Theoretical and empirical explorations of "Generalized Quantum Theory"

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1. Overview

This dissertation primarily revolves around a theoretical framework called Generalized Quantum Theory (GQT) and the documentation of experiments that I carried out in order to test predictions that were based on it.

GQT postulates that Quantum Theory can be generalized in the sense that some principles according to which quantum physical systems in the strict sense have been found to behave (e.g. subatomic, atomic and molecular quantum systems) also apply in a more generalized form to systems in general.

While there are probably more, the most relevant principles to be discussed in this study are complementarity, entanglement, probability and observables, with a particular focus on the first two. Complementarity, in short, denotes the relationship between descriptions that are mutually exclusive yet collectively required for an adequate description of reality. Entanglement (also called non-local or non-causal correlation) can be thought of as above-chance correlations between causally non-interacting probabilistic events. Probability is a concept used to describe situations where outcomes of individual events are in principle unpredictable, whereas average outcomes of many events are. One example of such an event is the interaction between two systems one of which can be defined the subject and the other one the object of an observation. The outcome of this interaction is dependent on both systems and is called an observable.

These principles are well known in quantum physics, where they have been observed in experimental systems consisting of subatomic, atomic and molecular quanta.

GQT proposes that these principles are relevant also in systems of larger dimensions, including for example some macroscopic systems of our everyday experience. This proposal is, on the one hand, based on the fact that also large systems are ultimately composed of individual quanta (reductionistic reasoning) and, on the other hand, on an interpretation of these principles as general, systems inherent principles (system theoretical reasoning): This latter approach means that, instead of viewing them as describing properties belonging exclusively to subatomic, atomic or molecular quanta, GQT postulates that they are principles of general applicability which describe phenomena arising whenever parts of the universe are organized into systems in certain ways. Conceivably, these general principles were first discovered in quantum physics because it is here that an absolutely rigorous and mathematically precise description of systems and their behavior was first possible, due to the exceptional clarity and simplicity of systems consisting only of very few well defined physical entities. According to GQT, however, these principles are not limited in their applicability only to systems of this kind.

In this dissertation I will outline and explore this proposal through theoretical reasoning, empirical observation and experimental investigation. While I shall not hesitate to point out those shortcomings and limitations of GQT that I have come to notice, I think it is important to make transparent that in the work leading up to this dissertation, my intrinsic motivation and focus were directed more toward providing arguments and evidence in favour of GQT.

I will start by explaining in the next chapter in more detail what is actually meant by the notions of complementarity, observables, entanglement, probability and self-referentiality. To do so, I will explore their use in quantum physics by giving examples of the kind of experimental observations that have led quantum physicists to formulate them. Some of these words and/or related concepts have existed already long before the advent of quantum theory and were then adopted by quantum physicists in order to describe their observations. This is interesting to keep in mind, because it hints at the potentially more general applicability of these principles. We will, however, initially focus only on the meaning of these notions in quantum theory, because nowhere else have these concepts been formulated with a combination of such theoretical rigor, mathematical precision and experimental evidence.

In the third chapter I will then describe how one can arrive at (or return to, if you like) a general interpretation of these principles, which builds on and incorporates the advances made by quantum theory and at the same time expands their applicability to systems in general. As mentioned above, this generalization is based on both reductionistic reasoning as well as system theoretical reasoning. With respect to the latter, particular consideration will be given to two system theoretical frameworks which have already proposed such generalizations, namely Weak Quantum Theory developed by H. Atmanspacher, H. Römer and H. Walach (Atmanspacher et al., 2002, p. 687) and the Model of Pragmatic Information developed by W. von Lucadou (1995; 2006).
I will also outline some areas where the generalized notions proposed by GQT may be potentially helpful to develop a deeper understanding or at least provide a fresh look at problems which have puzzled scientists for a long time. In chapter 3.4.3 I will give an example of the applicability of a generalized complementarity principle by illustrating how it could be used to describe the relationship between consciousness and body. In chapter 3.5.4.1 I will analyze whether telepathy and psychokinesis could be understood as examples of generalized entanglement. Other areas, which I will just mention briefly, include the indeterminism vs. determinism debate, purported effects in alternative medicine, possible mechanisms of evolution and the relationship between relativity theory and quantum theory.

In the fourth chapter I will describe two experiments which were designed and conducted in order to validate or disprove GQT with regard to the postulated occurrence of generalized entanglement. The aim was to create an experimental system which fulfils all the requirements for entanglement which GQT defines. If GQT were a correct description of reality, then in such an experimental system we should be able to observe entanglement. However, no indication for entanglement was detected in the experiments. More detailed analysis revealed that the experimental systems I developed did not operationalize in a satisfactory way all the theoretical requirements and that in fact this may be difficult to achieve even in principle. Therefore, the finding that no entanglement was observed in these experiments cannot be interpreted unambiguously to either support or disprove GQT. While on the one hand GQT may simply be wrong with respect to generalized entanglement, it is also possible that the experiments simply did not adequately fulfill some of the theoretical requirements for generalized entanglement to occur. What is more, my theoretical analysis will show that it may be in principle impossible to design an experiment that does fulfill these requirements.

It may be important to point out that much of this theoretical analysis took place after the experiments had been conducted. This explains why in chapter 4 of this dissertation I will report experiments which in light of the analysis presented in chapter 3 may not seem to have been very promising in the first place. Ideally, in scientific progress, negative results will lead to the formulation of new hypotheses, which in turn can be tested again experimentally. In the case of generalized entanglement, however, I have come to the conclusion that a rigorous experimental proof is probably impossible as a matter of principle. If that is so, the question about its existence will have to be assessed on grounds of plausibility and circumstantial evidence rather than the potential experimental falsification of its non-existence.

Finally, in the fifth chapter I will sum up the major conclusions and open questions that arise for me from the work so far and outline some possible avenues which further research could take.
While I think I will be able to convey the logical plausibility of Generalized Quantum Theory (GQT), illustrate its potential explanatory power and demonstrate that indirect evidence strongly supports it, I have to clearly state that, contrary to quantum theory in the strict sense, it remains speculative in nature for the time being.

Since this study is a highly interdisciplinary endeavor, I have made a strong effort to keep the language as simple as possible, in order to assure that it is accessible for readers from different disciplines, while remaining true to the facts and not oversimplifying the subject matter.

2. Some Aspects of Quantum Theory

2.1 Complementarity

Let us begin with a closer examination of what is meant by complementarity in quantum theory. In doing so, we will also have a chance to very briefly recapitulate the Nobel Prize laden beginnings of quantum theory even though it is of course beyond the scope of this chapter to go into all the intricacies of the discussion at the time and do justice to all the great minds involved in the development of quantum theory.

The complementarity principle was introduced into quantum physics most prominently by Niels Bohr in 1927 in a lecture in Como, Italy (reprinted in Bohr, 1928). It was inspired, at least partly, by the latest developments regarding a problem that had then puzzled physics for a long time, namely the paradoxical nature of light:

2.1.1 The Wave-Particle Duality of light and the Double-Slit Experiment

In 1905, Albert Einstein had published a mathematical description of the so-called photoelectric effect (Einstein, 1905).[1] The photoelectric effect concerns the emission of electrons from metal as a result of its surface being exposed to light. Einstein showed that this effect can only be properly understood when one assumes that light consists of discrete and localized particle-like units of energy, which he called "light quanta" (Einstein, 1909).[2]

In this analysis, Einstein built on observations by Max Planck (Planck, 1900; 1901).[3] Planck had shown that the radiation of electromagnetic energy can only be described in an accurate way by assuming that it occurred in quantized form.[4] Planck had considered this quantization as a merely formal assumption and also Einstein initially viewed it only as a heuristic point of view and not a logically binding conclusion. In the years to come, however, the predictions based upon Planck's and Einstein's theories were unambiguously confirmed by experiments (most decisively by Millikan, 1916 and

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[1] It is this work, for which he was going to be awarded the Nobel prize in 1921.

[2] Based on this understanding, Einstein made one crucial prediction, which is that the maximum energy of the electrons must vary linearly with the frequency of the incident light which was experimentally confirmed 10 years later (Millikan, 1916).

[3] Work for which Planck, too, was going to be honored with the Nobel prize in 1918.

[4] More precisely, energy is radiated in multiples of an elementary unit $E = h\nu$, where h is Planck's constant, also known as Planck's action quantum and ν is the frequency of the radiation.

Compton, 1923) and it became clear that in fact light had to be regarded as composed of particles, later to be called photons.[5]

This, however, was totally irreconcilable with the conception of light as a wave, which was generally accepted at the time. The understanding of light as a wave, i.e. as a continuous spatial distribution of energy, was not only very well formalized mathematically by the equations developed by James Clerk Maxwell (Maxwell, 1865), but also regarded as experimentally verified, because the wave nature of light offered the only way to explain the so-called interference effects which had been well studied since Thomas Young first observed them in his famous double slit experiment (Young, 1807).[6]

I will now describe a modern version of the double slit experiment in which both the wave-nature and the particle-nature of light can be observed and which thereby illustrates in a very tangible way the paradox that was beginning to emerge. In this experiment photons are emitted from a monochromatic point-like light source and absorbed by a detector, for example a photographic film which turns black at the place where it is hit by a photon. Between the source and the detector there is a screen in which there are two slits which can be individually closed or opened.[7]

To begin with, only one of the slits is opened (Figure 1).[8] One photon at the time is emitted from the source. It is then either absorbed by the screen or passes through the slit and hits the detector. Whenever a photon hits the detector, a dot appears on the photographic film, thus recording the location of the impact.[9] The source emits photons at such a low rate that the next photon is emitted only after the previous photon has been absorbed so that at any time there is only one photon in the experimental setup. After a large number of photons has been emitted and subsequently recorded at the detector, a pattern emerges at the detector that indicates a certain spatial distribution of the dots

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[5] The term 'photon' was first introduced by Gilbert N. Lewis in 1926 (Lewis, 1926).

[6] This experiment had therefore been considered the final resolution of the question about the nature of light that had already been the subject of argument between Sir Isaac Newton (Newton, 1704), who speculated that light was a stream of particles (then called corpuscles) and one of his contemporaries, Christiaan Huygens, who believed that light was a wave (Huygens, 1690).

[7] Please note that the description of the experiment is somewhat schematized and simplified with regard to technical issues in order to make the central conceptual issues more easily discernible. In real experiments the emission and detection of single photons is more complicated. The version described here, however, qualifies for what physicists call a thought experiment, an experiment that would be possible under ideal conditions.

[8] Figures 1-4 are modified screenshots from a program called "doppelspaltversuch.exe" which was developed by Klaus Muthsam and is available for download from http://www.didaktik.physik.uni-muenchen.de/materialien/inhalt_materialien/doppelspalt/doppelspalt.zip. It allows extensive simulations of the double-slit experiment. (The parameters used for the simulation displayed here were as follows: photon energy: 18eV, slit width: 400μm, slit distance: 1000μm, relative zoom on detector: 1000x.)

[9] To be more precise, what is recorded on the film is the location of the traces of a photochemical reaction. In the example of a photographic film for example, it is the location of the silver atoms which resulted from the halide crystal break down due to the absorption of the photon's energy.

where the photons hit the detector. This pattern can also be represented by an intensity distribution diagram (Figure 2). I will use this representation for the rest of this chapter, as it is more easily interpretable.

Figure 1: Double-slit experiment with photons passing through one slit, detection as dots on photographic film

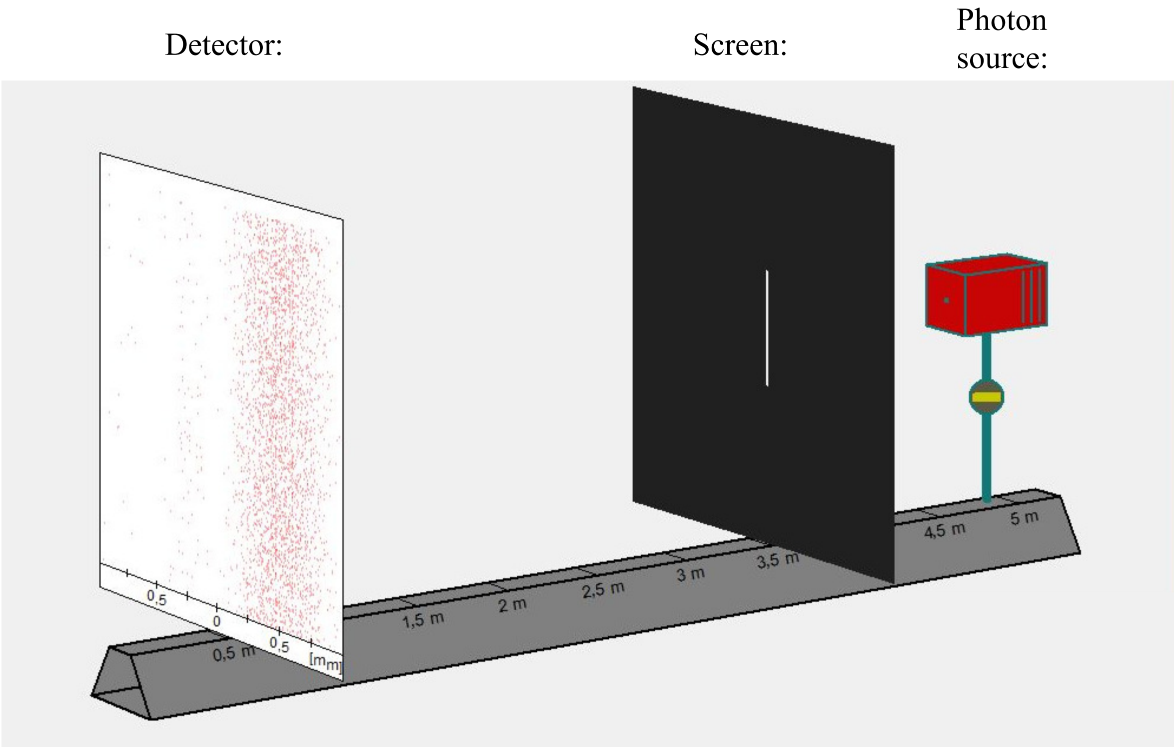
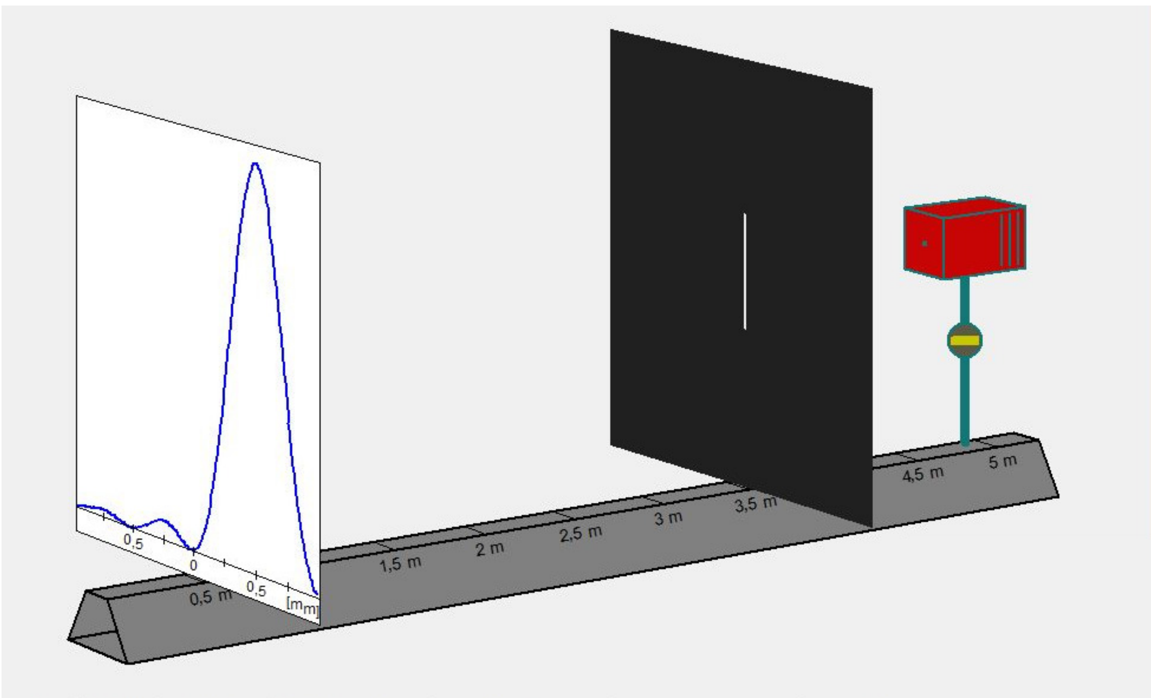
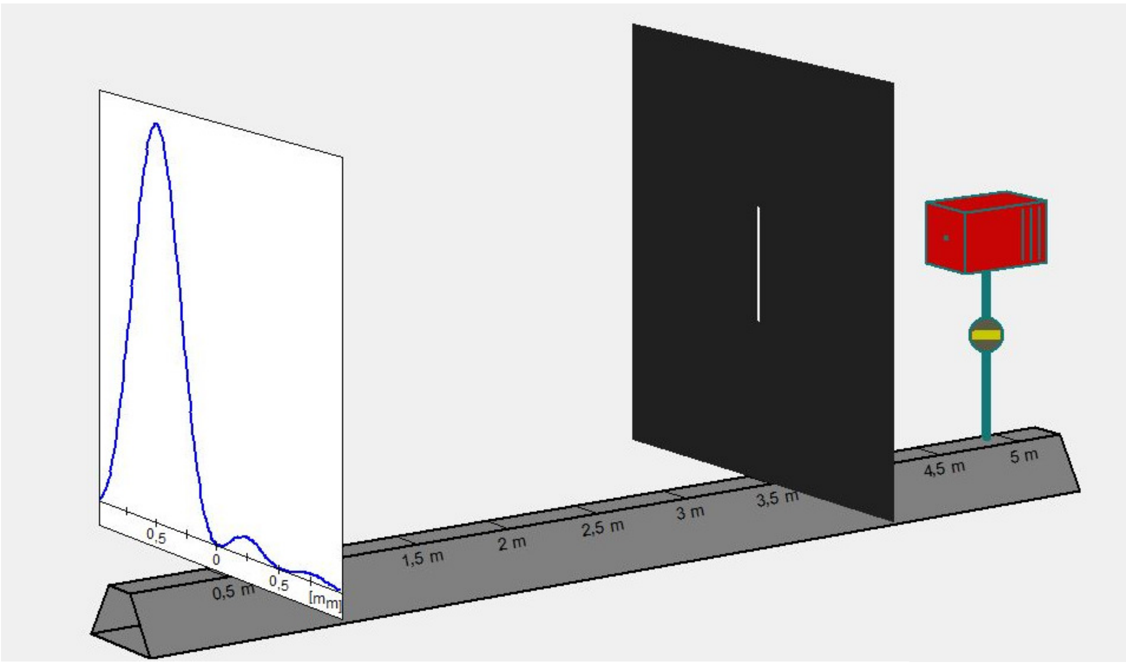


Figure 2: Identical double-slit experiment as in Figure 1, with distribution of dots represented by intensity distribution diagram



As a next step in the experiment, the slit which was open is closed and the one which was previously closed is opened (Figure 3). Now, after a large number of photons has been recorded at the detector, a pattern emerges at the detector that is in principle identical to the pattern that was recorded in the first experiment, except it has shifted, rather unsurprisingly, in accord to the shifted location of the slit in the screen.

