race. Albert Einstein is considered to have been one of the greatest scientists of all times; further description here is superfluous.

Niels Bohr (1885-1962, Nobel prize in physics 1922) was a Danish theoretical physicist, one of the founding fathers of modern atomic and subatomic physics. His Bohr Institute was for a long time the most important international meeting point for theoretical physicists.

Niels Bohr considered nature to be capricious and beyond reach for detailed physical analysis.

John Bell (1928-1990) was a physicist from Northern Ireland. He worked with accelerator physics, elementary particle physics and the foundation of quantum mechanics. Bell did the theory work for the best direct experimental tests of quantum mechanics. He was firm in his principle to solve physical problems within physics. I first met John Bell in 1960 and I got to know him quite well.

Hugh Everett (1930-82), American physicist, proposed in 1957 (at the time working with John Wheeler in Princeton) a 'relative-state interpretation' of quantum mechanics. This is like extending a superposition of the measuring device, entangled with the quantum system to Schrödinger's Cat, Wigner's Friend and beyond, until the whole universe is included in different components of an entangled quantum-mechanical state.

Bryce S. DeWitt (1923-2004) was an American physicist. With his famous article 1970 in Physics Today, he made Everett's Relative-State Formulation into a total world view, the Many-Worlds Interpretation of Quantum Mechanics. This is still a relatively common view among physicists.

Richard Feynman (1918-1988, Nobel prize 1965) was an American theoretical physicist. He worked in quantum physics, in particular quantum electrodynamics, where he developed his 'Feynman diagrams', a scheme for calculating transition amplitudes.

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The whole story deals with the solution of the old measurement problem in quantum mechanics. This work is based on relativistic quantum mechanics, known as Quantum Field Theory. The main ideas in the play date back to the 1950s.

The main discussion in Act 2 of the play goes along the following line:

Reminded by Bell, Bohr recalls his own picture of the measurement as a joint product of the measured (two-level) system and the apparatus. This immediately gives Einstein the idea to view unknown details of the apparatus as a cause of random influence, making the process statistical. Marie Curie, accepting von Neumann's dilemma for the non-relativistic quantum mechanics, asks for ideas in the emerging relativistic quantum mechanics (not ready in her time). Feynman responds to this and in his instant analysis, he finds the reversibility, requested by Bell in the discussion. On the relativistic basis, Feynman can refute von Neumann's dilemma and find a new opening. He also emphasizes the necessity for the apparatus to be statistically unbiased. Supported by this, Einstein resumes his analysis of the interaction between the measured system and the apparatus. It is a random walk on the probability interval for the two possible results. His conclusion is that a definite result always obtains and that it follows Born's rule.

In the play, I have tried to create constructive opportunities and a mutually constructive interplay for very gifted scientists of different times:

Marie Curie asks about ideas in the synthesis of relativity and quantum mechanics which she could see coming but after her time. Bohr and Einstein, very divergent in their thinking, are here given an opportunity to cooperate. The Quantum-Field-Theory man, Feynman, gets a chance to better appreciate his own theory. Here he hands over to Einstein relativistic results that came too late for Einstein in his life. Einstein who disliked the idea of God playing dice, can instead do a proper statistical-mechanical analysis of the measurement interaction.

Bell sees how Einstein's analysis supports the ideas in quantum diffusion of the late 1980s. At that time, Bell had found these ideas very promising but not yet ready to form a theory. In the play however, Bell can tell that quantum diffusion is now known to be closely related to the ordinary quantum mechanics.

Quantum diffusion, suggested as a solution to the measurement problem, was an active field of research 1985-95. The main paper in quantum diffusion, related to the play, was published by Nicolas Gisin and Ian Percival in 1993. Other persons in this field were Lajos Diósi and Philip Pearle.

Other works related to the play, done by Cederwall, Eriksson, Lindgren and Sjöqvist, are discussed in Chapter 1 of this book.

In the play, the Special Theory of Relativity and Quantum Mechanics are mentioned as forming a Constitution for Physics. The General Theory of Relativity that deals with gravitation and cosmology should be included as well but it is not yet clear how general relativity and quantum mechanics can function together. In this sense the constitution of physics is incomplete. As Bell points out towards the end of the seminar, we know now that our world picture is very far from complete.

