Quantum Mechanics –
the dream stuff is made of (Part 3)

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As we have seen in the second part of this essay, no interpretation of quantum mechanics has been found in the last decades that provides a convincing explanation for the astonishing phenomena presented in the first part. Do we really have to back down to the subjectivist approaches that give no explanations for the central questions and even declare the search for an underlying reality as meaningless? In face of the miserable failure of the reality-based alternatives, this seems to be the only possible conclusion.

There is however one approach left that may change this situation. It provides a realistic description of our world and has the potential to give physical explanations for many – perhaps even all – oddities of quantum mechanics. Although this interpretation was already published in the 80s, it leads a shadowy existence since then and is not even mentioned in many books on the interpretation debate. The reason is not hard to find. The basic element sound so implausible that many physicists regard it simply as not serious enough: the interpretation explains quantum correlations by *waves running back in time.*

In this third part I will try to convince you that this approach with the name "transactional interpretation" is not as crazy as it first appears. The central part will be a clarifying discussion of time itself, which will reveal a surprising result. Are you ready for the final part of the journey into the enigmatic world of quantum mechanics?

Obvious Questions

The transactional interpretation was published in 1986 by the American physics professor John G. Cramer[1]. His core thesis is the assumption that the quantum-mechanical wave function is not subjective, but rather describes a real physical wave that has not only causal effects on future events, but also on events in the past. On this base, many quantum mechanical phenomena can be explained, even (and in particular!) the otherwise so elusive entanglement effects.

Some obvious questions arise for such an approach:

- Do not our everyday experience and also all of our physical theories show that cause-effect chains take only place into the future direction?
- Are effects on the past not already logically impossible because the classification into past and future events is *defined* by the fact that the future can be changed by current events which were in turn influenced from events in the past?
- Is my grandmother in danger?

The last point refers of course to the often quoted time travel paradox: if changing the past would be possible, you could go back in time to kill your own grandmother before she gave birth to your mother[2]. You would therefore never have been born and were not able to perform the time travel, an obvious logical contradiction.

When you look at these questions, it is not surprising that the assumption of causal effects into the past – even if they provide entertaining twists in many books and science fiction films – must appear as a completely unserious trick that should have no place in science.

But is the case really so clear? Not at all. It will not be possible in this essay to give final answers or resolve the age-old riddle of time, but I will try to convince you that causal effects into the past direction are not inherently impossible. Maybe I will even succeed to provide some evidences that such effects indeed exist. Only then I want to come back to the transactional interpretation of quantum mechanics.

To achieve this goal, I would like to follow in the next chapter the thoughts of the Australian philosopher Huw Price. His book "Time's Arrow and Archimedes' Point" from 1996 shows – in my opinion in an excellently clear way – the fragility of the seemingly unambiguous direction of the arrow of time from the past to the future. On this basis, each to the above stated questions will find an answer.

The second chapter presents the interpretation of John Cramer. It is particularly well explained in the book "Schrödinger's Kittens and the Search for Reality" by John Gribbin and in two recent books by Ruth Kastner.

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[1] "The Transactional Interpretation of Quantum Mechanics", Cramer, J., Reviews of Modern Physics 58 (1986). This paper and other publications by the author can be found at www.npl.washington.edu/npl/int_rep/tiqm/TI_toc.html.

[2] Why this paradox refers to the grandmother of the time traveler and not to his mother will probably remain an eternal mystery of the history of science.