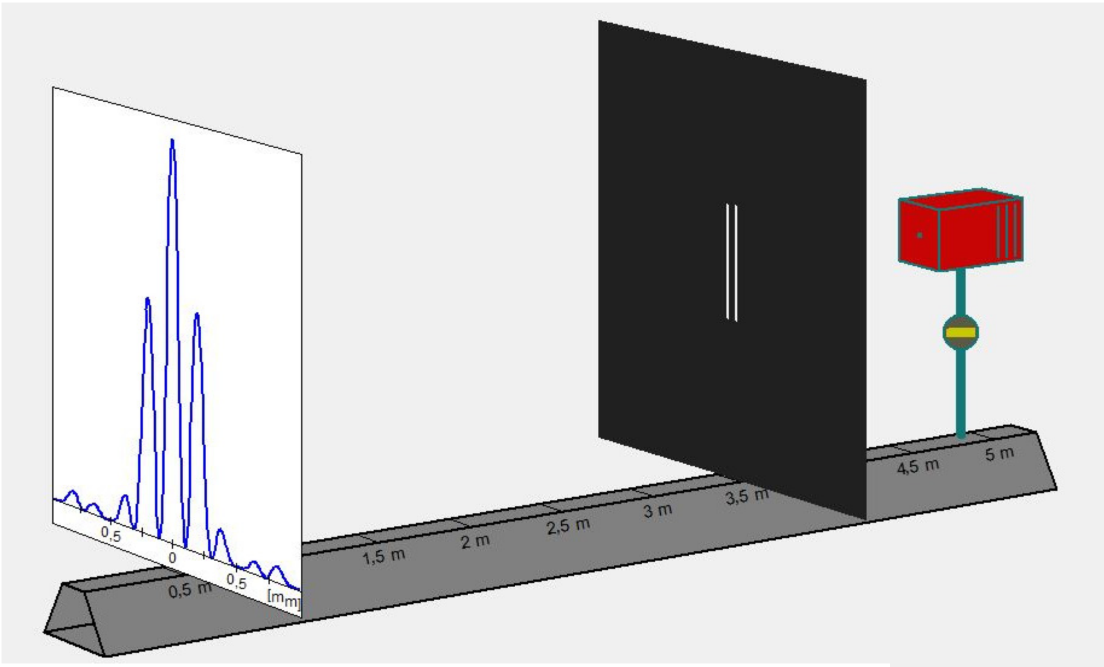
Figure 3: Double-slit experiment with photons passing through the other slit, dots represented by intensity distribution diagram



The fact that the impact at the detector happens in a localized way (single small dots) clearly suggests that photons are particles.
The observed distribution of dots, with one maximum and several smaller peaks, is somewhat more difficult to explain in keeping with such an understanding of photons.[10]
The view of photons as particles will fail completely when, next, both slits are opened. Now, after a large number of photons has been recorded at the detector, the pattern we might expect to see is a simple addition of the two previous patterns. This should result roughly in two main maxima on either side of a central minimum. However, this prediction turns out to be incorrect as the actually observed pattern looks quite different (Figure 4):

[10] Apparently, this distribution pattern could be explained by there being variations in the exact velocities of the particles and/or the deflection (scattering) of the particles by the walls of the slit (see e.g. Müller and Wiesner, 1997; Marcella, 2002). The more commonly used explanation is, however, in terms of diffraction, which rests on the understanding of photons as waves (e.g. Ambrose et al., 1999).

Figure 4: Double-slit experiment with photons passing through both slits, with observed distribution of dots indicating interference effects, thus disconfirming particle nature of light



Closer analysis reveals that such a pattern can only adequately be explained by assuming that each of the photons has in fact passed through both slits at the same time and interfered with itself. (Since only one photon was in the apparatus at any time, we know that it cannot be the result of multiple photons interfering with each other.) Such behavior can under no circumstances be attributed to a particle, which has only one localization in space and time and can not be in two places at once. To satisfactorily explain this observation one has to instead attribute wave-nature to the photon, because, as a wave, it can interfere with itself. What is interference? As one can easily observe on the surface of water, waves show a particular behavior: When waves meet, the peaks will add up to give a larger peak; where two troughs meet, accordingly, the trough increases; and where a peak and a trough meet, they eliminate each other. This phenomenon is called constructive and destructive interference, respectively (Figure 5 and 6).

Figure 5: The principle of constructive and destructive interference[11]

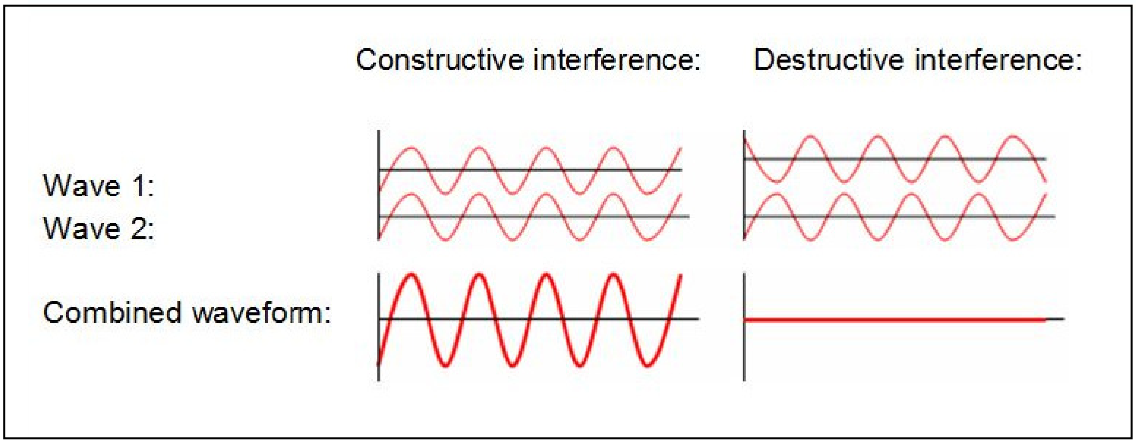
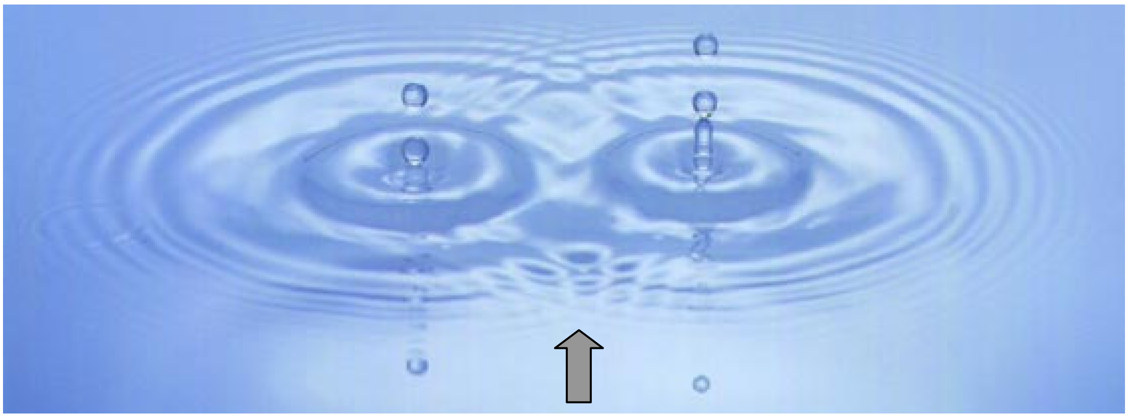


Figure 6: Constructive and destructive interference in surface waves[12]

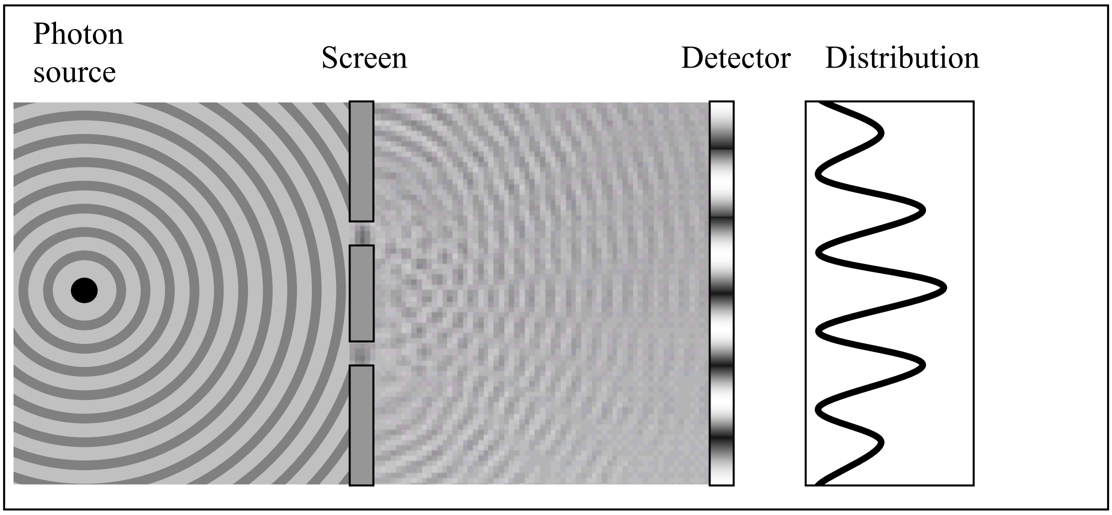


The double-slit experimental setup could from this point of view be considered analogous to a quay wall with two passages where a wave that hits the wall passes through the passages and then expands in a circular fashion from each of those passages. This understanding is illustrated in Figure 7.

[11] Illustration adapted with friendly permission from Theresa Knott, via Wikipedia.

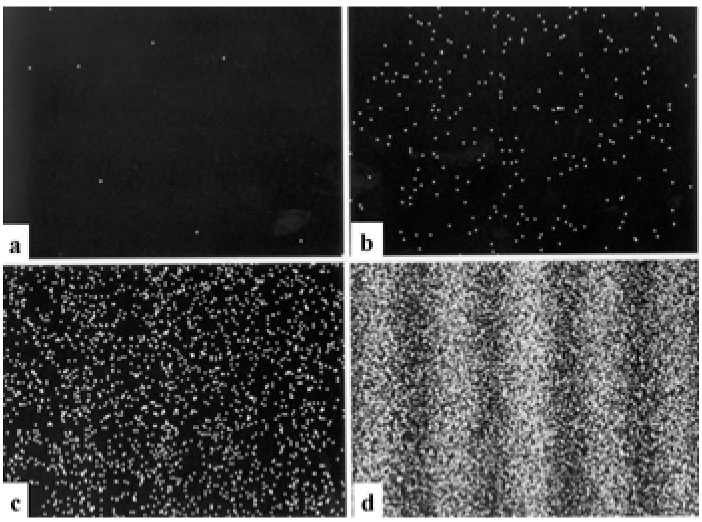
[12] Photograph by John Broomfield, with friendly permission by Museum Victoria Australia (Copyright © 2003).

Figure 7: Schematic double-slit experiment with light passing through both slits and causing an interference pattern, illustrating the wave nature of light



Nevertheless, also in the setup with both slits opened, the detector records only one localized event (one dot) for each photon. This indicates, as before, the discrete nature of the photon and cannot be explained by an understanding of photons as waves. (See figure 8 for a photograph of an original detector showing individual, well localized dots forming an interference pattern.)

Figure 8: Results of a double-slit experiment showing the build-up of an interference pattern from single detection events (Tonomura et al., 1989).[13] Here single electrons were used instead of photons but conceptually the same holds true for photons. Numbers of electrons are 8 (a), 270 (b), 2000 (c), 60000 (d).



[13] Copyright, © 1989, by the American Association of Physics Teachers.

The resulting dilemma is obvious: certain ways in which light behaves can only be adequately described by assuming a wave-like nature of light, in other cases only a description based on the particle nature of light offers satisfactory explanations. However, particle and wave are two absolutely incompatible concepts: waves are continuous, whereas particles are discrete.[14] A wave can, for example, easily be thought to pass through two places at the same time, for a particle this is impossible. Werner Heisenberg referred to this situation as follows (Heisenberg, 1958, p.49):

> *"The two pictures are of course mutually exclusive, because a certain thing cannot at the same time be a particle (i.e., a substance confined to a very small volume) and a wave (i.e., a field spread out over a large space)"*

In short, there is nothing wave-like to a particle and nothing particle-like to a wave. There is no common denominator.[15]

This contradictory situation was further intensified by the work of Luis de Broglie (De Broglie, 1925; 1926), where he showed that the electron, which was since its experimental confirmation by Sir Joseph John Thomson in 1897 (Thomson, 1897), thought of as a particle, also required a wave-type description.[16] In fact, De Broglie argued, all matter has to be attributed, in addition to its discrete corpuscular nature, a wave nature. And in fact, double-slit type experiments have by now been conducted not only with electrons and protons, but also with atoms and even molecules (e.g. Arndt et al., 1999; Hackermüller et al., 2003), giving analogue interference effects in all cases. (For larger sized objects, however, the wavelength gets infinitesimally small.[17])

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[14] Discrete means that particles occupy a finite space with definite boundaries. Continuous means that waves are homogenously spread out in space without a definite boundary.

[15] This becomes most clear when considering an ideal particle as a point-like structure and an ideal wave as represented by a sine wave: A point is represented by a set of as many co-ordinates as there are dimensions, each co-ordinate representing one. Particles can therefore never exist in more than one place at the same time. A pure sine wave, on the other hand, has no beginning or end, only a fixed period after which it repeats itself. It can thus not be considered to exist in a single place. Such idealized point-like particles and sine-like waves, however, are abstractions that can probably not physically exist, unless one allows for infinite energy (see e.g. Popp, 1984, p. 145). Absolute incompatibility therefore occurs between the descriptions available to us, whereas the actual physical phenomena to be described display only a gradual, relative incompatibility. This will be discussed again in more detail further down.

[16] Work for which both of them, too, were honored with the Nobel prize, Thomson in 1906 and deBroglie in 1929.

[17] DeBroglie's equation is: wavelength = h / momentum (where h is Planck's constant). Momentum, simply speaking, can be expressed as the product of speed and mass of a particle. For atomic particles, having small momentum, the deBroglie wavelength can not only be calculated but actually measured. Macroscopic objects, moving at relatively low speeds tend to nevertheless have large momentum because of their considerable mass, therefore the deBroglie wavelengths of these objects may be too small to measure for practical and, when the wavelength becomes smaller than Planck length (16.163×10^{-36} m), even for theoretical reasons.