A Reading of the play is being planned to take place at Chalmers a short time after the book has been published. We hope that we can film the event and make the film easily available.

3. THE ROLE OF QUANTUM MECHANICS IN THE CULTURE OF THE 2020s

Since the early days of quantum mechanics, many physicists have had a double attitude towards the theory. They have done regular research and they have developed the theory. But parallel to that they have described quantum mechanics as mysterious and difficult to understand. This double attitude still continues.

I recently had the opportunity to watch a very informative and pedagogical television documentary with David Kaiser on neutrino physics. Kaiser is also a science historian and I have read his very interesting paper [1] on Schrödinger's cat article and on the correspondence between Schrödinger and Einstein about the arguments of that article, meant to show the weakness of quantum mechanics.

In Kaiser's writings, I have also found the other attitude towards quantum mechanics. In the presentation of his book Quantum Legacies, "a series of engaging essays that explore iconic moments of discovery and debate in physicists' ongoing quest to understand the quantum world", quantum mechanics is described as follows [2]:

> The ideas at the root of quantum theory remain stubbornly, famously bizarre: a solid world reduced to puffs of probability, particles that tunnel through walls, cats suspended in zombielike states, neither alive nor dead; and twinned particles that share entangled fates. For more than a century, physicists have grappled with these conceptual uncertainties...

My interpretation is that this text extends the art of mystifying quantum mechanics to a new level: "ideas at the root of quantum theory remain stubbornly, famously bizarre".

'Cats suspended in zombielike states, neither alive nor dead', only refers to Schrödinger's cat fable; it is not part of any serious physical theory. I interpret 'puffs of probability' as an expression of the rather common view that quantum mechanics is a basically probabilistic theory. This would mean implicit rejection of the view that there could be a physical explanation behind the statistical effects, as suggested more than 30 years ago in papers on quantum diffusion. If a source of statistics can be identified, no mysterious 'puffs of probability' are needed. What is mentioned as 'tunnelling' and 'entangled fates' (of EPR pairs) are wellknown phenomena of quantum mechanics which do not have to cause any 'conceptual uncertainties'.

David Kaiser, an excellent popularizer of physics and of science history, thus chooses to follow and develop the tradition in the physics culture, to propagate a picture of quantum mechanics as mysterious and difficult to understand.

To be meaningful, the term 'quantum mechanics' should refer to relativistic quantum mechanics, not the non-relativistic quantum mechanics that John von Neumann or Erwin Schrödinger were struggling with. Relativistic quantum mechanics is the supreme scientific theory for explaining the human experiences of the structure of our material world. In some instances the agreement between theory and experiment is of a very high numerical precision.

Maybe it is still understandable that physicists look at quantum mechanics as mysterious. What happened in physics in the early 20th century, gave a taste for discovery of new and fundamental ideas. Niels Bohr considered nature as inherently unpredictable [3]. Eugene Wigner liked to think that the consciousness of the observer caused what was called "the collapse of the wavefunction" [4]. Among physicists, the belief in Everett's [5] and DeWitt's Many-Worlds Interpretation [6] still seems to be quite widespread.

The back side of the radical ideas, is a lack of respect for everyday physical work, with an ambition to explain physical phenomena from what is already known.

John Bell was very critical towards this kind of thinking, but he was well aware of the advantages of what he considered 'romantic approaches' to create a wider public interest [7]:

> It is easy to understand the attraction of the three romantic worlds for journalists, trying to hold the attention of the man in the street. The opposite of truth is also a truth! Scientists say that matter is not possible without mind! All possible worlds are actual worlds! Wow! And the journalists can write these things with good consciences, for things like

> this have been said ... out of working hours ... by great physicists. For my part, I never got the hang of complementarity, and remain unhappy about contradictions. As regards mind, I am fully convinced that it has a central place in the ultimate nature of reality. But I am very doubtful that contemporary physics has reached so deeply down that that idea will soon be professionally fruitful. For our generation I think we can more profitably seek Bohr's necessary 'classical terms' in ordinary macroscopic objects, rather than in the mind of the observer. The 'many world interpretation' seems to me an extravagant, and above all an extravagantly vague, hypothesis.