The View from Nowhen

Huw Price formulated in his book the following starting point for which he has some plausibility arguments, but does not try to prove it: space-time exists as a four-dimensional block universe in which past, present and future are equally real. The privileged status of the present and the apparent flow of time are artifacts of our perspective how we perceive the world as human beings. There is a quote from the American writer Thornton Wilder that perfectly fits to this picture:

> *It is only in appearance that time is a river. It is rather a vast landscape and it is the eye of the beholder that moves.*

This is of course highly unintuitive at first sight. How can the past be real when it is forever gone for us and how it can be the future that is not determined yet? Philosophically, this approach is nonetheless very attractive. It avoids for example the difficulties encountered in the definition of an objective "flow" of time and is compatible with the four-dimensional space-time description of the theory of relativity. It is actually very encouraged by this theory, because the already suspicious notion that only the world of the just happening nanoseconds between past and future can claim a reality status becomes practically absurd in face of the relativity of simultaneity. How could anyone limit the reality to her or his instantaneous moment of the present when it depends on the point of view of another observer (more precisely, of its state of motion) which events appear at the same time for him? You are welcome to think about an answer to this question before you continue[3].

For physical problems regarding the asymmetry of time, Huw Price sees therefore the need for a point of view "outside" of time, an Archimedean point "from nowhen"[4]. This perspective reveals some common misconceptions in current physics:

- The temporal asymmetry of our perspective is projected into the objective reality and thus mistakenly seen as universal.
- A time asymmetry is derived by the application of a physical theory in future-, but not into past-direction. The time asymmetry to be explained is in this case already presupposed.

The elimination of such errors leads to interesting reassessments of time asymmetries in various physical areas. The following sections show the results of this analysis.

[3] Very convincing arguments for this view can also be found in [Brandon 2013] and (completely independently!) from the fact that all current approaches for a unified quantum gravitational theory (including strings and quantum loop theories) lead to the complete elimination of the time parameter.

[4] Archimedes is said to have stated "Give me one fixed point and a long enough lever, and I'll unhinge the universe." An Archimedean point is also attributed to an indubitable truth from which one tries to explain the world.

Time Asymmetry in Physics

An important observation is the fact that *not one* of the fundamental physical theories such as Newtonian mechanics, special and general relativity or quantum mechanics contains an explicit temporal asymmetry! The temporal evolution equations of these theories can be applied into future- as well as into past-direction[5]. Thermodynamics is however an exception to this rule, so the search for the arrow of time shall start there.

A well-known phenomenon is the increase in entropy into the future direction. Just think about coffee mixed with milk, the spread of a cloud of perfume or the state of order of a child's room, whose decay to the chaotic state of equally distributed toys can only be slowed down by regular clean-up activities (believe me, I know what I'm talking about). But how is this commonplace principle justified physically? Thermodynamics as a phenomenological theory just describes these principles, but does not offer an underlying explanation.

An important insight is first of all that the high entropy state in the future does not need an explanation. It is by definition the most probable state. Would the location of the milk and coffee particles for example be determined by a pure random distribution, a uniformly-mixed condition would be much more likely than the concentration of the milk particles in one place. This "milk blob in coffee" macrostate would have much less possible microstates (exact constellation of all involved molecules) than the mixed coffee and the number of microstates compatible to a macrostate is exactly the mathematical core of entropy. No wonder then, that after some time always the "natural", i.e. more probable state is reached.

The fact that does need an explanation is however the low entropy in the past. The ratio of macro- to microstates is a time-independent system property, a previous state should therefore also have a high ratio as the most likely case, which refers to a uniformly mixed system. We know of course from our daily experience that this is not the case, but why is that? How can the kinetic theory of gases as microscopic basis of thermodynamics constitute these processes?

The most famous historical explanation is the so-called H-theorem of Ludwig Boltzmann. It describes an irreversible increase of entropy on the basis of time-reversible microphysics. Since this theorem can be applied into the future *and* past direction, if a time asymmetry is not already presupposed, it can however not explain the time asymmetry[6]. This applies also to other dynamic theories such as non-linear chaos theories. The time asymmetry of thermodynamics, i.e. the macroscopic arrow of time, can therefore not be derived from the properties of the laws of microphysics. Basically, this is not surprising, since it would be like a magic trick to derive a preferred time direction from temporally reversible laws.

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[5] There is actually one physical process that is not time-symmetrical, the so-called CP-violation in the weak interactions (weak nuclear force). Since this type of interaction has a very short range and is limited to processes within the atomic nucleus, it is however not seen as relevant for the explanation of the macroscopic arrow of time.