2.1.2 The Complementarity Principle

How could this paradox possibly be resolved? The only possible answer to this question, which was seen by Bohr at the time and which remains uncontested until today, is that in fact this paradox *cannot* be resolved and instead has to be regarded as fundamental principle. Whatever a quantum 'really' 'is'[18] will remain out of reach of rational understanding, because the only way in which we can rationally understand and describe the experimental observations is in terms of concepts which contradict and exclude each other and which cannot be reduced to each other. Bohr supported this analysis by showing that the experimental conditions, which allow the observation of either the wave- or the particle-nature of a quantum (and therefore the conditions under which it is possible to describe either of them), are also mutually exclusive. In Bohr's own words:

[...] any arrangement suited to study the exchange of energy and momentum [...] must involve a latitude in the space-time description of the interaction sufficient for the definition of wave-number and frequency [...]. Conversely, any attempt of locating the collision [...] more accurately would, on account of the unavoidable interaction with the fixed scales and clocks defining the space-time reference frame, exclude all closer account as regards the balance of momentum and energy. (Bohr, 1949, p. 210)

With respect to the double slit experiment, this means that in any experimental arrangement where the space-time location of a quantum within a fixed frame of reference can be measured with accuracy, the quantum will behave like a particle and no wave-like properties will be observed. In the experimental setup presented here, this is the case e.g. when the quantum hits the detector. When, in contrast, the experimental arrangement does not allow precise measurement of the location, the quantum will behave like a wave and not show any particle-like properties. The experimental arrangements for measuring and not measuring location exclude each other in the sense that they cannot be combined into one *simultaneous* arrangement.[19]

"Complementarity" is the term Niels Bohr introduced in his 1927 lecture in Como as a description of the relationship between these two experimental set-ups (and the descriptions of the resulting phenomena), which are mutually exclusive but nevertheless collectively required for a complete account of the physical system under consideration (Bohr, 1928).

It is important to clarify that the mutual exclusivity of the arrangements and the respective observations must not necessarily be absolute. Rather it is usually of relative and gradual nature and only means that observations of both types cannot be realized with arbitrary precision at the same time. It is, for example, possible to modify the

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[18] In this text I use " " to denote quotations and technical terms while ' ' is used to denote neologisms and metaphorical use of words.

[19] Although Einstein and others proposed experimental setups where the impossibility of combining precise measurement of both particle- and wave-properties was not at all obvious, all of these attempt were eventually shown to be impossible for principal reasons (A summary can be found in Bohr, 1949).

double-slit experiment in such a way that with the help of an additional detection mechanism it is possible to determine which of the two open slits a given quantum passed through (e.g. Jordan, 2001; Schneider and LaPuma, 2002). This additional detection mechanism can be adjusted in such a way as to determine the location of the quantum with varying degrees of accuracy. This allows to make the following observation: If the position of the quantum can be determined with absolute precision, an interference pattern can no longer be observed. If, however, the position of the quantum is determinable only with a low degree of precision, the interference effect will not disappear completely but only be weaker. This gradual relationship has been precisely quantified and experimentally tested (see e.g. Mittelstaedt et al., 1987; Jaeger et al., 1995; Schwindt et al., 1999; Badurek et al., 2000; Busch and Shilladay, 2006 and references therein).
It is also reflected in Heisenberg's uncertainty relation to which Bohr pointed as a prime example of complementarity (Bohr, 1928, Section 2):[20] Heisenberg had called attention to the fact that the uncertainty of a measurement of the photon's position Δx and the uncertainty of a measurement of the photon's momentum Δp follow the relation $\Delta x \Delta p \geq h$, where h is Planck's constant.[21] (Heisenberg, 1927; Wheeler and Zurek, 1983). As one can see, the uncertainty about the position will increase as the uncertainty about the momentum becomes smaller and vice versa, because the uncertainties have to factor up to $\hbar$. It is thus possible to design an experiment where both the position of a quantum and its momentum can be determined simultaneously to some lower degree of accuracy. The more precisely, however, the experiment can determine the position of a quantum, the less information it can provide regarding its momentum, and vice versa.

This leads to a property of complementary descriptions which is called "non-commutativity", meaning that the sequence in which measurements are made is decisive for the state of the quantum after the measurements. Consider, for example, first measuring the position of a particle and then its momentum: Depending on the degree of accuracy of the momentum measurement the location of the particle is indetermined afterwards. The same is true vice versa. In mathematical terms the sequence of quantum measurements is expressed as the sequence of factors in a multiplication. In contrast to commuting factors, where for example 2x3 gives the same result as 3x2 and therefore $2 \times 3 - 3 \times 2 = 0$, for measurements of the non-commuting variables position and momentum we get $qp - pq \neq 0$ (where q and p are matrices representing the variables referring to position and momentum) (Heisenberg, 1925).

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[20] There is some debate about the precise relationship between Heisenberg's uncertainty principle regarding position- and momentum-descriptions and Bohr's complementarity principle regarding space-time- and causality-based descriptions. (For an overview of the debate see e.g. Jammer, 1974; Busch and Shilladay, 2006.) I will not go into detail here because for the purpose of this chapter it is sufficient to show here merely that complementarity is a fundamental principle in quantum physics.

[21] The modern version of this uncertainty relation is based on Kennard (1927) who proved that $\sigma_x \sigma_p = \hbar/2$, where σ_x and σ_p are the standard deviations position and momentum measurements and "$\hbar$" is a constant called "Heisenberg's uncertainty relation coefficient" or "reduced Planck's constant" that equals $h/2\pi$.

A further characteristic that might be added to the definition of complementarity is that the complementary notions mutually require each other for definition and, as such, each does not make sense analyzed completely independently from the other: Basically no continuum can be defined without discrete points and all discrete points have to be defined in relation to a continuum. We will investigate this and other features of complementarity in more detail in chapter 2.5 on self-referentiality and in chapter 3.4 where I will attempt to outline a generalized notion of complementarity.

As one can imagine, the interpretation of the wave-particle paradox offered by the complementarity principle has not been received by the scientific community without hesitation. This has at least partly to do with the fact that it is not exactly the type of answer hoped for by many: It does not offer a coherent way of describing what 'lies beyond' and unifies the two contradictory 'faces' of the quantum and therefore, at first sight, does not help us to get rid of the paradox. Instead, the complementarity principle points out that there *cannot* be *any* such logically coherent description of the nature of reality as a whole. Thus, at a second look, it does get rid of the paradox but only by explaining that the paradox results from a question that is not reasonable to ask because its answer cannot in principle be found. Bohr therefore emphasized that the task of physics has to be seen as describing observations, and not as making statements about the ultimate nature of reality (Bohr, 1949).[22] He is often quoted with something like the following words (e.g. by Bell, 1981*):*

"It is wrong to think that the task of physics is to find out how nature is. Physics is concerned with what we can say about nature."

Complementarity can thus be seen not as a statement about how quanta 'really are' but about how they can be adequately and comprehensively described by an observer. Furthermore it tells us that any useful speculation about what unites the wave- and particle-nature of reality will not be rationally understandable and communicable in what Bohr termed "classical concepts", because there is no such classical concept which can unite the mutually exclusive complementary concepts. By "classical concepts" Bohr means concepts which can in principle be matched in an unambiguous way to a real life physical situation and which can be converted into each other by transformation operations (Howard, 1994).

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[22] By this, Bohr did not, in my understanding, mean that asking questions about the ultimate nature of reality was useless. Rather he wanted to point out that such questions can not be decided by physics (that is to say, rationally and objectively) and should therefore be regarded as philosophical or more precisely spiritual questions. In fact he himself did at times speculate on what lies 'beyond' wave and particle. Since he did not, however, always make explicit whether he was talking from the viewpoint of physics or philosophy/spirituality, this did not necessarily help to clarify his position. At the same time, it is important to note that Bohr may also have considered these different viewpoints as complementary, because they are mutually exclusive yet collectively required for an adequate descriptions of and interaction with reality. (For more details regarding Bohr's position on spirituality see chapter 3.4.1.)

Even though it may be hard to adjust one's thinking to this paradoxical nature of complementarity, this may be more called for than trying to ignore the complementarity principle or to hope for some future development to make it obsolete. At least up to now, some form of complementarity, in Bohr's sense, is revealed by all attempts to completely describe the nature of a quantum: A prominent example are the mathematical description achieved by Erwin Schrödinger and Werner Heisenberg. Schrödinger formulated the so-called wave equation (Schrödinger, 1926). The solution to the wave equation, called wave function, basically describes the fundamental nature of a quantum as a wave which evolves continuously in space-time.[23] This wave is usually interpreted (following Born, 1926a; b)[24] as representing, in essence, the distribution of likelihood of the possible outcomes of the interaction of the quantum with some measurement apparatus.[25] With regard to the double slit experiment, such a 'probability wave' could be visualized as a spherical wave expanding from the source, representing the distribution of possible outcomes of location measurements performed on the quantum. The wave function does not, however, contain any indication as to *which* of these possible outcomes will eventually be observed. That means that the wave function offers an accurate description of the quantum only before its interaction with a measurement apparatus. The result of this interaction, however, is that suddenly only one of the possible states (i.e. locations) of the quantum is 'chosen' in a probabilistic fashion. This second aspect is covered by the mathematical description formulated by Heisenberg using matrices, which does not, however, contain any description of the quantum before a measurement. Although Schrödinger and Heisenberg agreed about the equivalency of their formulations they did not manage to combine them into a single coherent and universal framework. This makes sense because they basically represent two mutually exclusive frameworks needed to fully describe the behavior of the quantum: firstly a continuous deterministic development of the wave function and secondly a discrete probabilistic choice of measurement outcome.[26] So here we are again confronted with complementarity: two irreducible, mutually exclusive aspects are both indispensable for a complete description of our observations.[27] It may be interesting to point out that this complementarity could be seen

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[23] Schrödinger's quantum wave function for one dimension can be developed relatively straightforwardly from the earlier mentioned classical concept of matter waves as proposed by deBroglie (for a more detailed mathematical account of this connection see e.g. Rayski, 1995 p.19) or from Maxwell's field equations (which also describe the particle-like properties of the photon when the fields are interpreted as being proportional to probability amplitudes for finding a photon particle in a particular state).

[24] Work honored with the Nobel prize in 1954.

[25] To be precise, it is the amplitude of this wave squared with its complex conjugate which represents the probability of the respective quantum to be detected in a certain place.

[26] This has also been described by Johann von Neumann (von Neumann, 1943) as linear 'Process 2' (automatic development of the wave-function over time) and non-linear 'Process 1' (changes introduced by measurement).

[27] The interpretation of these two descriptions as endo- and exo-perspective by Primas, Rössle, Atmanspacher and others might be one way of conceptualizing this complementary relationship (Primas, 1994; Atmanspacher, 1996; Rössler, 1998). Another interpretation is what Bohr and Heisenberg, among others, called the *"fundamental complementarity of space-time description and causality"* (e.g. Heisenberg, 1930, p.65): On the one hand, when one can precisely describe a quantum-phenomenon in space and time one

as a direct empirical confirmation of a postulate most famously advanced by Aristotle more than two millennia ago (in: Metaphysics IX, 3-4), namely that reality is irreducibly composed of potentiality and actuality. Understanding the relationship between potentiality and actuality in terms of complementarity may actually allow for a specification of Aristotle's motion: From this point of view, it might be more accurate to say *not* that reality *is composed of* potentiality and actuality but rather that *whatever* reality ultimately consists of can by us only be *described* by these complementary notions.

Another interesting case can be found in the so-called de Broglie-Bohm pilot-wave (De Broglie, 1925; Bohm, 1952): In this conception, the photon is assumed to consist of both a wave *and* a particle. The particle, so to say, 'floats on' and is guided by the wave. Particle and wave exist at the same time, thus apparently getting rid of the paradox. At a closer look, however, the wave/particle paradox has only been traded for another, equally irresolvable paradox, because the pilot wave is supposed to be immaterial while the particle is material. So one is again confronted with mutually exclusive frameworks which are both needed to describe the situation and the unanswerable questions simply shift from having to explain what can unite particle and wave to how an interaction between material and non-material can take place.

In a similar way, up to now, all attempts to coherently describe and interpret the observations of quantum physics have, to my knowledge, explicitly or implicitly required comparable irreducible and mutually exclusive components, thus indicating the fundamental nature and indispensability of the complementarity principle.[28] A number of formal analyses reach the same conclusion (see e.g. Englert et al., 2000; Kim and Mahler, 2000; Busch and Shilladay, 2006 and references therein).

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can in no way explain this phenomenon as the result of a causally continuous development from earlier states of this quantum or other phenomena. On the other hand, we *can* describe such a continuous development with mathematical precision but in that moment we loose the ability to describe the quantum as a physical phenomenon in space and time.

[28] As a final remark I would like to make clear, that what I am concerned with here, is the factual basis of this observation. It does not matter so much to me, which words are used to denote it. While I believe calling it "complementarity" does justice both to the history of quantum physics as well as the intention of Bohr, this does not seem to be an absolutely unanimous point of view in the scientific community, where sometimes the term "complementarity" is used in different ways. Some authors for example reserve it for operators like position and momentum, whereas wave-particle duality is considered a different concept.

2.2 Observables

As we have seen in the last chapter, (at least some) properties of quanta seem to be dependent on the conditions under which they are observed. If, for example, the conditions are such that the position of a quantum can be observed, it will have particle properties. If however, conditions are such that its position cannot be observed it will have wave properties. As we will see in chapter 2.3 on entanglement, this context-dependency applies not only to location but also to other properties of quanta. Thus, more generally speaking, certain properties of physical reality seem to come into existence only through the interaction of different elements of reality. Rather than properties *per se,* we should thus regard them as contextual properties.

What is more, the precise values of the properties which, so to speak, 'emerge' from the interaction of different elements of reality, seemingly cannot be predicted in advance but instead are 'chosen' out of all possible values without recognizable cause. This is why, for example, physicists speak of a probability distribution when referring to the location of a quantum in the double slit experiment before its interaction with the detector. This essential unpredictability means that the property of a quantum which we eventually observe cannot be reduced to or deduced from the state of the individual quantum before the observation or, to be more precise, interaction. (We shall return to the implications and interpretations of this unpredictability in some more detail in chapter 2.4 on probability.)

To pay tribute to these facts, quantum physicists, where appropriate, speak of observables rather than properties. An observable is defined as the product of the interaction between observer and observed.[29] For example, the location of the black dot on the detector screen is a product of the interaction of the photon with the screen. Since, before this interaction, the photon does not seem to have a definite location, one would not talk about the location as a property of the photon but as an observable.

Another example of observables pertaining to quanta of light (photons) is the so-called polarization. What is meant by polarization? A photon can, in the appropriate frame of reference, be understood as an electromagnetic wave. As such, it is best described using Maxwell's equations, which tell us that the electric and magnetic fields oscillate transversely in the plane normal to the direction of motion of the photon (and orthogonal to each other). Thus a photon coming directly toward us can be diagrammatically represented as a cross (Figure 9a). The orientation of the oscillations of the electric field is called the polarization of the photon.

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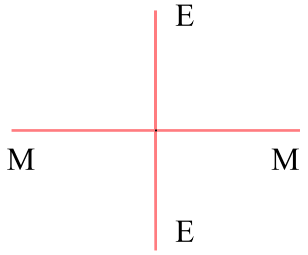
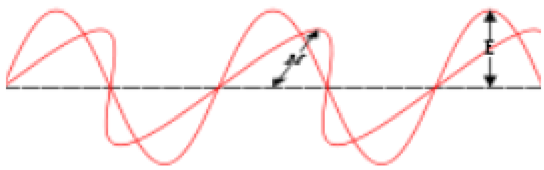
[29] Notice that here again we have a situation which could require the complementarity principle: observer and observed are mutually exclusive parts of reality and at the same time collectively required for an adequate description thereof. In fact, this could be regarded as a very fundamental complementarity: that between subject and object.

Figure 9: Oscillating magnetic (M) and electric (E) fields of a photon moving
a) directly towards or away from you



or **b)** sideways, parallel to the surface of this paper.[30]



To illustrate the nature of polarization, let me describe the observations that can be made in the following setup[31] (Figure 10): There is a photon source [S], which emits photons at a very low rate toward a detector [D] which can detect the absorption of a single photon, and there are two rotatable polarization filters [F_1] and [F_2] which can be individually placed in the path between [S] and [D].

A polarization filter can be conceptualized as a regular array of fine parallel metallic wires, placed in a plane orthogonal to the incident electromagnetic waves. If the electric field is aligned parallel to the wires, the wave will be absorbed because it induces the movement of electrons along the length of the wires whereby energy is absorbed. Conversely, an electric field which is oriented orthogonal to the wires cannot move the electrons very far across the width of each wire and therefore little energy is absorbed. Thus, for an idealized polarization filter (where the wires are so thin that the electrons can only move along, but not at all across the wire) photons with a polarization parallel to the wires will never pass through the filter, while photons with a polarization orthogonal to the wires will always pass through the filter (this polarization I will call the 'filter-specific polarization').