Bell himself viewed measurement, what we call 'determination' in our discussion, as a physical process. To understand this process is then a physical problem. Then neither metaphysics, nor epistemology or psychology, would have anything to contribute to the solution.

<u>The measurement problem</u> of quantum mechanics is stll considered by many physicists as unsolved. The theory that was developed during a decade around 1990, <u>quantum diffusion</u>, can in some ways be viewed as incomplete. Still it was a clear indication of one mechanism that can solve the measurement problem: The uncontrollable interaction between the measurement instrument and the system subject to measurement is the source of statistics. Neither a capricious nature nor the consciousness of the observer take part in the process which produces one single measurement result, not many results, requesting many worlds. This is discussed in some detail in Chapter 1.

One may wonder if there is an unconscious collective will in the physics community to preserve a mystical tradition, rather than to seriously evaluate ideas for physical solutions of the measurement problem.

The culture of the physics community is part of a wider culture. In the global culture of today, the common science-based reality concept is questioned. Arbitrary beliefs and conspiracy theories are expanding in combination with resistence against science and experience-based information. Postmodern relativism has gained influence in humanistic and social-science faculties of the universities, and led to erosion of the reality concept.

In this development, physics has not been innocent. Mysterious views of quntum mechanics have been gratefully received by postmodernists as a reason to question the concept of reality itself. What is real, becomes a question of opinion, rather than a question of truth.

The present global situation is that young people on Earth have to solve very difficult planetary problems created by earlier generations and still largely neglected by the generation that currently is in power.

In the generation in power, cross-cultural understanding is seriously missing. This is in contrast to the coming generation. Young persons communicate globally without hindrance from cultural or national barriers. It is now important to support the young people with the best possible scientific, technical and social knowledge available, and to help them take over responsibility for global development in a democratic and peaceful way.

A useful concept is <u>Modernity</u>, understood as a constructive enlightenment project, still remaining unfinished. It can be defined as: on one hand <u>Human Rights and Democracy</u>, on the other <u>Science and Technology</u>. At present, Modernization has slowed down and important decision-making follows largely premodern principles. We must support young people to restore Modernity as a common human project to form a livable global society.

To contribute to this, physics should leave the myths and mysteries of its past history and resume its role among the sciences. Physics has a great tradition, first in collecting scientific knowledge into large bodies of coherent understanding and, secondly, in structuring, analyzing, and solving problems in a scientific way. This tradition should be made available to the young generation.

References

1. D. Kaiser, Quantum Legacies (Univ. Chicago Press, 2020).

2. From the publisher's presentation of D. Kaiser's book [1].

3. N. Bohr, Atomteori og naturbeskrivelse (København 1957).

4. Wigner's Friend in Wikipedia (https://en.wikipedia.org/wiki/Wigner%27s_friend).

5. H. Everett, Rev. Mod. Phys. 29, 454 (1957).

6. B.S. DeWitt, Physics Today 23, 30 (1970).

7. J.S. Bell, "Speakable" (Ch. 1, ref. [1]), p. 193.

4. ROOTS OF BACKGROUND IDEAS AND SUPPORT OF MY WORK

Since 1956, nearly 66 years ago, when I first was confronted with quantum mechanics, I have lived with the measurement problem of quantum mechanics.

During long periods, my connection to the problem was dormant, but during other periods, it has been quite intense. I have afterwards understood that, also when I did not think of measurement, in my studies and work, I collected knowledge that I later found was relevant for understanding quantum measurement.

Many different impacts and ideas have given me hints in the direction of the theory that is outlined in this book. If the work is correct, I think I have been very lucky to receive many impulses pointing in the same direction.

(1) One essential aspect is the basic view on the science of theoretical physics as it was taught in Uppsala University with a main emphasis on understanding. I can mention my teachers there, Ivar Waller, Alf Sjölander, Stig Lundqvist and Ture Eriksson. Nils Svartholm and Jan Nilsson, my colleagues in Göteborg, were also very much part of the same tradition.

Another, quite different, aspect is my experience from a long intense period (roughly 1972-1987) of work on interdisciplinary collaboration at The University of Gothenburg with the aim of a better understanding of knowledge relevant for a global human future. There one had always to ask oneself: Do I get a sufficiently wide perspective or am I missing something essential?

Work related to knowledge for the future continued during my stay at Karlstad University (2001-2014). The close connection between Karlstad University and the regional cultural life was also very inspiring for me.