[6] Boltzmann's argument that we are in a cosmological area with an incidental low entropy past and thus increasing entropy, because we can only exist under such conditions, is also not valid: it would have been by definition much "cheaper", i.e. more probable, to directly create our current state by a product of chance. In addition, we observe the increase of entropy also in spatial and temporal regions that are irrelevant for the conditions of our existence, for example in other galaxies.

But where does the low entropy in the past come from? Each concrete example can always be explained by another process outside the system under consideration. The milk blob in the coffee could for example be arranged by a human whose energy comes from food which is itself based on photosynthesis and thus the energy of the sun. But where does the low entropy state come from that lit the fire of the sun over 4 billion years ago? If you continue this line of thought, you end up at the conclusion that it must have been the initial/early state of our universe that has started all these processes by its low entropy content. The cosmological models and astronomical observations (in particular the isotropy of the cosmological background radiation) show indeed that the early condition of our universe was very homogeneous, which corresponds to a very ordered and hence unlikely condition in a predominantly gravitational system. The question how it could come to this state represents an unsolved problem in cosmology until today. Maybe the current theories of an inflationary universe can give an answer to it, but that's a totally separate issue beyond the scope of this essay.

Let us summarize the thoughts of this section. We started with an everyday phenomenon and were left with a cosmological puzzle. This may not look particularly satisfactory. It lead however to a very important insight: the time asymmetry, thermodynamically described by the increase of entropy, is a purely macroscopic phenomenon that is not reflected in the basic physical principles. The kinetic theory of gases is therefore no exception – all physical evolution equations from classical mechanics to relativity and quantum mechanics are completely time-symmetrical. This is the answer to the first question of the introductory chapter.

Based on this intermediate result, it can now be examined whether causal effects into the past direction are generally possible. But what does the concept of causality actually mean?

The Possibility of Reverse Causality

Causality refers to the relationship between causes and related effects. The temporal asymmetry of causation consists in the principle that effects always occur after their causes, but never before. As obvious as this principle seems, it is difficult to find an exact physical meaning for it. The most popular view is the assumption of a time-asymmetric physical process to which causality can then refer by definition. As the previous section demonstrated, it is however anything but easy to find such a process, since all the relevant laws of microphysics are time-symmetric. How can this dilemma be resolved?

There are a whole range of philosophical approaches to the concept of causality, but none of them is undisputed. The conventionalist position, for example, reduces causality to pure conventions and therefore declares "causes" and "effects" as not existent. This is of course a very extreme and logically weak perspective that can’t explain the *apparent* objectivity of causality.

Huw Price argues in his book for the "perspective conventionalism" approach: causality is based on convention, but this is not arbitrary – it is a projection of an asymmetry *of our human perspective.* This gives causality, in particular as perceived by us humans, a degree of objectivity without contradictions with the laws of microphysics. The basis for this view is our temporal asymmetry as "agents" in the world, since we can remember the past and see the future as open. This macroscopic arrow of time would then be the reason that all causal processes *appear* temporally asymmetric to us.

Against this background, a reverse causality (also called "retrocausality") could consistently be defined. It wouldn't simply be a reverse forward causality, but rather correspond to an objective structure of the world that allows causal relations into future- as well as into past-direction in our time perspective.

This approach is the answer of Huw Price to the second question of the introductory chapter: effects into the past direction are not logically inconsistent and the concept is also no tautological term without objective meaning. They are thus possible in principle.

But what about the problem of the time traveler?

Avoiding the Time Travel Paradox

The previously mentioned time travel paradox illustrates that there are causal relations into the past direction that lead to logical inconsistencies and are therefore not possible. This does however not proof the impossibility *of all* such causal relationships. The problems arise only when a past event is influenced that is already known to us, but not for causal relationships with effects in the past that are inaccessible to us. This may just appear as a trick, but it is an answer to the question whether the time travel paradox is a general proof that causal relations into the past direction are generally impossible. A logical contradiction would arise only from the empirically unjustifiable assumption that the whole past is available, i.e. knowable, for us.