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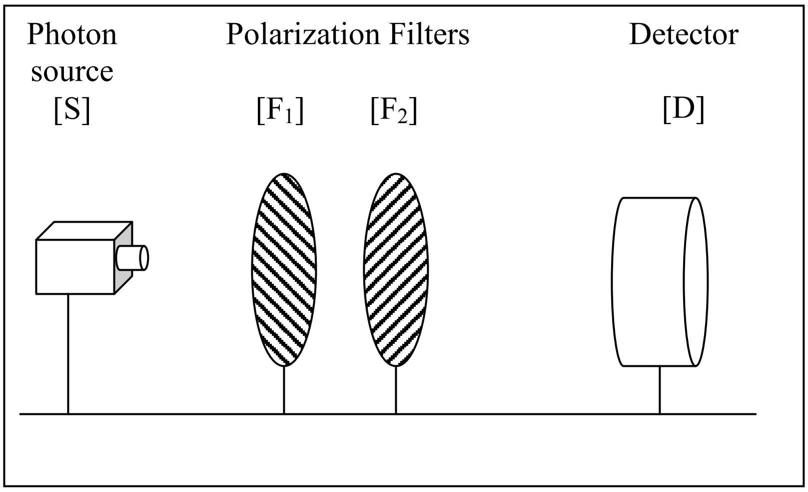
[30] Figure 9b is an adaptation of a figure that was retrieved on 22.02.2009 from http://en.wikipedia.org/wiki/File:Light-wave.svg according to the GNU Free Documentation License (http://www.gnu.org/copyleft/fdl.html).

[31] You can explore a virtual version of this experiment for yourself using the simulation program "polfilter.exe" which was developed by Albert Huber and which can be downloaded for free from http://www.didaktik.physik.uni-muenchen.de/materialien/inhalt_materialien/polfilter/polfilter.zip

Figure 10: Experiment with polarization filters



Let us now observe the behavior of photons in this setup: To start of, let us have only the Laser [S], and the detector [D] in the setup. From [S], photons are emitted one after the other toward [D]. All of them are subsequently detected by [D]. (In this process the photon is absorbed by the detector, so every photon can only be detected once.) Now, a polarization filter (F_1) is placed in the path of the photons. We will observe that on average half of the emitted photons will reach the detector. There is, however, no recognizable order in which half of the photons pass the filter and the other half do not.

We now rotate the polarization filter [F_1] so that its filter-specific polarization changes. We will find that the result remains constant: No matter which axis the filter is rotated to, half of the photons will reach the detector and half of the photons will not, in an unpredictable sequence.

Now a second polarization filter [F_2] is placed between the first filter and the detector. This filter can also be rotated so that different relative orientations of filter specific polarizations of filter [F_1] and [F_2] are possible. When the orientation of filter F_1 and filter F_2 is parallel, we observe no changes: Still half of the photons reach the detector. When filter F_2 is now rotated, however, the number of photons that reach the detector decreases until, when the filters are oriented orthogonal to each other, none of the photons reach the detector. When this experiment is repeated many times a certain pattern emerges: If the two filters are oriented at an angle θ relative to each other, then the number of photons passing all the way through is found to be approximately $N\cos^2(\theta)$ where N is the total number of photons emitted from the source. The larger N is, the more precisely the observations will match this prediction.

How can these observations best be described? The simplest and most exact way is formulated by quantum theory, which proposes that polarization (and other characteristics of quanta) should be thought of as the probabilistic outcome of an interaction between a photon and a polarization filter. Quantum theory would say that every photon, when it first encounters a polarization filter, irrespective of the filter's orientation, has a probability p=0.5 of exhibiting a polarization parallel to the wires (and consequently be absorbed), and an equal probability p=0.5 of exhibiting a polarization orthogonal to the wires (and consequently pass the filter). If a photon has passed the filter, it will always (p=1) pass a second filter oriented exactly in parallel and it will never (p=0) pass a filter oriented orthogonally.[32] We might be tempted to think that now the photon has taken on a certain polarization and we could safely speak of this as a fixed property of the photon. One can, however, from the fact that it passed the first filter not derive any definitive prediction about the future behavior of the photon at polarization filters oriented at any intermediate angle θ ($0° < \theta < 90°$). There is for example again a 50/50 chance (p=0.5) of passing or not passing a filter oriented at a relative angle $\theta = 45°$. What is more, once it has passed a second filter oriented at a different angle, we can once again not predict whether it will or will not pass a third filter oriented exactly the same way as the first one, and so on. Therefore, quantum physicists, instead of speaking of fixed properties, would prefer to state merely that the probability distribution for the outcome of a future interaction with a polarization filter (this is the observable called polarization) has changed, the probability of passing this next filter being $\cos^2(\theta)$ where θ is the relative orientation of that filter to the previous one.[33]

To conclude: what we call polarization of a photon is best described as an observable: the probabilistic result of an interaction between the photon and the measurement apparatus.[34] (As we will see in the following chapters 2.3 and 2.4, this probabilistic nature of observables can be interpreted in different ways which are subject to further discussion.)

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[32] This can also be understood in terms of the before mentioned formula because $\cos^2(0) = 1$ (for parallel filters $\theta=0°$) and $\cos^2(90) = 0$ (for orthogonal filters $\theta=90°$).

[33] This actually has some astounding practical consequences. Let us, for example, consider the two polarization filters F_1 and F_2 oriented orthogonally to each other. As we have seen, no photons will be able to pass. Let us now place a third polarization F_x filter in-between these two. When this filter is oriented at any intermediary angle between the orientations of filter F_1 and F_2, we will observe that some photons reach the detector again. The maximum number of photons (a quarter of the emitted) reach the detector when this filter is oriented exactly half way at 45° relative to filter F_1 and F_2. This is because the probability of a photon to pass F_2 is changed once it passes the intermediary filter F_x.

[34] In addition to illustrating the probabilistic nature of quantum observables the interaction of photons with a polarization filter can also teach us something interesting about the meaning of the word quantum: Not only is energy and therefore matter quantized into discrete units, but so are interactions: Given the understanding of how a polarization filter works, we could have assumed that if a photon with a polarization of say 45° (or, to formulate it more precisely, a photon that has just passed a filter at 45°) encounters a vertical polarization filter, that proportion of the electric field which is parallel to the wires will get absorbed while the proportion of the electric field which is orthogonal to the wires will pass. We would thus expect the photon to pass, but be reduced in its energy by half. This, however, is obviously not the case. There is always only a discrete either/or choice. Even a photon whose electrical field is almost exactly parallel to the wires will pass the filter undiminished, albeit with a very low probability.

2.3 Entanglement

We are now ready to consider another crucial feature of the behavior of quanta, namely entanglement, also referred to as "non-local correlations".

In quantum physics the term entanglement denotes the situation where probabilistic quantum events correlate with each other, even if they are not causally interacting, in the sense that no information of one can reach the other by any causal mechanism, which is why non-local correlations are sometimes also called non-causal correlations.

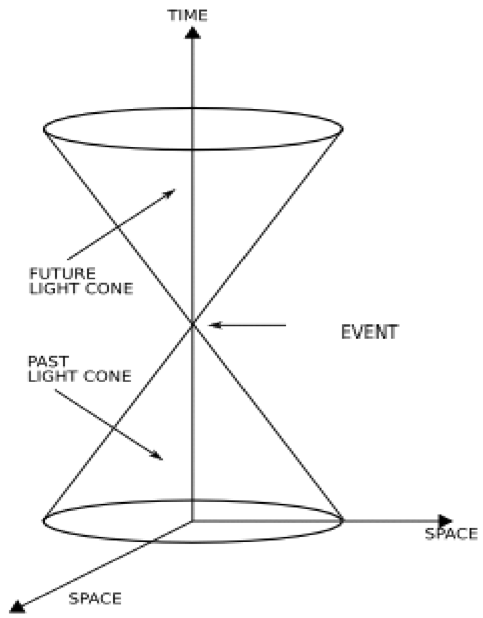
What exactly is meant by "causal mechanism" and, respectively, "causally non-interacting"? There is ample discussion in philosophy of science and also in physics about the notion of causality and so far no definition is agreed upon which holds in all theoretical frameworks (Bunge, 2008). For the purpose of this chapter, however, a minimal consensus will suffice to outline the characteristics of causality which are relevant to our discussion of entanglement.

In the sense in which the term causality is mostly used in physics nowadays it refers to the relationship between events which are connected by a transfer of any of the fundamental forces (gravity, the strong and weak nuclear forces, and electromagnetism). According to General Relativity Theory (and widely confirmed by empirical evidence) such a transfer of force can occur only with a certain maximum speed, namely the speed of light in vacuum.[35] This means that a cause will always precede its effect by a certain time interval which is at minimum the time it takes for light to cross the distance in space between the respective locations of cause and effect.

The theoretical causal 'reach' in space of any event can thus be imagined as a sphere which is expanding as time passes. Alternatively, for easier illustration in a static diagram, the three spatial dimensions can be collapsed to two, and time can be displayed as a spatial dimension. Such a diagram is called the "light cone" of an event (Figure 11).

[35] The speed of light in the vacuum of free space, usually denoted by the symbol 'c' is defined as exactly 299,792,458 meters per second (Taylor and Measures, 2001).

Figure 11: Light cone diagram of an event [36]

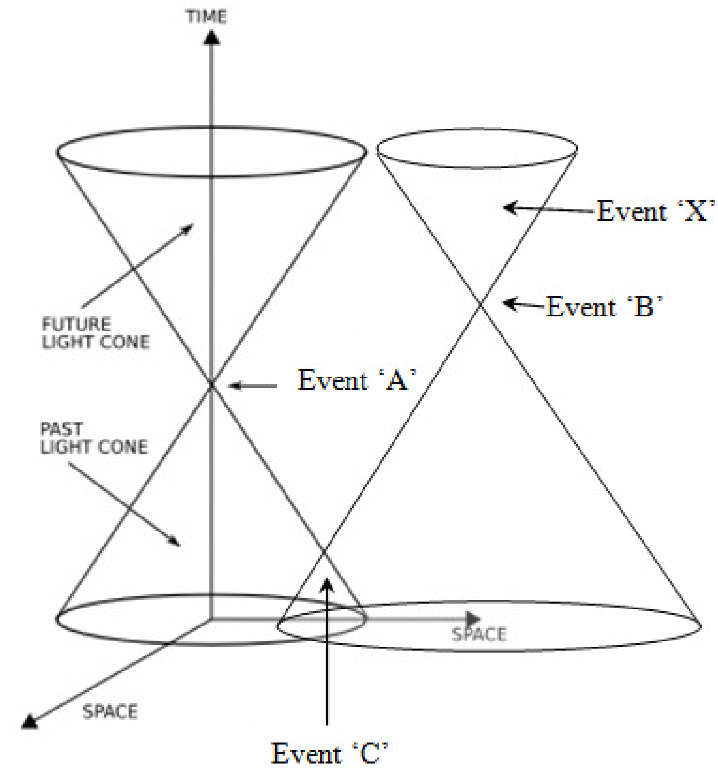


Here, the future light cone marks the maximal reach in space-time within which a given event can have a causal effect and the past light cone marks the area in space-time where a different event would have to have occurred in order to potentially have a causal influence on the event under consideration here.

In order to illustrate what is meant by "causally non-interacting" we can now look at the light cone diagram of two events 'A' and 'B' with indicated space time location of two additional events 'C' and 'X' (Figure 12):

[36] Retrieved 11.1.2009 from Wikimedia: http://upload.wikimedia.org/wikipedia/en/f/fd/Lightcone.png according to the GNU Free Documentation License (http://www.gnu.org/copyleft/fdl.html).

Figure 12: Light cones of two causally non-interacting events 'A' and 'B' with a potential common cause 'C' and a potential effect 'X' of event 'B'



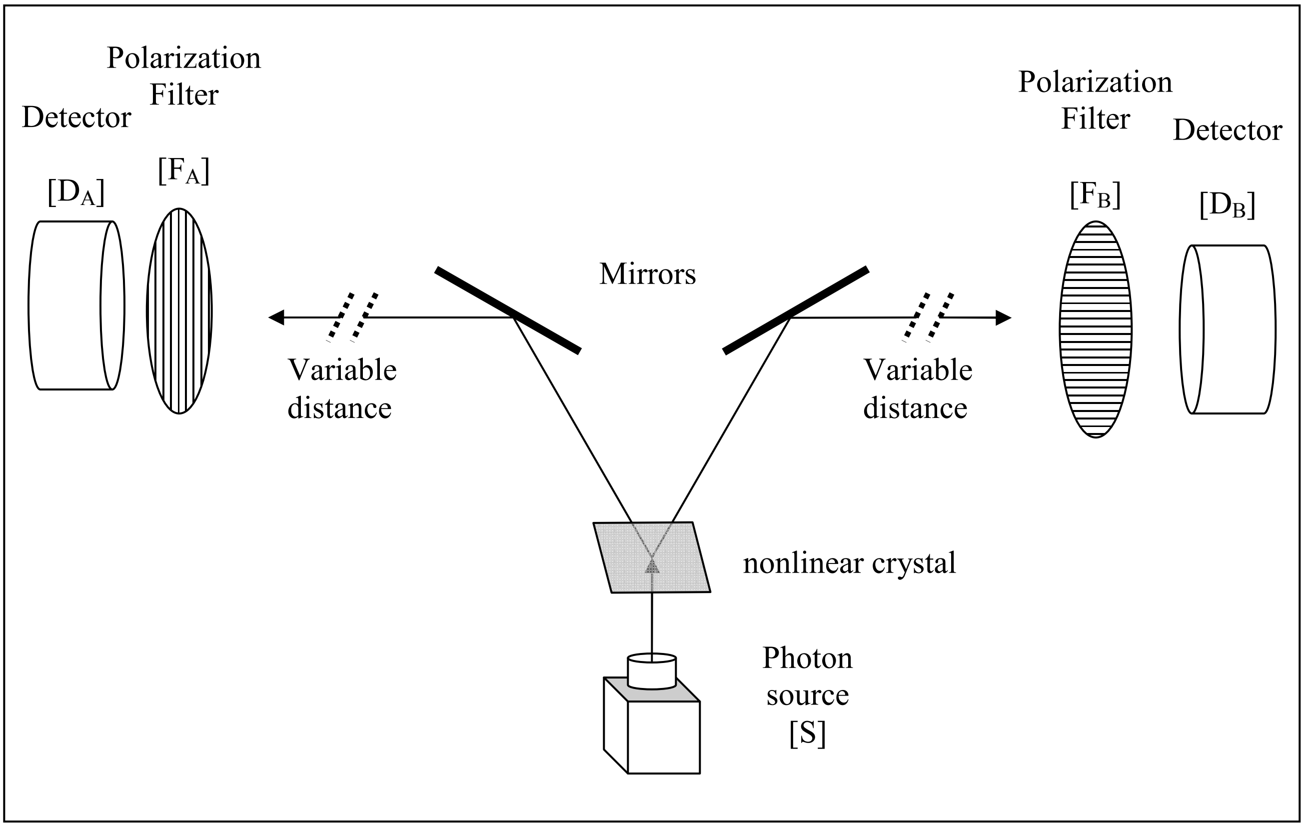
Since the event 'X' is within the future light cone of 'B', there could be a causal influence of 'B' on 'X'. In contrast, since events 'A' and 'B' are not in each other's light cones, there can be no causal influence of one onto the other. We will therefore call such events causally non-interacting. There is, however, the possibility that both events under consideration are actually effects of a common cause 'C' which lies in the intersection of both past light cones. As we will see, this possibility can not be completely excluded for entangled events but it can be shown that if entanglement is due to such a common cause, this common cause would have to determine all other events in the universe as well.

2.3.1 The EPR-type experiments

For illustration let us consider the following idealized experiment (Figure 13). This type of experimental setup is the one of the most frequently used nowadays in order to produce and investigate non-local correlations. Making use of the initials of the scientists involved in its initial conception, it is commonly called the EPR-B-type.[37]

[37] It is analogous to a setup which was proposed by David **B**ohm (Bohm, 1951, p. 614-619) in response to a thought experiment by Albert **E**instein, Boris **P**odolsky and Nathan **R**osen (Einstein et al., 1935) who, ironically, proposed this thought experiment in order to show that its implications were so obviously contrary to common sense that it proved the incompleteness of quantum theory.

Figure 13: EPR-B type experimental setup for the production and investigation of polarization-entangled photons



A nonlinear crystal splits an incoming photon into a pair of photons (each having half the frequency of the incoming photon), which are refracted into different directions. This process is called "spontaneous parametric down-conversion" (for detail see e.g. Kwiat et al., 1995b). "Spontaneous" denotes that it is a probabilistic process where the photon pairs are created at unpredictable times, and only at relatively rare occasions (in the order of 1 in 1 billion photons emitted from the source). "Parametric" refers to the fact that the state of the crystal is left unchanged in the process, which means that energy, momentum and angular momentum must be conserved.

The resulting photons propagate towards rotatable polarization filters and subsequent detectors. (Whether or not they are reflected by mirrors as in the setup depicted in Figure 13 is not relevant.) By varying the distance between source and detector, one can arrange for either of the photons to be detected before the other one.[38]

Given an appropriate orientation of the crystal relative to the incoming photon, the resulting photons are emitted from the crystal in what is called a state of anti-symmetry, which means that their respective polarization angles are always orthogonal to each other.

[38] Such statements of temporal sequence are of course only meaningful for observers in the same space-time frame of reference as the experimental apparatus as a whole.