A lot of my work was done during visits to Ghana, mainly during the period 1985-2015. In most of these visits, I stayed with my colleague and friend, Francis Allotey, in connection with teaching in mathematics courses for West-African graduate students. During a period, I was also a frequent guest of the Physics Department of the University of Cape Coast. The possibility to consider my research problems in a totally different context, was very stimulating.

I shall now go into more specific topics and ideas.

(2) In 1956, I first learnt quantum mechanics in Stig Lundqvist's lectures in Uppsala. I still remember my problem with the measurement postulate. The postulate itself was clear. My problem was the question why it was just postulated and not derived. The year after, I read Dirac's book Quantum Mechanics [1] with one of the classical formulations of the measurement postulate.

When I asked Alf Sjölander, about the problem, he referred me to a book by Werner Heisenberg from 1930 with an attempt to describe the formation of a track in a cloud chamber. The work by Mott and by Heisenberg [2] on this is also well described in John Bell's Speakable [3]. I found this discussion interesting and relevant. It was interesting to see that pioneers in quantum theory had been struggling so early with the problem of understanding measurement.

(3) In 1959, I came to the Theory Division of CERN in Genève as a research fellow. There I worked with André Petermann who gave me the task to compute radiative corrections to muon-electron scattering. At this stage, I had already studied quantum electrodynamics (QED) in Uppsala. I used the book Theory of Photons and Electrons by J.M. Jauch and F. Rohrlich [4] as a handbook. In this work, I learnt about the infrared problem of QED, which had been discussed already by Jauch and Rohrlich. I saw that I could continue their work and sum the perturbation expansion to all orders with an improved accuracy.

The infrared part of the interaction means the long-range part. It affects the ingoing and the outgoing states of a process. The change of the energies and momenta of the ingoing and outgoing particles is however small and the effects on amplitudes can usually be neglected. The main effect of the infrared interaction is a factor in the transition amplitude, related to the total energy loss through soft-photon emission by the incoming and outgoing charged particles. It was shown by Jauch and Rohrlich that the dynamics is the same as if the charged particles were classical point particles, simultaneously reaching or emerging from a pointlike collision centre.

This experience was useful later in my research on particle scattering. (The very convenient use of coherent states to describe the soft part of the electromagnetic field came some time later.) It took time before I understood that the factorizable interaction via the infrared part of the electromagnetic field is very relevant for the description of the interaction in measurement processes. Finally, it led me to describe the influence of non-destructive measurement on the measured system as a factorizable final-state interaction.

(4) With Ernst C.G. Stueckelberg, André Petermann had discovered the renormalization group of QED [5]. This group was also independently found by Murray Gell-Mann and Francis E. Low [6]. The renormalization group was used by Russian physicists as a quite powerful mathematical tool to connect terms of different orders in the perturbation expansion of QED with each other.

After reading about this, I found that I could continue along these lines and make partial summations over the perturbation expansion and in that way reduce the needed computations of radiative corrections.

In my paper with Kristian Lindgren in Entropy [7], the summation over the no-change graphs of measurement interaction, can be viewed as a renormalization of the ingoing state of A, the relevant part of the measurement apparatus.

(5) In the CERN Library, I found and read the 1957 article by Hugh Everett on the relative-state interpretation of quantum mehanics [8], the basic work in the direction of the Many-Worlds Interpretation. This was probably in 1960. I remember that I found Everett’s article amusing but I did not take it very seriously.

(6) In 1960, John Bell joined the permanent staff of the Theory Division at CERN. He got an office very close to mine. One day when we told each other about our research, he said something that stayed in my mind after that. He said: “I would like to do what should be on page 25 in any textbook on quantum mechanics.” I understood immediately what he meant: He would like to find a way to derive the measurement postulate within the theory. During a period, I also followed Bell’s important work in quantum mechanics, that he regularly reported at conferences. Bell also came and visited our particle physics group in Göteborg several times.

(7) Before I got a room of my own at CERN, I had shared office with Franco Selleri from Bologna. We had similar interests and a few years later, he came and stayed with me for a year in Göteborg. During this stay, we had a few seminars on quantum measurement. The main actors in the discussions where Franco and my Göteborg colleague Nils Svartholm who had worked near Niels Bohr in København. After the time in Göteborg, Franco devoted much of his research to the study of the foundations of quantum mechanics.