It follows however also from this that reverse causality is not directly empirically falsifiable or verifiable. Even if it exists, only the part of the past could be influenced by our present actions that is unknown to us. The evidence for the existence of such effects can therefore only be indirect in form of greater conceptual simplicity and elegance. There is in fact an established physical theory that is based on exactly these concepts.

Surprises in the Theory of Light and Matter

Developed in the 40s by Richard Feynman, Julian Schwinger and Shinichiro Tomonaga, quantum electrodynamics (short QED) provides a theoretical framework for the description of photons and charged point particles such as electrons. This theory extends electrodynamics, which is included in it as a limiting case, to the laws of quantum mechanics. The QED was awarded with the physics Nobel Prize in 1965 and can claim itself to be one the most accurate experimentally verified theories of physics[7]. Its scope is almost universal and – thanks to a complete description of the atomic shell – includes also the full range of chemistry, which in turn forms the basis of biology. This makes it one of the most important and successful theories of physics.

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[7] The QED predicts for example for a particular property of an electron, the gyromagnetic factor, a value of 2.0023193048 ± 8. The measured value (which can curiously determined more precisely) is 2.002319304365 ± 5

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Positrons are the so-called antiparticles of electrons: they have the same physical properties, but exactly the reverse charge, i.e. they are positively charged. This particle can be produced artificially, but can also be detected in the cosmic radiation that continuously strikes the earth. When such a particle hits its antiparticle, the two destroy each other and generate a high-energy photon. According to the QED, each photon can also decay into a positron-electron pair which parts fly away in opposite directions until they hit their next antiparticle, starting the process again. Richard Feynman, probably the most important physicists of the second half of the century, realized that the description of this process is much easier when the positron is seen as an electron *that moves backward in time.* In this perspective, the electron is temporally mirrored by a photon, so that it moves – as a "positron" – backwards in time until it hits the next photon, which sends it back to the future. This approach needs only two instead of three elementary particles and leads to the exact same experimentally verifiable predictions.

This is a remarkable result. The assumption of effects running back in time is not only consistent with the experimental results, but also simplifies the physical description of electron-photon interactions.

But that's not all. Another basic concept of this theory is the idea that a particle or photon is not simply moving in a straight line from position A to position B, but that *all* paths are traversed that begin in A and end in B, even warped and twisted ones. This does not mean that these paths *could* be traversed, but that they actually *will* be traversed. If we think of the double-slit experiments, in which the electron seemingly passes through both slits for producing an interference pattern behind it, this idea does not sound as crazy as at first glance. It is now possible to calculate a probability for each of these paths whose summation leads to the conclusion that almost all these paths extinguish, i.e. compensate each other. As observable result remains – depending on the considered system and its external influences – a path near the straight line between A and B, in accordance with the experimental facts and (in the case of light) with our everyday experience. This is the commonly known part of QED. Feynman posed however the question if effects running back in time could also be a possible mode of interaction. He thought specifically about incoming, so-called “advanced” waves, that converge simultaneously from all sides ending up as if by magic in the center. They represent the time-reversed version of the outgoing, so-called “retarded” waves, that we know from our everyday experience, for example in the form of radio or water waves. He found out that the effects of advanced and retarded waves compensate each other so that the overall effect corresponds exactly to the observable phenomenons. More precisely, Feynman's analysis revealed that they compensate each other *almost* completely. The difference results in an increased resistance opposing the electron acceleration that is actually measurable. There is no convincing alternative explanation for this increased resistance to the present day.

The World from the Perspective of a Photon

One last thought on this subject. According to the theory of relativity, the proper time of an observer passes slower when it moves faster. At a speed just below the speed of light, only fractions of a second pass for such an observer, but years for the world around it. How could therefore the world look like from the perspective of a photon that moves at the speed of light through the universe? It would experience its entire history from the moment of generation at point A until its destruction at point B as a single moment without past or future. There is therefore not the slightest difference for the photon whether it runs from point A to B or from B to A, even if A should be the light of a distant galaxy and B the eye of a human observer. Maybe this picture tells us something about the relevance of the concepts past and future!?