This is due to the before mentioned rule of conservation of angular momentum (angular momentum is also called spin): Because the system is causally isolated with respect to spin, no spin can be lost or gained by it. Therefore the total spin of the two refracted photons has to match the spin of the original photon. Since, in this experiment, the spin of the original photon is zero, the spins of the refracted photons have to compensate each other and thus take on opposite values. And since the polarization of a photon depends on its spin, opposite spins give rise to orthogonal polarizations.[39]

In agreement with this requirement we will make the following very important empirical observation:

> Whenever both polarization filters are set to the same angle (it does not matter which), we will for each pair of photons observe opposite behavior of photons A and B. Either photon A passes and photon B does not pass or photon B passes and photon A does not pass. Never will both pass or both be absorbed.[40]

This indicates that there is a correlation between behavior of photon A and photon B. (If photon A and photon B were to behave independently, both would pass their filter with a probability of 0.5 and we would, on average, see both photons of a pair behave the same in a quarter of all cases.) A fact which will become important in the analysis of these observations, is that the same correlations are observed, even if the interactions of Filters F_A and F_B with photon A and B, respectively, take place at exactly the same moment (instantaneously).

2.3.2 How to explain these EPR correlations?

The most widely used explanation is based on an interpretation of the probabilistic behavior of photons as a consequence of indeterminism which means that photons do not actually possess any property which determines their behavior at the polarization filter. They are instead thought to only possess a certain probability of passing or not passing a polarization filter.[41] Now as soon as one of the photons interacts with a filter and randomly 'decides' whether to pass the filter or not, the other photon assumes an

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[39] In addition, due the law of conservation of energy, each of the two resulting photons have exactly double the wavelength of the original photon or, if they have different wavelengths, these average to double the wavelength of the original photon. In this way, the energy of the original photon is entirely conserved in the resulting pair of photons (as mentioned before, the energy of a photon is inversely proportional to its wavelength).

[40] Strictly speaking, this is only true for an idealized version of the experiment. In real experiments, a large part of the photons are never detected because of detector inefficiencies and hardware inaccuracies. This "detection-loophole" problem will be discussed in more detail further down.

[41] This is analogous to the view that a quantum does not actually have a location but only a probability to be detected in a certain location.

orthogonal polarization (or, more correctly speaking, it assumes an inverse probability distribution). In other words, each photon somehow 'knows' which (not previously determined) decision was taken by the other one. The fact that this happens instantaneously indicates that it cannot be a causal mechanism by which the decision of the first photon becomes 'known' to the second one, since all causal processes would take at least some time to propagate from one to the other.[42] Therefore it is postulated that there exist "non-causal" (and in that sense "non-local") correlations between the photons, a phenomenon also called entanglement.

As an alert and critical reader you may now ask why one should hypothesize a mechanism as counterintuitive as non-local entanglement, instead of using the following, more 'down-to-earth' explanation: Maybe the assumption that photons do not actually have a certain polarization before they interact with a polarization filter is simply wrong. Instead one could interpret their probabilistic behavior as the result of some fixed property which is assigned to the photons at their source in a probabilistic way and which determines the outcome of the interaction with the filter. In that case, could it not be that there is a common cause for the behavior of the photons (such as the event 'C' described in Figure 12)? Could it not be that the photons, already in the moment when they split up, somehow take on certain opposite properties which will enable one of them to pass the filter while for the other one making it impossible to do so? To use anthropomorphic language again, could it not be that the photons 'know all along' how each of them is going to behave?
Indeed, for the experimental observation just described, such a mechanism would really be able to provide an explanation. If, for example, in the simplest case, one of the photons were to always have a property enabling it to pass all kinds of filters, while the other photon were always to have a property which makes it be absorbed by the filter, then we would of course always observe opposite behavior.
Such types of explanation are called "realist" interpretations of quantum theory. Realism in this context means that objects (in this case photons) are assumed to possess at all times actual properties independent of any measurement processes and/or interactions with other systems and that these properties determine the outcome of measurements performed on these objects.

In the next paragraphs we will see that a realist explanation can indeed explain the observed correlations but *only* if we allow as an additional assumption that the orientations of the filters and the properties of the photons are not independent but co-determined by a common cause. What would that imply? Given that the filter settings themselves are (or at least could be) dependent on many more factors (last but not least

[42] As mentioned, the fastest possible speed of anything propagating through space is the speed of light in vacuum (usually abbreviated with the letter "c"). Thus, two simultaneous events lie outside of each other's light cones as long as there is any spatial separation between them. (For a diagram of two light cones see figure 12.) In fact, to exclude any causal communication between the two events, these would not even have to happen simultaneously but only within a time-span $t < c/d$ where (d) is the spatial distance between the events.

the experimenter's decisions), this implies a form of absolute determinism which requires that a large number of processes in the universe (if not all), including the decisions of apparently 'free-willed' experimenters, are precisely determined in such a way as to always give rise to the specific pattern of correlations which we observe. (By some, this extreme form of determinism is therefore also sometimes called "conspiracy-determinism" (e.g. Kronz, 1990; Lewis, 2006; Lewis, 2007).) As the only alternative to the concept of a non-causal mechanism we will thus be left with a concept which appears at least as counterintuitive.

2.3.2.1 Bell Inequalities

In order to understand exactly why a simple realist explanation (without "conspiracy-determinism") does not suffice to explain the correlations observed in this type of experiment, we have to expand the experiment to include polarization measurements with the filters oriented not only in parallel but also at different angles. This will result in an experiment where the outcome predicted by such a realist theory differs from the outcome predicted by quantum theory. Inequalities of this type were first pointed out by John Bell (Bell, 1964), which is why they are commonly called "Bell inequalities". The particular set-up which I will describe here, is adapted from a more recently proposed Bell inequality by Mermin (1985a) and Styer (2000).
In this setup, we will perform the experiment in such a way that the polarization filters are rotated independently of each other to three different angles of orientation so that all possible combinations of angles occur equally often. We will call these angles α, β and γ, and assign the values $\alpha=0°$, $\beta=120°$ and $\gamma=240°$. (The reason why we choose precisely these values will become clear as we proceed.)

Let us start by considering what kind of behavior of the photons we would expect, if they were to obey a realist mechanism: First of all we can note that no matter how complicated a version of realist mechanism we assume, it will ultimately amount to the fact that each photon carries with it one or more variables which will 'instruct' its behavior at the filter. Let us call the hypothetical variable(s) instructing a photon to pass a filter with orientation α the 'instruction' [α+], and conversely the variable(s) instructing the photon not to pass a filter with orientation α the 'instruction' [α-].

Assuming that the photons cannot, anthropomorphically speaking, 'know' which filter to expect (and vice versa), they have to carry instructions for all possible filter orientations. That means for *all* possible filter orientations the 'behavior' of the photon *has* to be defined. With regard to the possible filter orientations chosen in the setup, a photon

could, for example, carry the 'instruction set' [α+ β+ γ–], meaning it would pass a filter oriented at 0° and 120° but not one oriented at 240°.[43]
Please note that we have just introduced an assumption, namely that photons and filters do not 'know' of each other. More technically speaking, we assume that the instruction sets of the photons do not influence the filter orientation and vice versa; that they are in this sense independent of each other. Let us hence call this the 'independence-assumption'. Let us hence call this the "independence-assumption". It is often linked to the "locality-assumption", because in order to definitely exclude the possibility that the photons and the filters could influence each other, we need to be able to causally separate them. This is only possible if we assume locality (or, as Einstein (1948) called it, the Principle of Local Action). This principle states that physical influences can travel only at speeds less or equal to the speed of light, which secures that each event can only be influenced by events in its own past light cone. We are therefore now presuming not only a realistic but a local-realistic mechanism. This is common to all versions of Bell inequalities. (The independence-assumption will become important later on, when we discuss possible loopholes of this Bell inequality. As we will see then, satisfying the locality-assumption is not necessarily enough to satisfy the independence-assumption.)

It is clear that irrespective of the kind of local-realist mechanism we assume, it will have to be in agreement with the empirical observation we have already made, namely that if both filters are oriented at the same angle, the entangled photons will always behave in opposite ways. Therefore, clearly, we have to assign to each of such a pair of photons the opposite instruction set. For example, if photon A were to carry the hypothetical instruction set [α+ β+ γ–] then photon B must carry [α– β– γ+].

Suppose now, for example, that this pair of photons encounters filter F_A set to angle β and F_B set to angle γ. In this case, photon A will pass (it has β+) and so will photon B (it has γ+). If this same pair of photons were instead to encounter filter F_A set to α and F_B set to β, photon A will pass (it has α+) and photon B will not (it has γ–). We can in this way draw up a list of all possible outcomes for this pair of photons, depending on the different possible settings of the polarization filters (Table 1):

[43] In fact, given that we could theoretically also rotate the filters to any other orientation, the photons actually have to carry an instruction for all other possible angles, too. Limiting our considerations to only the three chosen angles is sufficient, however, for the purpose of the argument of the Bell inequality.

Table 1: Possible outcomes for a pair of photons where photon A carries the instruction set [α+ β+ γ–] and photon B carries the instruction set [α– β– γ+]. ("+" stands for "passes", "-" stands for "does not pass")

Filter setting F_A	Filter setting F_B	Photon A	Photon B	Photons A and B behave differently
α	α	+	-	yes
β	β	+	-	yes
γ	γ	-	+	yes
α	β	+	-	yes
α	γ	+	+	no
β	α	+	-	yes
β	γ	+	+	no
γ	α	-	-	no
γ	β	-	-	no

As we can see from table 1, there are 9 possible filter settings. In 5 of those, the photons behave differently, one passing and the other one not. Since, as mentioned above, all filter orientations occur equally often the predicted ratio of photons A and B behaving differently would thus be 5/9 if the photons were always equipped with the instruction set [α+ β+ γ–] and [α– β– γ+], respectively.

Drawing analogous tables for all other possible instruction sets (this list of tables is given in Appendix 1) we find this ratio to be the same for all instruction sets, except for the instruction sets [α+ β+ γ+] and [α– β– γ–], where naturally the photons behave differently for all possible combinations of filter orientations. This finding is summarized in Table 2:

Table 2: Ratio of photon pairs where photons A and B behave differently, calculated for all possible combinations of instruction sets

Instruction set for Photon A	Instruction set for Photon B	Ratio of photon pairs where photon A and B behave differently
[α+ β+ γ+]	[α– β– γ–]	1
[α– β– γ–]	[α+ β+ γ+]	1
[α– β– γ+]	[α+ β+ γ–]	5/9
[α+ β+ γ–]	[α– β– γ+]	5/9
[α– β+ γ+]	[α+ β– γ–]	5/9
[α+ β– γ–]	[α– β+ γ+]	5/9
[α– β+ γ–]	[α+ β– γ+]	5/9
[α+ β– γ+]	[α– β+ γ–]	5/9

We can thus predict that the overall ratio of photons B and A of one pair behaving differently ***has to be somewhere between 5/9 and 1***, depending on the mix of instruction-sets the photons in our experiment are equipped with. (For example, if the source were to produce only pairs of [α+ β+ γ+] and [α– β– γ–], all pairs (a ratio of 1) would always behave differently. If, however, the source were only to produce pairs of [α+ β– γ–] and [α– β+ γ+], then the photons of these pairs would behave differently in 5/9 of all filter combinations. A balanced mix of only these two types of pairs would result in a ratio of 7/9 of pairs behaving differently.)

Quantum theory, on the other hand, predicts a different ratio: for the filter orientations 0°, 120° and 240°, photon A and B should behave differently ***only in half of all*** photon pairs.

This prediction is derived from the following considerations: According to quantum theory, the first photon, in the moment when it interacts with a filter, has a 50% chance (p=0.5) of assuming a polarization parallel to the filter, and subsequently pass, and a 50% chance (p=0.5) of assuming a polarization orthogonal to the filter and subsequently be absorbed. Since both photons of a pair are subject to a collective conservation law, the second photon then *instantaneously* assumes a polarization orthogonal to that of the first photon, even though it has not itself interacted with any filter yet. When the second photon then, too, interacts with a filter, its chances of passing are therefore given by the already-mentioned formula $p= \cos^2(\delta)$ where δ is the angle by which the filter differs from the photon's assumed polarization.[44] The probability that it will not pass the filter is thus $p=1- \cos^2(\delta)$ which is mathematically equivalent to $p=\sin^2(\delta)$.

Thus, given that one of the photons passes a filter at 0°, the probabilities that the other photon does not pass are as follows:

For a filter at 120° it is $\sin^2(120) =0.75$,
for a filter at 240° it is $\sin^2(240) =0.75$
and for a filter at 0° it is $\sin^2(0) =0$.

Since each of these angles occur a third of the time, the overall probability of the photons of one pair to behave differently is therefore

$1/3 * 0 + 1/3 * 0.75 + 1/3 * 0.75 = 0.5$.

Quantum theoretical predictions therefore clearly differ from predictions based on the assumptions of local-realist theories, which means we have arrived at a Bell inequality

[44] Basically here the behavior of the photon A at F_A depends on the behavior the photon B at F_B in an analogue way as in the earlier described experiment the behavior of a photon at F_2 depended on its earlier behavior at F_1.

which presents us with a way of experimentally differentiating between local-realist and non-local indeterministic theories.[45]

The first experimental tests of Bell inequalities (Freedman and Clauser, 1972) and many experiments after that (e.g. Aspect et al., 1982; Shih and Alley, 1988; Ou and Mandel, 1988; Kiess et al., 1993) have clearly confirmed the predictions of quantum theory and thus disproved the predictions based on local-realist assumptions. Regarding the setup described here, indeed, only half of all detected pairs of photons will ever be found to behave differently.

The logical conclusion one would have to draw from the violation of local realism is that either locality or realism or both cannot be true, at least not for quanta.

There are, however, two so-called "loopholes" to this argument, which we have to consider before accepting either of these conclusions.

Loopholes for a local-realist interpretation of EPR-correlations

The first loophole is called the "detection loophole": Unlike the idealized experiment I have presented here, 'real world' experiments conducted with photons, up to now, suffer from the fact that by far not all pairs of photons which are emitted by the source will actually be detected. A large percentage gets lost in the experimental apparatus or does not get registered at the detector. Under these conditions it is possible to think of a scenario where the observed photon behavior can be explained by local realistic mechanisms. (For example, there could be a third instruction (x) 'do not get detected' in addition to (+) 'pass' and (-) 'do not pass'. Depending on the ratio of photons carrying this instruction the observed distribution of results could be explained (Mermin, 1985b)). In order to close the detection loophole, experiments have been conducted which allowed for high enough detection coefficients by using atoms instead of photons (Rowe et al., 2001, Grangier, 2001). These experiments gave essentially the same results, thus closing the detection loophole and vindicating the rejection of local-realist theories.

The second loophole is sometimes called the "locality loophole" and argues that the independence-assumption might actually not be justified in the experiments, because the local isolation of the photons and the measurement apparatus might not be fulfilled. Theoretically, there could be some kind of causal influence of the first photon onto the second one or of the measurement apparatus onto the photons. In that case, the observed

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[45] Now it also becomes clear why we chose the angles 0°, 120° and 240°: These angles result in the largest difference between the quantum theoretical prediction and the local-realist prediction. Other combination of angles would result in probabilities either closer to 5/9 (making it more difficult to distinguish between the predictions experimentally) or even larger than 5/9 (in which case the predictions no longer differ, i.e. the inequality would be lost). The important thing here are not the absolute angles, but the difference of 120° between them: 1°, 121° and 241° would obviously give the same result.

correlation between the photons could also be explained without resorting to non-local mechanisms: for instance, some radiation might be sent from the first photon to the second photon signaling which polarization filter it encountered and if it passed it or not. As mentioned earlier, this possibility can be excluded by arranging the experiment in such a way that the two photons hit their respective polarization filter instantaneously or at least within such a short time interval that it is impossible for any causal signal to propagate from one to the other. But how about the possibility that some kind of signal from the polarization filter causes the photons' instruction-sets to differ depending on what polarization angles they are 'to expect'? In this way, too, the observed photon behavior could be explained with a realist theory. (This is why for formulating the Bell inequality above we had to assume that the assigned instruction sets were independent of filter settings, i.e. they do not 'know' what to 'expect'.) In order to also exclude this possibility, the filter settings could be changed at the last moment before the photon arrives at the filter. In this way it is ensured that a causal signal from filter F_A can reach neither photon B nor filter F_B before those interact. Experiments excluding in such a way the possibility of causal influence between either the quanta or the measurement instruments or both have been carried out (e.g. Aspect et al., 1982; Weihs et al., 1998; Pan et al., 2000), giving analogous results.

Nevertheless, one option for a realist explanation still remains (see e.g. Shimony, 2006): It is theoretically possible that the independence assumption is not justified because both the filter settings and the photons' instruction sets were pre-determined by a common causal event in the past. If it is true that the entire universe shares a common past in the "Big Bang", this is an irrefutable possibility, because no two things can be found which do not share a common past.
Since theoretically the filter settings could be made to depend on a variety of things (for example the current position of a particular star relative to earth), and almost inescapably involve decisions by the experimenters. This option means, however, that a huge number of processes (if not all) in the universe, including supposedly 'free-willed' human decisions, have to be causally predetermined by a common event in exactly such a way as to always (at least up to this point in time) result in exactly the correlations described above. Hence the notion of "conspiracy determinism".