Years later, when I visited Franco Selleri in Bari, the relevance of the measurement problem to the wider theory of science became clear to me. I was in Franco’s office when Franco was out for a short time. The phone rang and I picked it: “This is Karl Popper.” When Franco returned, I told him about the call. It was clear that Franco had an ongoing dialogue with Karl Popper on the nature of physical reality.

(8) In the mid-eighties, I developed a mathematical model of measurement as a random walk in a probability simplex with the mean of each step being zero [9]. Near the corners the step size had to be close to zero to guarantee that each step stayed within the simplex. Each random walk led to one of the corners of the simplex (reduction of the wave packet). Because of the zero mean of the steps, the statistics of the walks agreed with the Born rule. Kristian Lindgren helped me with the numerical work in simulations of this model.

This was a purely mathematical model; I had no physical picture of what was going on. When I tried to make a physical picture, I made a mistake and got an unwanted drift; for some time, the model did not feel right. The idea was not new but it took time before I found it in a paper by P. Pearle [10].

I soon learnt that Nicolas Gisin of Université de Genève had made a more elegant model in quantum diffusion that led to the same result. We had contact for a few years and visited each other. For me this contact was very stimulating. I especially appreciated an elegant paper [11] by Gisin and Ian Percival, where measurement interaction was included. Their starting point was a generalized high-degree stochastic Schrödinger equation. As mentioned in Chapter 1, I have recently shown that their equation, translated into density matrix form, can be derived from linear quantum mechanics [12]. I therefore consider their work as an early solution to the measurement problem. I have to confess that I have not evaluated in a similar way, other works in quantum diffusion from this time.

It was also fascinating to follow, at a distance, the experimental work of Gisin and his colleagues: in quantum cryptography and on EPR pairs, entangled over large distances.

(9) During a period around 1990, Kristian Lindgren and I worked with self-organizing systems, such as chemical systems which spontaneously form geometrical structures [13]. This gave us an experience of bifurcating systems where microscopic fluctuations can have a decisive influence on the macroscopic scale. Kristian Lindgren has done quite a lot of modelling in this field of research. He has also done fundamental work on the connections between information theory and statistical mechanics.

(10) A major step in my understanding of the measurement process was, when I saw the interplay between non-linear relations that apply to single measurements and linear relations that apply when determining the means. It became clear to me that my work on random walk in a probability simplex was quite relevant after all.

When I reached this insight, the results could be properly derived instead of being postulated and there was no more any tendency for a drift to appear together with the random walk. Still it took me a long time to get a clear picture of what it all really meant. Several years of intense discussions and collaboration, mainly with Kristian Lindgren, but later also with Erik Sjöqvist and Martin Cederwall, were necessary for this.

(11) Over several decades, from time to time, I have troubled my colleague and friend Kazimierz Rzazewski in Warszawa with discussions on the measurement problem. He has been willing to offer his time; he has listened to me and he has answered my questions. From his field of expertise, quantum optics, he has told me about phenomena that are relevant to my questions and that I should know about. Kazik’s willingness to offer his time and knowledge has been very valuable to me.

(12) When nobody seemed to bother to read what I had written in arXiv [14] or in Journal of Physics [15], I decided to choose another forum to present my work: art. Karin Bodland-Johnson had introduced me to the art life of Värmland. In the summer of 2010, Marc Broos at The Alma Löv Museum in Östra Ämtervik in Värmland, gave me his Finland Pavillion where I could present my own exhibition, both of quantum mechanics, as it is commonly known in physics, and of the measurement process as I had learnt to understand it. The same exhibition has also been shown at Museum Gustavianum, Uppsala, at Karlstad University and KKV-Bohuslän (KKV = Konstnärernas Kollektivverkstad, The Artisis' Collective Workshop).