An Interim Conclusion

The previous reflections about the concept of reverse causality can be summarized as follows:

- It appears counter-intuitive only due to our time-asymmetric perspective.
- It can be meaningfully defined and is logically consistent.
- It is consistent with our empirical experience.
- It is compatible with the time symmetry of the fundamental physical theories.
- It is an important component of the theory of quantum electrodynamics.

This concept does however not lead to phenomena that would not be explainable by alternative theories. It could only be justified by a greater conceptual simplicity and elegance in the physical description of our world. This prospect, which already showed up in the theory of quantum electrodynamics, can actually be fulfilled in the interpretation of quantum mechanics. We can thus add a further property:

- It provides a realistic interpretation of quantum mechanics and natural explanations for many quantum mechanical phenomena.

How this little miracle happens (we remember the many unsuccessful attempts in the second part of this essay) is shown in the following chapter.

The Transactional Interpretation of Quantum Mechanics

We have finally arrived at the presentation of the last missing interpretation of quantum mechanics. It was invented 25 years ago, but leads an undeserved shadow existence since then. Curtain up for an exciting new perspective in this debate!

Basic Idea and Formalism

The central idea of John Cramer's interpretation of quantum mechanics can be summarized in a single sentence: The quantum-mechanical wave function Ψ describes a real physical wave that obeys the evolution equations of special-relativistic quantum mechanics and propagates not only into the future- but also into the past-direction. This is the essence of the transactional interpretation, the rest are details.

Apart from the already treated aspect whether such a reverse causality may be possible at all, the question of the exact physical basis of such an approach must be answered. In other words, is there an underlying mathematical formalism that is consistent with the experimental results? Almost all new ideas to reinterpret the basic concepts of physics fail on this point. Does the transactional interpretation pass this test?

In short, it succeeds with flying colors. This interpretation is based on the same formalism of the theory of quantum mechanics that describes and precisely predicts the results of the countless experiments carried out in the recent decades. Nowadays this incredible empirical success of quantum mechanics is also reflected in our everyday life in the form of computer chips, lasers and many other technological devices, and even completely new applications such as quantum computers and quantum cryptography move more and more into public awareness.

In fact, Cramer's interpretation fits even *better* to the mathematics of quantum mechanics than the conventional approach. If you look closely at the formalism, it can't be avoided to use two exactly opposite varieties of the wave function Ψ in order to create a connection to the experimental results. As mentioned in the first part of this essay, the wave function Ψ obeys the time evolution of the Schrödinger equation, but is in itself not directly observable. This can already be seen by the fact that it is represented by a complex number. Only after the multiplication with the so-called "conjugated" wave function $\overline{\Psi}$, an experimentally verifiable number is obtained, namely the probability that a system is in a particular state. The conjugated wave function $\overline{\Psi}$ fulfills the quantum mechanical equations just the same as Ψ, thus representing a perfectly valid solution. It is therefore worthwhile to examine this wave function $\overline{\Psi}$ more closely.

Mathematically, we obtain the conjugate of a complex number, which is composed of a real and an imaginary part, by reversal of the sign of the imaginary part. In the two-dimensional complex plane, this corresponds to a reflection at the real axis. What could be the physical meaning of this conjugation in the framework of quantum mechanics? As early as 1926, the inventor of the quantum mechanical probability mapping Max Born pointed out that this variable $\overline{\Psi}$ could be interpreted as time-reversed version of the wave function Ψ. Because this idea seemed too crazy, only the wave function Ψ was taken seriously as a physical quantity in the following decades. This point of view has not changed until today, although any empirical application of quantum mechanics is based on this multiplication of the wave function with its conjugate wave function.