2.3.2.2 Summary

To summarize, the following possible interpretations of the experimentally observed correlations remain (see e.g. Weihs et al., 1998):

1) Since the locality loophole and the detection loophole have so far only been closed in separate experiments but not yet both at the same time in the same experiment, there remains the possibility of a simple realist explanation. This is not regarded as very likely by the majority of physicists, because it would mean that under different experimental

conditions nature would use different loopholes to give rise to exactly the same experimental observations (another kind of conspiracy).
2) Realism is not correct. The behavior of quanta is indetermined. There exist non-local correlations (entanglement) between quanta. In this case the non-locality of the observed correlations has to be equated with their non-causality, meaning that quanta can somehow be connected beyond, or at least independent of, space-time and causality.
3) Realism is correct. Quanta have properties which are independent of interactions and which determine their behavior. These properties are predetermined by a common causal factor ("conspiracy") in such a way that the properties of the photons and the entire measurement apparatus including the experimenters' actions are coordinated ("conspire") precisely so as to lead to the observed correlations.

Assuming that future experiments where both loopholes are closed at the same time will result in the same correlations we are left with the latter two, equally counterintuitive if not bizarre interpretations. Interestingly, in addition to being counterintuitive these not only seem mutually exclusive but also to some extent seem to require each other and might possibly be best regarded as complementary. We will return to this question of interpretation in chapter 2.4, but for now shall follow Bohr's advice and pragmatically return to the descriptive level: Regardless which interpretation or interpretations we choose, we have to accept that probabilistic events can correlate with each other even if there is no causal interaction taking place between them. This minimal consensus we shall call entanglement.

2.3.2 Properties of entanglement

Let us now explore in some more detail the characteristics of entanglement. First of all: Under what circumstances does it occur? How do particles get entangled? Can we abstract from these experiments a general 'mechanism'?

Generally, as stated by Alain Aspect, the following two conditions must be met, in order for non-local correlations to become discernible in quantum systems (adapted from Aspect, 2002):

> 1) The two separated subsystems must be in an entangled state, non-factorizable, such as the symmetric or antisymmetric state for two spin $^1/_2$ particles such as photons.
>
> 2) For each subsystem, it must be possible to choose the measured quantity among at least two non-commuting observables.

Let us examine these conditions more closely, starting with the second condition: Why does it demand that the quantities to be measured have to be *non-commuting* observables? As briefly mentioned in chapter 2.1.2, non-commutativity relates to observables which are complementary descriptions of one and the same quantum. Measurements of

complementary observables are thus not independent of each other: The outcome of a measurement of one of them affects the outcome of a subsequent measurement of another. Very simply speaking one could say, non-commuting observables 'have something to do with each other'. In the case of the EPR-experiment described above, the polarization measurements are non-commuting in the sense that the probability of photon B passing filter B differs depending on whether photon A passed filter A or not.
Why does Aspect's second condition demand that the quantities to be measured can be chosen among *two or more* such non-commuting observables? This is because only in these cases can Bell inequalities be applied successfully in order to disprove any local-realistic interpretations of the observed correlations. For the particular inequality described above, three such non-commuting observables were needed.[46] The fact that at least two non-commuting observables are necessary for *distinguishing* the non-local nature of entanglement from classical local-causal correlations does not, however, mean that they are necessary for entanglement to *occur*. What is necessary for entanglement to occur is that the local observables to be measured on the individual quanta are complementary to a global observable, pertaining to the overall system, which these individual quanta are subsystems of (Atmanspacher et al., 2002).

What about Aspect's first condition? At first it sounds like a circular statement: In order to observe entanglement the quanta need to be in an entangled state. But why do the separated subsystems have to be non-factorizable in an entangled state, what does that mean and how do quanta get into such a state? In general, a quantum system must be "prepared" in order to make entanglement visible. This preparation entails that some observable of the overall system has to take on a fixed value. For example the energy or the angular momentum of the original photon before it is split into two photons at the non-linear crystal could be known to have a certain value. In order to make sure the respective value is fixed, one has to ensure that the system is isolated in respect to this observable, for example any interaction with other atoms which could change the angular momentum of the quanta is made impossible. (This is why it is crucial that the nonlinear crystal remains unchanged in the process of splitting the photon into two.) This isolation now means that the overall state of the system with respect to this quality cannot change, for example no energy or angular momentum can be gained or lost. Thus, by invoking the laws of parity and conservation of angular momentum and/or energy for the whole system and at the same time respecting the fact that the states of the individual subsystems (such as the individual photons in the described experiment) are unpredictable, the following situation arises: The overall state of the system is fixed, but the individual states of the subsystems are not knowable. Thus the precise state of the system (before measurement is conducted at any of the subsystems) has to be written as a combination of possible combinations of states. Such a combination of possible combinations of states is called "superposition" in quantum physics. The most frequently

[46] In addition the particular non-commuting observables had to be well chosen, because only particular sets of filter orientations (e.g. 0°, 120° and 240°) lead to the necessary difference between local-realist and non-local indeterministic predictions.

used formalism to describe a superposition is the wave-function. The superposition state to which such a wave-function pertains is then typically called non-factorizable when the factors (possible states of the subsystems) cannot be separated: they mutually depend on each other since they can only occur in certain combinations which match the overall prescribed state.[47]

How can such a superposition state be generated? There are basically three options: One method is to let a particle emit (or decay into) other particles. Conservation rules dictate that the properties of these 'daughter'-particles will be correlated and possibly entangled. Another option is to allow two particles to interact for a length of time. If the interaction depends on the states of both systems, they can become entangled.[48]

Of course, all particles interact with each other in one way or another, which also means that entanglement is not such a rare feature of nature at all. In fact, the challenge for experimental physicists who want to observe entangled particles is to isolate them completely from anything else, in order to avoid that they get entangled with the rest of the universe, because a system where everything is entangled with everything else is indistinguishable from a system where nothing is entangled. Strictly speaking, however,

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[47] For example (adapted from Weinfurter, 2005), two photons can be entangled when they are emitted in quick succession from an excited atom. The only condition is that the photons are emitted such that the initial and the final state of the atom both have zero orbital angular momentum. If the first photon is then, say, horizontally polarized (we can say it has a quantum state $|H\rangle 1$), then the second photon has to be vertically polarized (i.e. have a quantum state $|V\rangle 2$). Similarly, if the first photon is vertically polarized ($|V\rangle 1$) then the second photon will be horizontally polarized ($|H\rangle 2$). Provided that the final state of the atoms is the same in both cases, a "coherent superposition" of the two decay options is obtained and the overall wave-function for the two entangled photons is $|\Psi\rangle=(|H\rangle 1|V\rangle 2)/\sqrt{2}-(|V\rangle 1|H\rangle 2)/\sqrt{2}$. (Here the minus sign reflects the fact that the final state has zero spin and the factor $1/\sqrt{2}$ is needed for normalization of the probabilities to give a total of 1 which means that one of the possible combinations *has* to be observed: since the amplitude of the wave is squared to give the probability, the factor $1/\sqrt{2}$ will result in a probability of $1/2$ for each possible outcome). This state cannot be factorized because this wave-function is not the product of the quantum states of the two photons separately. Instead each of the factors is composed of possible states of both photons. Such a state, that can only be thought of globally, is an entangled state. In contrast, the wave function for two non-entangled photons each of which could either be horizontally or vertically polarized can be written as $|\Psi\rangle=(|H\rangle 1|V\rangle 2)/2+(|V\rangle 1|H\rangle 2)/2+(|H\rangle 1|H\rangle 2)/2+(|V\rangle 1|V\rangle 2)/2$ (here the normalization factor needs to be $1/2$ because there are four terms). This wave function can be factorized like this: $|\Psi\rangle=((|H\rangle 1)/\sqrt{2} + (|V\rangle 1)/\sqrt{2}) \otimes ((|H\rangle 2)/\sqrt{2} + (|V\rangle 2)/\sqrt{2})$. As can be seen, in this case the original wavefunction can be factorized into terms which contain only quantum states of one of the photons each (see e.g. Williams and Clearwater, 2000, p. 158-162). An illustration of non-factorizable states using matrix notation is given e.g. by Kronz (2002).

[48] Erwin Schrödinger, who coined the term 'entanglement' to describe the apparently non-local connection between quantum systems, put it this way (Schrödinger, 1935b):

"When two systems, of which we know the states by their respective representatives, enter into temporary physical interaction due to known forces between them, and when after a time of mutual influence the systems separate again, then they can no longer be described in the same way as before, viz. by endowing each of them with a representative of its own. […] By the interaction the two representatives [the quantum states] have become entangled."

this isolation is not a feature necessary for entanglement to occur but only to be able to observe it and discern it from other (causal) types of correlations.

A third, closely related method to prepare an entangled quantum system is by performing a so-called Bell-measurement: this means performing a measurement on two or more subsystems (i.e. quanta) in such a way that a global observable (e.g. the total angular momentum) is determined while the individual contributions of the subsystems (local observables) remain unidentifiable. As soon as an observable describing the system as a whole is fixed while the subsystems remain indistinguishable with respect to this observable the subsystems become entangled with respect to this observable (see e.g. Eckert et al., 2002).[49]

At this point we can summarize the conditions necessary for the occurrence of entanglement: Firstly the events which are to be entangled need to have at least one degree of freedom, and it must be unpredictable which state they are in at any given time. Secondly the events which are to be entangled need to be subject to a conservation law, that is to say they must be subsystems of a system with a precisely defined and conserved global state.

Additional conditions which may be necessary for observing entanglement and distinguishing it from local (i.e. causal) correlations may be that it involves complementary observables and that it occurs in sufficient isolation. (There may be more of these conditions.)

It is important to make clear that entanglement does not only occur in respect to polarization and is not a special feature of photons and that the EPR-B type experimental setup described above is only one of a number of different possible situations which satisfy the conditions for non-local correlations to be observed. In fact there is a wealth of experiments demonstrating entanglement involving various types of observables, different kinds and numbers of quanta and various ways of entanglement preparation. For an overview see Appendix 2.

Finally there is one more very crucial feature of entanglement correlations which I want to specifically point out here because it will be of importance again when discussing the generalized application of the notion of entanglement: Unlike correlations which result from causal interaction, the correlations which arise due to entanglement *cannot be used to transmit signals*. This means that it is not possible to use entanglement correlations to predictably influence anything or obtain reliable information about anything other than

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[49] This principle is also demonstrated in experiments which have become known as "entanglement swapping": Here one starts off with, for example, two pairs of symmetrically entangled photons (pair A (a1 and a2) and pair B (b1 and b2)). Then a joint polarization measurement is performed on photons a2 and b2. If this measurement gives a result indicating e.g. that a2 and b2 had the same polarization (without specifying which) then a1 and b1 are subsequently also symmetrically entangled, even though they have never causally interacted (see e.g. Pan et al., 1998).

the probabilistic observables of the entangled quanta themselves. For illustration consider two entangled photons which are emitted from a source and then directed in opposite directions towards distant galaxies A and B. These entangled photons would not allow two hypothetical observers in the distant galaxies to exchange information. Instead, the observers would only share information which is generated by the probabilistic outcome of polarization measurements on each of the photons. In other words, if the observer in galaxy A were to find her photon to pass a polarization filter in a given orientation then she could infer from that the exact probability of the other photon in galaxy B passing a polarization filter with a given relative orientation but since she can neither predict nor influence the outcome of the interaction of photon and filter in 'her' galaxy she would not be able to change the distribution of outcomes in the other galaxy. Therefore neither of the observers can infer from their observation any information about the current state (e.g. filter settings or measurement outcomes) of the other galaxy. This limitation of non-local correlations has also been called Eberhard's Principle (after Eberhard, 1978).

What could be the reason underlying this limitation which nature apparently imposes on non-causal correlations? One possible answer is that if non-causal signal transmission were possible, it would seriously disrupt the continuity of space-time and causality. What is meant by that, can be illustrated more easily with arguments relating to temporal than to spatial continuity: since instantaneous signaling across space means signaling outside of the light cone, it is equivalent to signaling across time (see e.g. Fitzgerald, 1971; 1974; Bell, 1990). It would thus imply, for example, the possibility to change things in the past (see e.g. Eberhard, 1978), which could lead to the so-called "time-traveler's paradoxes", like for example preventing ones own birth and hence not existing, hence not being able to prevent ones birth, hence existing and thus preventing oneself to be born etc.. Apart from creating grave grammatical problems (see e.g. Adams, 2002, p. 213f), these disruptions of space-time continuity would violate Relativity Theory, which could be one of the reasons why Einstein objected to the idea of entanglement until his death. Since quantum entanglement has been found unsuitable for signal transmission, however, it does not result in the possibility of "time-travelers paradoxes" and does not conflict with Relativity Theory in that respect.[50]

[50] Nevertheless, since quantum theoretical principles do not appear in relativity theory and vice versa, the question remains open if and how quantum theory and relativity theory can be united into a coherent framework. This particular question will be briefly discussed again in chapter 3.4.1.

2.4 Probability and the "interpretation problem"

As we have seen in the previous chapters the concept of probability plays a central role in the description of quantum physical processes.

Firstly, in the case of the wave-particle complementarity, the wave-nature of a quantum is often thought of as a probability wave, where the square of the amplitude of the wave at a certain space-time coordinate represents the probability of observing the quantum in its particle-nature at that specific coordinate when the conditions are suitably arranged for its detection (Zeilinger et al., 2005).
In the case of the double slit experiment, for example, the spherical wave radiated from the photon source represents the equal probability of observing the photon at any point of its surface. When the wave reaches the photographic plate, the photochemical reaction will, however, only occur in one localized place out of all the equally probable places. When this procedure is repeated a large number of times, then a pattern will emerge. This pattern can most adequately be described mathematically by probabilistic equations. Therefore, the way the exact place is 'chosen' from all the possible places, is thought of as a probabilistic process.

A second example of probability was already mentioned in the context of polarization (see chapter 2.2): What we see when we statistically analyze large numbers of interactions between individual photons and a polarization filter, is a distribution of results that can most adequately be described in terms of a binomial (i.e. binary) probability distribution. Therefore standard quantum theory assigns to the photon before this interaction no "real" properties related to its behavior at the polarization filter, but rather only a certain distribution of probabilities for all possible outcomes.

But what does 'probability' actually mean? Reduced to its essence, the concept of probability describes situations where *individual* events *cannot* be predicted with certainty but *averages* over large numbers of events *can* be predicted, whereby the accuracy of the prediction increases with the number of events. This clearly seems to be the case for quantum observables: We cannot predict with certainty which outcome will be observed in any particular measurement. We can only assign different probabilities to different outcomes, and with increasing numbers of measurements we can with increasing accuracy predict the frequency distribution for different outcomes.

While there is little disagreement regarding this descriptive definition of probability, there are different ways in which to interpret it. The main difference between these interpretations lies in the assumed reason for the unpredictability. Basically one can interpret the unpredictability either as the result of an 'actually' indetermined event ('actually' meaning in this context that there *is* absolutely nothing that determines it) or as the consequence of a lack of knowledge about the factors which 'actually' determine the event.[51]

In the current quantum physical discourse, the probabilistic distribution of possible outcomes of particular quantum-events is often interpreted to mean that the outcome of each individual event is to some degree 'actually' indetermined in the above sense (e.g. Zeilinger, 2005). That is to say that nothing which happened in the universe prior to the event has enough influence on the event to determine its outcome exactly. Thus, the outcome of a quantum interaction does not usually depend entirely on prior conditions; instead there is usually a degree of freedom. That of course also implies that the outcome of such an event can not be predicted, not even in principle.

One can, however, also follow an alternative interpretation of probability in general and of probabilistic quantum events in particular: As already discussed in the chapters on entanglement it seems as though we cannot rule out the possibility that by a thus far unknown mechanism all individual events under consideration are precisely pre-determined ("conspiratively") in such a way that they appear probabilistic to us. In that case any unpredictability is 'only' due to a lack of knowledge about the determining variables.[52]

As we have seen there seems to be no way to distinguish experimentally between these interpretations, not even based on Bell inequalities. This has to do with the fact that for applying Bell inequalities one needs to assume locality in addition to realism but in the case of an absolutely deterministic universe, locality can no longer be assumed a priori. The existence of two contrasting and equally valid interpretations of the probabilistic nature of quantum events has been noted by many authors, including Bell himself. (See e.g. Peres and Zurek, 1982; Bell, 1985; 1987 p. 154; Laloë, 2001; Zeilinger in Zajonc and Houshmand, 2004 p.43;Daumer et al., 2006; Lewis, 2006; Lewis, 2007.)

Nevertheless, as mentioned, the currently most widespread interpretation is the one implying indeterminism while the deterministic interpretation ("conspiracy theory") is often dismissed at first sight if not ignored altogether.[53] This has probably primarily to do with the following implications of "conspiracy determinism": Firstly, it appears to violate

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[51] These different interpretations are also often referred to as ontic or ontological (from the Greek *on* (gen. *ontos*) "being") and epistemic or epistemological (from Greek *episteme* "knowledge"). Sometimes, however, these terms are also used differently, referring to any deterministic interpretations as ontic. In this sense, no such thing as ontic indeterminism can exist. In order to avoid potential misunderstandings, I thus chose to use more colloquial expressions here.