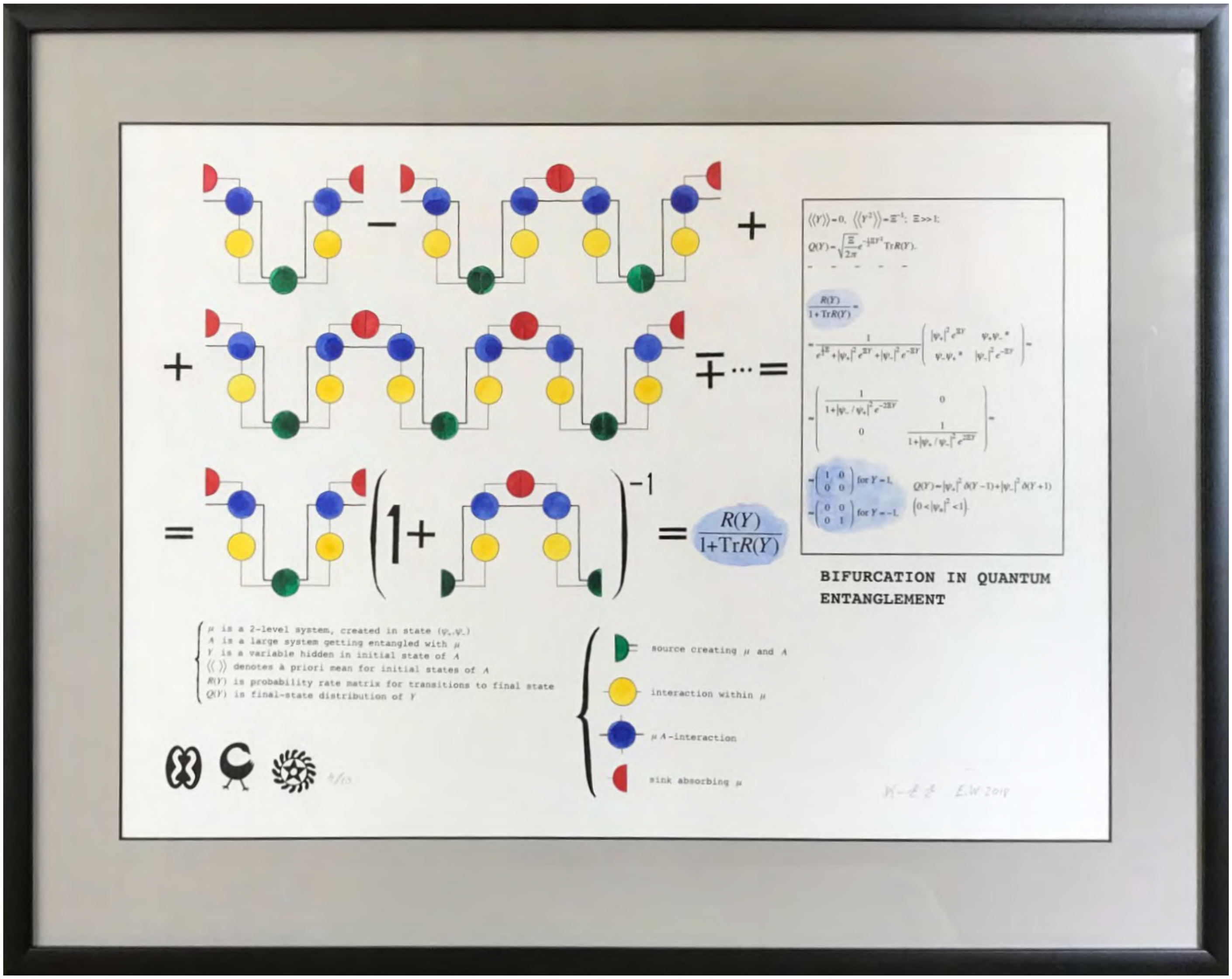
This new way of presenting things had its own dynamics. Marc Broos had the idea that art which had served its purposes could be solemny buried at Alma Löv. When I asked him, he accepted the idea that outdated scientific ideas could also be buried. Before that, in the morning of 8 August 2014, I presented a doctoral thesis in art, as a performance at Alma Löv; in the afternoon it was followed by a funeral for ideas.

The doctoral examination followed the usual procedure, played by persons in the usual functions, thanks to Hans Olof Boström, Karin and Marc Broos, Bengt Gustafsson, Bo Göranzon. Erik Sjöqvist, Roland Spolander and Elin Wikström. Two physics colleagues took the trouble to travel to Östra Ämtervik for the occasion from Vienna and Warsaw, respectively, Herbert Pietschmann and Kazimierz Rzazewski.