Summarizing, the transactional interpretation is not only compatible with the mathematical formalism of quantum mechanics, it even reflects an absolutely central element of this theory. But is there also a clear picture of the basic principles of this interpretation? The following section is an attempt by John Cramer for this task. I would however like to issue a warning. As with all illustrations of physical theories, one should be aware that the presented images can't provide a direct reflection of the real processes. It is only possible to give a basic idea about the principles of an abstract theory that is formulated in the language of mathematics.

The Basic Physical Principle

The core of the transactional interpretation can be illustrated by the interaction of two charged particles such as electrons. When an electron starts to vibrate, it can in the conventional viewpoint emit a photon that travels at the speed of light until it is eventually absorbed by another electron. In contrast, the electron emits two types of "offer wave" in Cramer's interpretation, namely retarded waves into the future direction with positive energy and advanced waves into past direction with negative energy in a perfectly symmetrical manner. Both waves propagate with the speed of light. The retarded waves will eventually reach another electron, but instead of just being absorbed, they stimulate this electron to emit retarded "confirmation waves" which cancel out the retarded offer wave of the first electron, leaving no waves left in the future direction of the two electrons. In addition, an advanced confirmation signal travels back on the connecting line between the two electrons into the past direction until it reaches the first electron where it triggers the same effect in reverse: the first electron is stimulated to emit advanced waves that cancel out the originally sent advanced waves of this electron. In sum, there remains therefore a retarded signal from the first to the second electron and an advanced signal into the opposite direction, both on the direct line between the two electrons. Since the advanced wave carries a negative charge, these two waves do not extinguish, but reinforce each other. Depending on the perspective, both waves carry positive energy into the future direction or they both carry negative energy into the past direction, respectively. This "quantum mechanical handshake," as John Cramer calls it, forms the basis of all quantum mechanical interactions and replaces the sudden collapse of the wave function.

This concept is a perfect example for the above-mentioned "view from nowhen" idea by Huw Price. Due to the perfect symmetry of the directions of time, these concepts become basically redundant, the result is simply a specific relationship or connection between two electrons that does not follow the usual time-ordered cause-effect principle. This also fits to the fact that time does not pass at all in the view of the waves according to the laws of relativity because they travel at the speed of light. For them, the starting and destination point refer to the same moment of time.

Does that sound hard to believe? For myself, and probably for most readers, it certainly is. We are ultimately temporal thinking and acting beings, past and future appear fundamentally different to us. But it would be premature to discard the atemporal principle of the quantum mechanical world just because it conflict with our intuition. Why should our intuition, that we have acquired in the course of human evolution, be a reliable guide not only in our daily life but also in the world of electrons and atoms? There are enough counterexamples for this fallacy even outside of quantum mechanics.

A New Look at the Mysteries of the Quantum World

Only one chapter remains in this small quantum mechanics tour. I want to show how the strange phenomena presented in the first part appear in the light of the transactional interpretation.

Actually, this chapter is not really needed. Based on the basic principle described above, these phenomena turn out as specific varieties of this principle, they could have even been derived without knowledge of the experimental results. It would therefore be a very worthwhile exercise, before reading this chapter, to go back to the first part of this essay and to think for yourself how the phenomena could be interpreted from this perspective. You may be surprised how easy this is. Hopefully, you also remember from the second part which mental acrobatics and downright ridiculous additional assumptions all other interpretations had to make for being compatible with the observed results. This is in my opinion the most convincing evidence for the interpretation of John Cramer.

Let's start with an experimental setup in which the peculiarities of the quantum mechanical world become particularly clear. In the first part I presented the actually carried out "delayed choice" experiment. An electron is sent through a wall with two narrow gaps, behind the wall is a screen that can quickly be taken away and behind this screen are directional detectors that can “catch” the electron in flying through the upper or lower slit. On the screen, the typical interference pattern shows up; without the screen, the interference effects vanish. The special feature of this experimental setup is that the screen is taken away only *after* the fly-through of the electron through the wall with the two slits, i.e. the electron doesn’t "know" at the wall if it should go through both slits as a wave or through only one of the slits as a particle. It can therefore at this moment not decide between these the two mutually exclusive properties, the actual result manifests itself only in the act of the measurement.