[52] That this is in principle possible can for example be illustrated by the fact that by using certain algorithms and seed numbers one can produce sequences of binary events which are absolutely unpredictable and indistinguishable from the sequences produced by binary quantum events such as passing or not passing a polarization filter (a method used in so-called Pseudo-Random Number Generators). These pseudo-random sequences are, however, entirely pre-determined by the algorithm and the seed-number. If these are known, the sequence is absolutely predictable.

[53] See for example the review by Zeilinger et al., 2005.

human experience of free will, because it implies that the physical properties of quanta and the experimenter's decision of how to measure them must be determined by a common cause. Secondly, it requires additional assumptions, such as either the possibility of structures as simple as quanta to carry or receive large amounts of information by which their behavior is determined (theoretically so large as to potentially correlate with the behavior of all other quanta in existence) or some other mechanism(s) that leads to the precise orchestration of very diverse types of events such as e.g. experimenter actions, open or closed slits, angles of polarization filters and the location of photons.

I think it is important to keep in mind, however, that even if indeterminism may be intuitively more appealing to the majority of scientists at present, it, too, is not free of problematic implications: Firstly, it, too, violates an element of human experience, namely that of meaning and purposiveness: how can life in a universe ruled by mere randomness be meaningful? Secondly, it also requires some counterintuitive assumptions, for example that individual events occur in a particular way entirely without cause, that is to say spontaneously and in total independence of anything else, in other words 'out of nothing', and that these absolutely spontaneous events are nevertheless precisely determined collectively and can correlate with each other even if they are causally separated in space and time.

Preferring one interpretation over the other can in my opinion not be rationally justified because both have comparable advantages and disadvantages with respect to simplicity and plausibility and there seems to be no way of ever experimentally distinguishing between them. On the contrary, it is not even *theoretically* possible to completely isolate the concepts of absolute determinism and absolute indeterminism without getting caught up in contradictions. For, on the one hand, when we interpret probability as indeterminacy of individual events we have to, at the same time, recognize that the collective behavior, i.e. the average over a large number of individual events asymptotically approaches a distribution which is precisely determined and predictable. On the other hand, absolute determinism actually implies an element of arbitrariness because it leaves open the question as to what determined the universe in such a way that quanta exhibit the observed probabilistic behavior instead of any other behavior.

It may be of help at this point to recall once more Bohr's admonition that physics and rationality serve well the development of more and more precise descriptions of reality, but have to fail when interpreting those descriptions so as to yield unambiguous statements about the true ultimate nature of reality. In fact, all descriptions of that reality have to remain complementary, i.e. mutually contradictory. To my eyes, it seems that the most adequate characterization of determinism and indeterminism may actually also be in terms of complementary notions because they are, albeit mutually exclusive, defined by each other and collectively required to adequately describe probabilistic behavior: After all, probabilistic events are characterized by individual unpredictability (≈ indeterminacy) paired with collective predictability (≈ determinacy).[54]

What is more, the difference between the interpretations of unpredictability in terms of either 'lack of knowledge' or 'actual indeterminism' is likely not to be an ultimately substantial one: While for some purposes it is undoubtedly useful to draw a distinction between them, these categories actually converge regarding their effect, if the hypothetically deterministic properties of quanta are *in principle* unknowable. And indeed, this could well be the case: In order to make a prediction about the outcome of a quantum event, e.g. the interaction of a photon with (a quantum in) a polarization filter, we would have to know the exact state of all the quanta involved. But this is not possible: To find out their exact state, we have to make a measurement. Since, however, this measurement outcome itself depends in turn on the (relevant quanta in the) according measurement apparatus as well as the measured quantum, measuring the exact state of any quantum requires exact knowledge about the state of the relevant quanta in the measurement apparatus, which in turn is dependent on exact knowledge of the relevant quanta in another measurement apparatus which allows to measure the state of the first one and so on, leading to an continuous regress which is infinite or finite depending on whether the universe is finite or infinite. For a finite regress, one would have to argue that in order to know the exact variables determining a quantum, it would be necessary to know the precise state of the entire universe which is *in principle* impossible because it would require observing the entire universe without being part of it, i.e. without interacting with it.[55] For an infinite universe the precise state can also never be known because the final measurement can never be conducted. If this argument is correct, then

[54] This is also the case for those approaches which, instead of viewing probabilistic behavior as unobservable (and in that sense non-manifest) properties which only manifest themselves (become observable(s)) in a large number of repetitions of identical events, view them as manifest properties of an identical event which takes place in a large number of mutually unobservable universes. This so-called "many worlds interpretation" was introduced by Hugh Everett (Everett, 1957). In this interpretation, for example, instead of saying that a photon has as its non-manifest property a 50% probability of passing or not passing a given polarization filter one would say that the photon actually has both "passing" and "not passing" as properties but manifests them in two universes which come into existence as a result of the interaction of the photon with the polarization filter and between which absolutely no interaction (i.e. observation) is possible. While such a model may challenge traditionally well established conceptions in physics (such as conservation laws) and philosophy (such as identity) it does seem to provide a logically consistent solution to the Schrödinger equation. Nevertheless, it does not get rid of the question of unpredictability. Rather it only shifts it from the observed event to the observer. The question then changes from, for example, "Why did this particular photon pass the filter instead of being absorbed?" to "Why am I now in the universe with the particle that passed the filter instead of the universe where the particle got absorbed?", or, more precisely, from "Why can I not predict the behavior of the photon?" to "Why can I not predict in which universe I will find myself?". This question again leads to the two alternative interpretations of unpredictability in terms of either indeterminism or determinism which, as outlined, appear complementary.

[55] If the observer of the universe is part of it, then as his observations change him, they change the universe, thus never allowing him to come to a final observation.

even an absolutely deterministic universe is *in principle* unpredictable, at least on the scale of quantum events.[56]

In other words, the observations in quantum physics show that the assumption of predictability ("if one knows the exact present state of the universe one can predict all its future states with certainty")[57] fails either because the second part of the statement is not true (in the case of indeterminism) or because the first part of the statement cannot be fulfilled (even in the case of determinism) or both.

[56] Such and similar considerations about a principal limit on the things we can know with certainty independent of the issue of whether they actually exist, have been raised many times throughout history and have been investigated most thoroughly with respect to mathematical formal systems by Kurt Gödel (Gödel, 1931). For attempted proofs of the ontic nature of epistemic limits in general and particularly in quantum physics based on Gödel's considerations, see e.g. Breuer, 1995, Breuer, 1997 and Peres and Zurek, 1982.

[57] The most famous formulation of this assumption is the omniscient intelligence (later to be dubbed 'demon') hypothesized by Pierre Laplace: *"We ought then to consider the present state of the universe as the effect of its previous state and the cause of that which is to follow. An intelligence that, at a given instant, could comprehend all the forces by which nature is animated and the respective situation of all the beings that make it up, if moreover it were vast enough to submit these data to analysis, would encompass in the same formula the movements of the greatest bodies of the universe and those of the lightest atoms. For such an intelligence nothing would be uncertain and the future, like the past, would be open to its eyes."* (Laplace, 1995, p.2)

2.5 Self-referentiality

The characteristics of quantum physics which we have looked at up to now are quite well established in the scientific discourse: Firstly and most importantly the validity of the experimental data is almost unequivocally accepted. Secondly, while there is considerable disagreement about interpretational issues, there is a certain consensus regarding the impossibility to decide between the possible interpretations on purely rational grounds. In this last section I would like to introduce a notion that has up to now not been explicitly discussed very much in the context of quantum physics but may turn out to be relevant and helpful for a deep and coherent understanding of the seemingly strange findings in the quantum realm. It seems to me that the concept of self-referentiality could be seen as a central theme underlying both complementarity and non-locality.

A central characteristic of pairs of complementary notions is that even though they are mutually exclusive each of them considered on its own is not definable but requires the other one for its definition or even its very existence.[58] With regard to the wave/particle complementarity this becomes apparent in the fact that one cannot define a continuum without discrete points and discrete points can only be defined in relation to a continuum. As Carl Friedrich von Weizsäcker noted *"[space-time description and causal description] condition each other mutually in the sense that the space-time description is needed for the description of observations on the basis of which the Schrödinger [wave] function can be set up in each given situation and the Schrödinger function is needed to make the best possible predictions of classical measurement results."* (quoted in Jammer, 1974, p.103).

Descriptions that use such pairs of notions which require each other for definition, are called self-referential because they refer to nothing but themselves and cannot be defined other than in relation to themselves.

Whenever such self-referential notions are used to describe a situation, the resulting description depends on the sequence in which the complementary notions of the description are applied, because the partial description obtained by one of them defines the outcome of the partial description by the other. (Consider, for example, Heisenberg's uncertainty relation: a precise description of the location of a photon makes it impossible to precisely describe its impulse.) As mentioned earlier, in a situation where the end product of a number of interaction events depends on the sequence of these events, one speaks of non-commuting events. In mathematical language this is expressed e.g. as $AB \neq BA$.

This appears to be the case for the descriptions based on the mathematical formulation of the wave function which indicates that it, too, is in essence self-referential, because its

[58] In fact, as mentioned before, a pure point-like particle or a pure sine wave may not even exist because such a state would contain an infinite amount of energy (Popp, 1984, p. 145).

components are defined by each other. This self-referentiality is the reason why the components of this equation do not commute, making it necessary to represent them in matrices or as non-commuting operators using complex numbers.[59]

Self-referential descriptions can also be applied to non-self-referential objects. But when self-referential descriptions are inevitable, this indicates that the object of the description is self-referential. The seeming inevitability of complementarity in quantum physics, therefore, may point to self-referentiality as a feature of the nature of quanta and thus of (at least a part of) reality in general. If this is true, reality can never be adequately described by any finite number of non-self-referential descriptions, but only by self-referential descriptions.[60]

As we have seen, entanglement also seems to allow for (or rather require) complementary interpretations which could serve as a further indication for the self-referential nature of (quantum) reality. In fact, one aspect that is common to both interpretations of entanglement is that they point to self-referentiality in physical reality: Either by requiring violation of the locality principle or by rendering it meaningless, they indicate that some (if not all) parts of reality cannot be isolated from or regarded independent of some (if not all) other parts.[61]

Another indication for self-referentiality in quantum theory is that the answers one gets by way of Bell inequalities depend directly on the assumptions which inform our questions: if we assume independence of photon properties and measurement apparatus (that is to say 'locality') the experimental observations will require us to reject realism and instead accept indeterminism which is the basis for making the locality assumption in the first place (namely by allowing us to assume that some processes (including the free will of the experimenter) can be completely unrelated to other physical processes in the universe). If, however, we start with the assumption of absolute ('conspiracy'-type) determinism, then the experimental observations confirm this and likely lead us to reject

[59] In the latter case, the imaginary part of complex numbers is representative of the fact that the state of the quantum as described in the wave-function is not 'manifest' in the sense that it can only be considered in probabilistic terms (sometimes called a statistical superposition of defined states).

[60] Bohr may have voiced a similar point of view when he proposed an analogy with the dependence of relations of simultaneity upon frames of reference postulated by special relativity theory: *"The theory of relativity reminds us of the subjective [observer dependent] character of all physical phenomena, a character which depends essentially upon the state of motion of the observer"* (Bohr, 1929). It has thus been suggested, e.g. by Henry Krips (Krips, 1999) that Bohr proposed that, like temporal relations in special relativity, properties in quantum physics exhibit a hidden relationalism - "hidden", that is, from a classical point of view. Krips also mentions that Paul Feyerabend gave a clear exposition of this Bohrian position in his "Problems of Microphysics" essay (Feyerabend, 1962) and that it can also be found in commentaries upon Bohr by Vladimir Fock and Philip Frank (Jammer, 1974, section 6.5).

[61] The question whether all or only some quanta can be assumed to be non-locally correlated depends on the conditions necessary for non-local correlations to occur. As we have seen in Chapter 2.3 on entanglement it seems indeed necessary to consider non-local correlations as a direct consequence of the interaction of quanta. If, then, one assumes a big bang singularity scenario for the origin of the universe, one has to expect non-local correlations between all of its parts, i.e. quanta.

the concept of locality as meaningless, a rejection which was actually a precondition for making the assumption of absolute determinism.[62]

This is reminiscent of the well known examples for self-referential sentences where the answer is part of the question, i.e. where there are different possible answers which confirm themselves, only one of which can be true at any time. As an example, consider the following self-referential statement (quoted from Small, 2006):

> *5 divided by the number of characters in this sentence plus the answer output as a fraction is*

We find that there are two possible answers which are consistent with the way the question is formulated. (Character count includes spaces.)
We can either complete the statement with 99, in which case we get this fully consistent statement:

> *5 divided by the number of characters in this sentence plus the answer output as a fraction is 5/99*

We can, however, also complete the statement with 100, in which case we get a different, but again fully consistent statement:

> *5 divided by the number of characters in this sentence plus the answer output as a fraction is 5/100*

Having chosen one way to complete the sentence the other possibility immediately becomes invalid, and from that moment on the only correct answer is the one we selected. This is also reminiscent of the description of quanta in the wave-function as a superposition of a number of potential states only one of which can be actualized. Once it is actualized, all other, previously possible states, become impossible. The two completed sentences above form analogous potential states of the statement and completing the sentence forces the choice of one of them.[63]

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[62] As Richard Gill notes (Gill, 2002): *"I find it fascinating that in order to prove that quantum mechanics is intrinsically probabilistic (the outcomes cannot be traced back to variation in initial conditions) we must assume that we can ourselves generate randomness. And in order to demonstrate the kind of non-separability implied by entanglement, we have to assume control and separation of the physical systems which we use in our experiments."*

[63] We can end this mind-boggling quantum theoretical chapter on a light note since self-referentiality can be entertaining without stopping to be mind-boggling. To illustrate this I will give a few examples of self-referentiality: This sentence is the first example of self-referentiality. This sentence claims not to be an example of self-referentiality while it actually is. The sentence word order of mixed up this is. This is the last sentence of this chapter. The previous sentence is not an example of self-referentiality since it is obviously not true. But is this?

3. Some Aspects of Generalized Quantum Theory (GQT)

3.1 Introduction

We can now approach the central subject of this thesis: the claim that some or all of the principles found in quantum mechanics are applicable also to large (macroscopic) objects and thus potentially to the subjects of our everyday experience. This claim I am going to call Generalized Quantum Theory (GQT).[64]

This is not an entirely new hypothesis, already some of the founding fathers of quantum theory held the idea that some of the principles of quantum mechanics were of fundamental relevance to *all* aspects of reality (see e.g. Jordan, 1947; Pauli, 1955; Heisenberg, 1958; Laurikainen and Park, 1989; van Erkelens, 1991; Pietschmann, 1995; Bohr, 1999). Since then, a number of authors have taken up this idea or formulated similar concepts, models and theories, as we will see in the following chapters. What I call GQT here, is the general underlying notion that certain principles, in particular probability, observables, complementarity and entanglement, can be applied not only to what are traditionally called quantum systems but to systems in general.[65]

Why should this be the case? The principles of quantum mechanics could be of general relevance in two ways or a combination thereof: firstly, because fundamentally all matter is composed of quanta, and/or secondly, because the principles found in quantum systems are actually more general principles which are at work both in quantum mechanical systems in the strict sense as well as in other systems.

While the difference between these options may ultimately turn out not to be substantial, let us adopt this distinction for now in order to make transparent that in the following I will consider both possibilities:

On the one hand some characteristics of quanta in the strict sense should extend into mesoscopic and macroscopic systems, simply because the latter are composed of the former. This I shall call the reductionistic aspect of GQT. Much has been written about this aspect in the context of efforts to define border-conditions which divide reality into the ‘strange’ quantum realm and ‘normal’, ‘classical’ macroscopic reality (e.g. Bell, 1973; Joos, 2003; Ball, 2008).

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[64] A remark may be in order here, regarding the use of the word “theory”. Essentially, in science it can be used for any plausible general principle or body of principles offered to explain a phenomenon (see e.g. “Theory in Science” in: Merriam-Webster Dictionary, www.merriam-webster.com). By convention, however, it is usually reserved for explanations which are well supported by evidence or considered plausible by a large number of scientists. By using the word here, I do not mean to suggest a premature assessment of the presented hypotheses in this regard. Rather, since the object of the proposed generalization is already called “Quantum *Theory*”, the use of that term was unavoidable.

[65] In this sense the acronym GQT could also stand for the collective of Generalized Quantum Theor*ies*.

On the other hand it is possible that systems both in the quantum realm and the world at large are subject to a set of fundamental systems-inherent principles and in that sense the observations made on subatomic quanta are only one particular case in which these general principles manifest themselves. This latter assertion I shall call the system theoretical aspect of GQT. Up to now only relatively few authors have dealt with this aspect (e.g. von Lucadou, 1991a; 1995; Primas, 1996; Atmanspacher et al., 2002; Milgrom, 2002; Primas, 2003; Hyland, 2004; Gernert, 2005; von Stillfried and Walach, 2006b; von Lucadou et al., 2007; von Stillfried, 2008b).