Doctoral examination as a performance.
In the morning of 8 August 2014, at the Museum of Alma Löv, Östra Ämtervik, we performed a doctoral examination. My thesis, Quantum Art and Interactual Reality, was examined with respect to its physical content and its artistic value. For the occasion, I was dressed in my Ghanaian fugu. Sitting next to me was the physics opponent, Erik Sjöqvist. Bo Göranzon was the chair person, and Elin Wikström was the artistic opponent. The idea came from Roland Spolander and Marc Broos opened the museum for us. (Photo: Denis Romanovski.)

After the doctoral examination, in the funeral performance, three ideas were solemnly buried: Schrödinger's cat idea, Bohr's idea of a capricious nature [16] and Everett's and DeWitt's Many-Worlds idea [17]. To me, the situation where both scientific and artistic criteria had to be met was very challenging. After these events, Erik Sjöqvist, who had been the scientific opponent on my art thesis, joined Kristian and me for collaboration.

Funeral of outdated physical ideas as a performance.
In the afternoon of 8 August, 2014, a second performance took place, a funeral for outdated ideas. It was inspired by a relatively new art form in Ghana where coffins are made in the spirit of the life of the dead person. The idea of quantum mechanics as an intrinsically probabilistic theory was buried in a dice in the colours of Niels Bohr's nation; Schrödinger's cat idea was buried in a cat-shaped coffin; the Many-Worlds interpretation was buried in a coffin symbolizing parallel worlds. My arts opponent, Elin Wikström and I performed the funeral rituals, assisted by Nana Akoto Bruce, master drummer from the Music Department of The University of Cape Coast. Karin Bodland-Johnson followed the whole event closely. (Photo: Denis Romanovski.)



Poster session: Physical theory of measurement as graphic art. Erik Weststrand, a graphic artist in Bohuslän, invited me to make art with him in a professional way. At a stage when I expressed our theory in a series of Feynman diagrams, Erik and I formed it into this picture which we called ‘Poster Session’. (Photo: Jan Holmstrand.)

(13) When my collaboration with Kristian Lindgren and Erik Sjöqvist had been established, it became clear that I was the only one in the team who had direct experience of work with field-theoretical computations. Since my ideas had to be checked, we felt the need for having one more person in the group with work experience in field theory and we invited Martin Cederwall to join us. This is how our group of four persons was formed. When we had a common paper ready, we presented it in arXiv [18]. To have it published in a journal turned out to be difficult however. Among editors, there seems to be a belief that quantum measurement can not be understood within quantum mechanics. Kristian Lindgren and I had a reedited version published in Entropy [7]. In some sense, this is a final version of our theory.

A way of describing this final version, is that it is done within relativistic quantum mechanics and that the step to relativistic theory is crucial. In a separate arXiv paper [19], I have given detailed arguments for the importance of relativistic theory.

The collaboration with Kristian Lindgren has been essential for the completion of the work reported in this book.

(14) As part of my thesis in art, I had written a theatre play about the difficulties to communicate quantum-mechanical ideas. An article by Melanie Bayley [20] had given me the idea of using Lewis Carroll's Wonderland as a setting for this. I was strengthened in my theatre idea by encouraging comments from my art opponent at Alma Löv, Elin Wikström. With improved understanding, I found it mecessary to have living and historical persons together to discuss measurement in Wonderland. To have a person who could be an authority for both Niels Bohr and Albert Einstein, my choice was Marie Curie.

Whether this is a good way of presenting ideas, I am not sure, but it was amusing to write the play. On 6 October 2019, it was read (in the version of that time) by colleagues at Physical Resource Theory, Chalmers, under the guidance of an experienced theatre director, Magnus Wetterholm. Tomas Kåberger is helping me with various aspects of the play. Magnus and Tomas are planning to arrange a second reading within a few months.

(15) I had read Andrew Whitaker's book Einstein, Bohr and the Quantum Dilemma [21]. When in January 2018, I was in Dublin for a conference, I took the opportunity to sneak away from the conference and visit Andrew Whitaker in Belfast for one day. This led to a period of dialogues between him and Kristian and myself, still continuing. These dialogues have helped me to a more profound understanding of several issues and also to a new view on how ideas can be presented. Andrew Whitaker has also been very kind and read this manuscript.