Can you see the trick? The fundamental mystery of this experimental arrangement disappears instantly if one does not cling to the temporal sequence of cause and effect. As an implicit assumption, it is seen as impossible that the interaction with the measuring device influences the electron when passing the wall, because this took place at an earlier time. From the perspective of transactional interpretation there is however no chronological order. The act of measurement influences the entire path of the electron from its starting point up to its detection, just like it is affected by the electron source and the slits in the wall. The advanced waves from the direction detectors "force" the electron to fly through the upper or lower slit. The wave-particle duality is still maintained in this picture, this remains a novel and counterintuitive property of quantum mechanics. The transactional interpretation is however capable to solve the mystery how measurements can cause a sudden collapse of the wave function and thus a manifestation of the real system properties. There is only a consistent non-temporal description of the *overall result* of the experiment, predicted by the laws of quantum mechanics with a fantastic precision.

This view sheds also new light on the phenomenon of entanglement. In this ghostly connection between two widely separated parts of a quantum system, the measurement of a particle leads to an instantaneous change in the second. How is that possible? None of the interpretations in the second part of this essay is able to explain this mystery. At best, it has been advocated that there simply *is* no true physical explanation of this effect, which can nowadays be reproduced over distances of more than 100km.

From the perspective of transactional interpretation, the fact that the measurement can have an influence on the state of the overall system is however completely natural. The measurement on the first particle can be seen as an interaction that leads to an emission of retarded and advanced waves. The advanced waves run back to the origin of the system and act there on the second particle by setting it to the complementary state to the first particle. No wonder then, that the measurement of the second particle shows exactly this property. Even without an exact knowledge of such a mechanism it becomes obvious that the problem to find a proper interpretation is caused by the desperate attempt to bring the outcome of this experiment into a fixed temporal order. There is therefore no other example in physics in which the merits of the atemporal perspective are as obvious as for the quantum mechanical phenomenon of entanglement.

As last remark about the transactional interpretation, it should be mentioned that this theory was generalized rather recently by Ruth Kastner into the relativistic realm under the name "Possibilist Transactional Interpretation". The two books of this author from 2012 and 2015 provide not only an excellent description of the transactional interpretation, in the latter book in a completely non-mathematical way, but show also a wide range of philosophical implications of this theory that go far beyond the realm of quantum mechnics. I am sure that these books will receive a great deal of attention in the next years.

Closing Remarks

That's it. I have nothing more to contribute to this fascinating topic of quantum mechanics. The result is quite different from what I had thought at the beginning of this essay. Although I knew the mathematical formalism of quantum mechanics and also the main historical interpretations and some of their weaknesses, I was really surprised how miserably they fail – despite of the wealth of different variations – to provide convincing explanations for the quantum mechanical puzzles. Are the subjectivist perspectives finally victorious that regard the search for a real world behind the observed phenomena simply as pointless? This conclusion seemed unavoidable for me, so I had to give up my deep conviction that things are the way they are, even if we are not looking. This point of view had survived many years of critical confrontation with highly profiled realism critics such as Paul Feyerabend, Thomas Kuhn or Bas van Fraassen and this ancient philosophical discourse should now be decided by quantum mechanics?

As I tried to get used to this idea, I came across the book by John Gribbin. His clear explanation of the transactional interpretation made immediately sense to me and reminded me also of the book by Huw Price that I had read with great fascination some years before. The presentation of these two perspectives was the intention of this essay.

This approach does of course not claim to be the last word on the interpretation of quantum mechanics and provides also no proof for a realistic worldview. But it appears to me as a completely consistent view with the only drawback that it turns our usual conception of past and future completely upside down. Perhaps the time has come for a few headstands? I agree with everyone who finds this venture childish. To again quote Albert Einstein:

> *The pursuit of truth and beauty is a sphere of activity*
> *in which we are permitted to remain children all our lives.*