(16) To write a simple account of measurement on a two-level system, I have gone back to the idea of random walk on the probability interval [9, 10]. An interaction between a two-level system and a non-biased first part A of a measurement apparatus, considered to be composed of a series of independent parts, free from bias, would lead to a random walk (zero mean value for each step) on the probabiliy interval. The random walk ends at one of the endpoints with a definite result; the probabilities for the endpoints are given by the starting point and agree with Born's rule. In this way, the whole picture of the measurement process, or as I have preferred to call it, the determination process, becomes very simple.

As written in Chapter 1, I have come to view work in quantum diffusion by persons such as Nicolas Gisin, Ian Percival[11], Philip Pearle and Lajos Diósi [22] to give an acceptable explanation of the measurement process as an interaction between the measured system and part of the measurement apparatus. In his book [3], John Bell did not consider this line of thinking (the way it looked at the time) as a finished theory. In one of the main papers [11], Gisin and Percival described their generalized Schrödinger equation as quantum mechanics for an open system, but Andrew Whitaker [21] interpreted their theory as phenomenological. I have recently shown [12] that the basic equation of Gisin and Percival [11] (transformed into density matrix form) can be derived from linear quantum mechanics.

(17) To understand more of science history and of the cultural aspects of scientific theories, I have started a fruitful dialogue with Sven-Eric Liedman. He has also kindly read my presentation in Chapter 1 and found it comprehensible.

I have collected my writings in this small electronic book, which is now freely available at Chalmers. To finish the work, I have needed much support, not only from Kristian Lindgren but also from Tomas Kåberger and Christian Löwhagen. For this, I am very grateful.

In the rural area where I live, essential technical support has been given to me by Lennart Ericson, Per Olof Hahne and Jan Holmstrand.

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From my family, my wife Kristina and our children, Gunnar, Magdalena and Elin, I have received much love and support. Because of the general nature of the work, my family members have also commented and criticized and given me valuable ideas.

References

1. P.A.M. Dirac, The Principles of Quantum Mechanics (Oxford 1930).

2. N.F. Mott, Proc. Roy. Soc. A126, 79 (1929).
   W. Heisenberg, Physical Principles of Quantum Theory (Chicago 1930). New work along this line can be found in

   J. F. Schonfeld, Foundations of Physics 51, 47 (2021).

3. J.S. Bell, Speakable and Unspeakable in Quantum Mechanics (2nd ed., Cambridge, U.K. 2004).

4. J.M. Jauch and F. Rohrlich, The Theory of Photons and Electrons (Cambridge, Mass., 1955).

5. E.C.G. Stueckelberg and A. Petermann, Helv. Phys. Acta 26, 499 (1953).

6. M. Gell-Mann and F.E. Low, Phys. Rev. 95, 1300 (1954).

7. K.E. Eriksson and K. Lindgren, Entropy 21, 834 (2019).

8. H. Everett, Rev. Mod. Phys. 29, 454 (1957).

9. K.E. Eriksson, Phys. Scr. 32, 277 (1985).

10. P. Pearle, Found. Phys. 12, 249 (1982).

11. N. Gisin and I. Percival, J. Phys. A 25, 5677 (1992).

12. K.E. Eriksson, arXiv.2203.00586 (2022).

13. K.E. Eriksson and K. Lindgren, Phys. Scr. 35, 388 (1987).

14. K.E. Eriksson, arXiv:quant-ph/0206099 (2002), arXiv.0705.1649 (2007).

15. K.E. Eriksson, J. Phys. B 42, 085001 (2009).

16. N. Bohr, Atomteori og naturbeskrivelse (København 1957).

17. B.S. DeWitt, Physics Today 23, 30 (1970).

18. K.E. Eriksson, M. Cederwall, K. Lindgren and E.Sjöqvist, arXiv:1708.01552v2.

19. K.E. Eriksson, arXiv:2106.07538 (2021).

20. M. Bayley, New Scientist (16 December, 2009).

21. A. Whitaker, Einstein, Bohr and the Quantum Dilemma (2nd ed., Cambridge, U.K. 2006).

22. L. Diósi, J. Phys. A 21, 2885 (1988).