I use the term system theory[66] for a theoretical framework built upon the assumption that one can describe certain mechanisms and principles according to which systems behave, irrespective of the particular nature of the systems' components.
Although this way of thinking can be traced back much further, Ludwig von Bertalanffy is usually identified as its earliest exponent relevant for modern science. In his formulation of a "General System Theory" (von Bertalanffy, 1949; 1950; 1951) he states that some of the patterns which are discovered and described in different areas of science (e.g. physics, chemistry, biology, psychology, sociology) are so similar to each other that one can formulate common principles which describe processes in several or all of these areas. (This is sometimes also expressed as "scale invariance" of system theoretical principles, a view which has contributed to the development of fractal and holographic models of reality.)
One classic example of such an "isomorphy" (von Bertalanffy's terminology (von Bertalanffy, 1968, e.g. p.48)) are the oscillations caused by principle or positive and negative feedback cycles in systems as diverse as chemical reactions (e.g. Lee et al., 1993; Stange et al., 1998), predator-prey populations (e.g. Briggs et al., 1999; Murdoch et al., 2002; Dambacher et al., 2003), hormonal regulation (e.g. Sherman and Korenman, 1975; Karsch et al., 1977), neuronal activity (e.g. Delcomyn, 1980; Aronson et al., 1994; Galuske et al., 2002), political trends (e.g. Drazen, 2000; Rhee, 2000; Steinbruner, 2002) and stock-marked trade (e.g. Benhabib, 1992; Bak et al., 1997; Koutmos, 1997). The common underlying principle is the feedback cycle concept which was first recognized as a broadly applicable principle by Norbert Wiener in his 1948 work on Cybernetics (Wiener, 1961).

As Erwin Laszlo has formulated it, the predominant scientific way differentiates reality into what we can picture as a stack of horizontal layers of complexity, corresponding to the different disciplines (e.g. physics at the base, on top of that chemistry, then biology,

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[66] In this text, I use the term system theory rather than system*s* theory because even though the plural seems to be more widely used, the singular appears to me as the more correct form. As A.H. Louie writes (2009, p. 85): *"["systems theory"] is a solecism that became accepted when it had been repeated often enough, a very example of 'accumulated wrongs become right'. Recall that von Bertalanffy's masterwork is called General System Theory. […] Just think of 'set theory', 'group theory', 'number theory', 'category theory', etc. Of course one studies more than one object in each subject! Indeed, one would say in the possessive 'theory of sets', 'theory of groups', 'theory of numbers', 'theory of categories', ...; one says 'theory of systems' for that matter. But the point is that when the noun of a mathematical object (or indeed any noun) is used as adjective, one does not use the plural form."*

psychology, sociology etc.). System theory then offers an additional way of organizing our knowledge vertically, in terms of universal principles which act at all levels (Laszlo, 1996).

Possibly the most important and difficult task of research in system theory is to identify these universal principles. This requires first and foremost to distinguish them from what may be merely superficial similarities. The methodologies employed in doing so, consist primarily of a continuous investigation of the analogies with asymptotic precision, and a process of generalization and re-specification (see e.g. von Bertalanffy, 1949; 1950; 1968; Luhmann, 1984; Gloy and Bachmann, 2000; Itkonen, 2005; Juthe, 2005). Although a discussion of methodological issues is not intended in this dissertation, we will come back to them at some points in the following chapters.

In the following sections I will explore the generalizability of the notions of complementarity, probability, observables, and entanglement.[67] In some cases this will be more straight-forward than in others.

[67] Generalized self-referentiality will be implicit in these chapters but it does not require treatment in a chapter of its own. This is because the notion of self-referentiality actually does not originate from quantum theory but primarily from mathematics, philosophy and system theory, where its general applicability has already been demonstrated (see e.g. von Bertalanffy, 1968; Varela et al., 1974; Maturana, 1975; Varela, 1975; Rosen, 1978; Luhmann, 1984; Rosen, 1991; Linde, 1994; Gott and Li, 1998; Stange et al., 1998; Kahn et al., 2000; Heller, 2004b; von Lucadou, 2006; Wolkenhauer and Hofmeyr, 2007).

3.2 Generalized probability

Using the reductionistic approach, the generalized applicability of the concept of probability as used in quantum physics can be demonstrated in a relatively straightforward way and this has been widely recognized in physics as well as philosophy (e.g. Zeilinger, 2005): Simply because quantum behavior is probabilistic, that is to say unpredictable, the behavior of the whole universe is so, too, at least to a degree.

At first sight, our everyday experience may seem to be in conflict with this statement since macroscopic objects appear to have stable properties which do not change probabilistically from interaction to interaction, in other words they behave predictably. But at a closer look, it becomes clear that macroscopic objects really only have *approximately* predictable properties: Macroscopic objects consist of very large numbers of quanta which interact with each other and usually also with the quanta in their environment (and thus ultimately with the rest of the universe). In the course of these interactions, the state of superposition of all possible observables decays into a mixture of discrete actual observables. This process, called decoherence, happens so fast that macroscopic superposition states are unnoticeable for all practical purposes.[68] (For more detail regarding decoherence see e.g. Arndt et al., 1999; Joos, 2003; Dür and Briegel, 2004; Schlosshauer, 2005; Arndt et al., 2006; Zurek, 2007; Ball, 2008.) Decoherence is still probabilistic in the sense that it is unpredictable which one of all the possible observables will be actualized (e.g. Adler, 2003; von Stillfried, 2008a). This probabilistic behavior of individual quanta, however, 'averages out' over the large number of quanta contained in macroscopic objects and what results is a comparatively predictable collective behavior, or in other words comparatively stable properties.

To be precise though, one can still not speak of absolute predictability but only of asymptotic predictability. There always remains a margin of uncertainty. There is, for example, a certain probability for any macroscopic object to change its location in space for no cause other than the unlikely but possible coincidence of all of the probabilistic quantum events which take place within the object occurring in parallel. More generally speaking, we can say that the behavior of macroscopic systems can be to varying degrees unpredictable but never in principle entirely predictable.

Theoretically, the more quanta are involved in such a system the more infinitesimally small the degree of unpredictability becomes due to decoherence and 'averaging' (which is why we rarely observe macroscopic objects actually measurably changing their location in space without cause).

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[68] For example, if a large molecule could be prepared in a superposition of two positions just 10 ångstroms apart, it would decohere in standard atmospheric conditions within about 10^{-17} seconds because of collisions with the surrounding air molecules (Ball, 2008).

Nevertheless, quantum unpredictability can be of substantial relevance even in macroscopic systems, because a large number of systems which make up our everyday experience are so-called “chaotic systems”. Chaotic systems are characterized by the fact that even immeasurably small variations in initial conditions or at so-called “bifurcation points” can lead to large changes in overall systems behavior (see e.g. Gutzwiller, 1990; Baker and Gollub, 1996). (This concept has become famous as “the butterfly effect”: Theoretically the flap of a butterfly wing in Brazil can trigger (or prevent) a tornado in Texas, because global weather formation is a chaotic process (Lorenz, 1967 and Gleick and Hilborn, 1988). Quantum probability can enter such systems, when the initial conditions are dependent on quantum events and the system is sensitive to changes at this scale (Briggs and Peat, 1992).

What is more, quantum probability can be of macroscopic relevance even in systems which would traditionally not be considered chaotic but rather only amplifying systems. As an example we can consider any macroscopic event triggered by a quantum event such as the described experiments where the state of a macroscopic measurement device changes due to a photon passing or not passing a polarization filter. To make the consequence more dramatic we could consider a hypothetical bomb which is triggered by the measurement device. Here, clearly, a macroscopic event takes place with the same probability and according unpredictability as the quantum event which triggers it.

Having shown that quantum probability can apply to reality in general we also have to generalize the respective caution about interpreting this probability in terms of absolute determinism or absolute indeterminism as we discussed in chapter 2.4: Quantum probability can be understood both in the framework of absolute determinism as well as indeterminism. Therefore generalization of the notion of probability from quantum systems to reality in general does not allow any statements about the ultimate nature of reality being determined or indetermined. What seems plausible to me, however, is to state that independent of which interpretation is chosen quantum events are *in principle* unpredictable (for the reasons explained in chapter 2.4). If this is true, then the generalization of quantum probability implies the *in principle* unpredictability of reality in general.

From a more general, system theoretical perspective we can identify in addition to the *in principle* unpredictability also various degrees of *in practice* unpredictability. This unpredictability is on the one hand due to systems-inherent factors such as a system’s autonomy and the degrees of freedom it possesses. The more different states a system can take on and the more its behavior is independent of external influences (i.e. self regulated) the more its behavior will be unpredictable to an observer. On the other hand the degree of unpredictability depends on the extent to which an observer has knowledge about and/or control over the systems’ internal processes and any external influences affecting the system. ‘*In practice’* here refers to the fact that, in contrast to ‘*in principle*’ unpredictability, the unpredictability may be overcome by more precise or more ingenious measurement and calculation technology and methods. These may, however, be applicable only in controlled conditions, so that certain spontaneous 'real life' events could be regarded as in principle unpredictable, even though they may lose their unpredictability, once investigated under controlled conditions.

A somewhat different but related approach to generalized quantum probability (as well as other generalized features of quantum theory) is being explored by a number of scientists, who show that by applying mathematical frameworks modeled along the lines of quantum theory, some macroscopic systems are better describable than by using classical mathematical models. Examples of such systems include cognitive processes (Aerts et al., 2000; Aerts et al., 2009), in particular probabilistic inference problems (Busemeyer and Trueblood, 2009), lexical processes (Bruza et al., 2009a), judgment and decision making processes (Franco, 2009) and bistable perception processes (Atmanspacher et al., 2004; 2009), as well as economical processes (Cockshott, 2009; Haven, 2009), and others (Aerts et al., 2003). For an overview see Bruza et al. (2008; 2009b). In most of these studies the question about the ontological status of the quantum-like nature of these processes is not explicitly addressed. Furthermore, it is difficult to classify them as reductionist or system theoretical at this point in time, although most authors would probably tend towards the latter.

3.3 Generalized observables

Quite analogous to the notion of probability, the notion of observables can be generalized using both the reductionistic as well as the system theoretical approach.

As mentioned in chapter 2.2, quantum observables arise from the interaction of quanta. Before such an interaction, quanta can only be described as probability distributions of potential values an observable can take on.
Based on reductionistic reasoning, the same is in principle true for all kinds of objects: In order to be able to make a statement about a property of an object, an interaction with the object has to take place. Since this interaction must, on a fundamental level, be composed of quantum interactions, the outcome of the interaction will be to some degree probabilistic.[69] This means that its outcome cannot be predicted and hence a definitive property cannot be assigned to any object independent of its interaction with other objects. It is therefore, in principle, misleading to speak of objects having certain properties independent of their interaction with other objects and in fact it is even misleading to speak of objects as independent entities. By way of decoherence and 'averaging', the probabilistic component may of course asymptotically approach zero for objects involving increasing numbers of interacting quanta and therefore become negligible for all practical purposes. *In principle,* however, the notion of observables remains necessary to adequately speak about reality.

This means that it is impossible not only to locate a definitive split between the probabilistic quantum world and a stable classical world but also between subject and object in general. This has become famous as one aspect of the so-called "measurement problem" and has repeatedly been pointed out in philosophical analysis of quantum mechanics.[70] As, for example, J.S. Bell put it: *"In extremis the subject-object division can be put somewhere at the 'macroscopic' level, where the practical adequacy of classical notions makes the precise location quantitatively unimportant. But although quantum mechanics can account for these classical*

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[69] This applies even to so-called interaction-free measurements, which have been devised using quantum mechanical principles (see e.g. Elitzur and Vaidman, 1993; Kwiat et al., 1995a). Here, too, outcome is probabilistic. What is more, also interaction-free measurements are accompanied by a change of quantum states, even though there is no interaction between the material components of the systems (see Filk and von Müller, 2009, p. 65).

[70] As mentioned in the last chapter 3.2, there is another aspect to the measurement problem which is not addressed by decoherence (Adler, 2003; Schlosshauer, 2005; von Stillfried, 2008a; Zeh, 2009): Decoherence only explains why there is no longer a superposition of all possible states, but rather a mixture of discrete actualized states. What remains unanswered is the question of why *at all* one state (or observable) is 'chosen' out of all the possible states. Whatever answers may be given to this question (see chapter 2.4 on probability), they will in my understanding ultimately require the notion of complementarity: either between the continuous development of a probability distribution (the wave function) and its asymptotically discrete narrowing or between a causally determined continuous development of the universe and its seemingly arbitrary first cause.

features of the macroscopic world as very (very) good approximations, it cannot do more than that. The snake can not completely swallow itself by the tail. This awkward fact remains: the theory is only approximately *unambiguous, only* approximately *self consistent"* (Bell, 1973, p. 687).

In addition, as discussed in the previous chapter, even the smallest probabilistic component can become amplified to macroscopic dimensions in chaotic systems.

Taking a more general system theoretical approach we can see that there are also a number of additional ways in which a somewhat looser 'in practice' notion of observables is applicable to everyday situations:
To perceive anything, there needs to be interaction with the perceived object and this interaction changes both the perceived object (e.g. a thermometer changes the temperature of the water it is supposed to measure, sunlight changes the appearance of objects,[71] etc.) and ourselves. Both are not the same after the interaction, thus the properties we observe cannot be attributed independent of the interaction.

Moving further from the objectively physical to the subjectively experiential domain we can note an even more general relevance of the concept of observables: What we perceive is dependent on who we are and what state we are in; therefore it is ultimately impossible to make statements about reality independent of ourselves. At the same time who we are at each moment is impossible to determine without some kind of interaction or mirroring which closes the circle of mutual dependency. Experimental psychology and embodiment research, among other areas of science, give plenty of illustration of this, for example through experiments which show that our perception of reality is a process of active construction, so that the reality we perceive differs depending on our previous knowledge, our current mood, divers physical factors etc.. Even the same wavelength light is very probably experienced differently by each of us due to differences in neurophysiology. (For an overview see e.g. Lakoff and Johnson, 1999; Weiss and Haber, 1999; Adams and Aizawa, 2008.)

The fact that reality emerges from the interaction of its parts and that no reality can be attributed to anything in isolation has also long been recognized in philosophy, the social sciences and system theory although, instead of "observables", different terminologies were used. The most widespread application of the concept was probably promoted

[71] Since this discussion is often paraphrased as the question "Is the moon there when nobody looks?" (e.g. Mermin, 1985a), a fitting example is the moon: Paraphrasing the argument of this chapter accordingly we would say that the moon exists even when we don't interact with it because it consists of many quanta interacting with each other and their environment. When we want to determine where exactly the moon is, however, we have to enter into some kind of interaction which is to some degree probabilistic and even changes the object we will get to observe: The light from the sun (which facilitates the interaction between the moon and our retina) upon hitting the lunar dust causes it to become charged through the photoelectric effect. The charged dust then repels itself and lifts off the surface of the moon by electrostatic levitation. This manifests itself like an "atmosphere of dust", visible as a thin haze. This was first photographed by the Surveyor program probes in the 1960s. It is thought that the smallest particles are repelled up to kilometers high, and that the particles move in "fountains" as they charge and discharge (Sickafoose et al., 2000; Sickafoose, 2001).

under the heading of "radical constructivism", where in essence tribute is paid to the fact that whatever we are able to say about reality comes from our interaction with it and thus depends on ourselves and the interaction in addition to any reality 'out there'. (see e.g. Piaget, 1967; Watzlawick, 1984; von Glasersfeld, 1990).

3.4 Generalized complementarity

In the following I want to provide arguments for the possibility that the notion of complementarity is applicable well beyond the realms of what we today call quantum physics. Some of these arguments, especially the ones based on reductionistic reasoning, are logically binding to a high degree while others, in particular the more system theoretical ones, can merely point out the plausibility of such a proposal. The latter ones I nevertheless include because of the extraordinary descriptive power and beauty which potentially rests in understanding complementarity as a universal principle.

3.4.1 Proposed examples of generalized complementarity

First of all it may be interesting to know that in addition to the wave-particle duality and the related complementarity of position vs. momentum which I outlined in chapter 2.1, there are a number of other complementary notions in quantum physics.

Energy and time can apparently be regarded as complementary. This refers on the one hand to the well known fact that the description of a wave in terms of its energy (its frequency) and its duration are subject to an uncertainty relation: signals can be classified according to their bandwidth or according to their duration but not both simultaneously (Primas, 2007). The shorter the duration of a wave, the broader its frequency distribution (e.g. Meyer-Abich, 1965; MacKay, 1974). Others refer to a complementarity of the notions of time and energy in an even more general sense (Gustafson and Misra, 1976; Tjøstheim, 1976; Atmanspacher et al., 2002).

Other variables which are considered complementary in quantum physics include angle and action, spins on different (non-orthogonal) axes (Zeilinger, 2003, p. 172; Atmanspacher et al., 2002) and wave number and phase (Busch et al., 2001; Zeilinger, 2003, p. 172; Hilgevoord and Uffink, 2008).

In fact, Anton Zeilinger goes so far as stating that in quantum physics "*it seems to be a fundamental premise that to every physical concept there is another one that is complementarily connected to it*" although he does not exemplify this assertion (Zeilinger, 2003, p. 172, my translation).

The complementarity of quanta may also be of importance for more macroscopic systems simply because all systems are made up of quanta:

I already hinted at a possible complementarity between deterministic and indeterministic descriptions of quantum processes in chapter 2.4. Such a complementarity would by necessity apply to reality in general, given that quantum processes can be amplified to have macroscopic consequences. This has also been suggested by others and brought into relation with a potential complementarity of ontic versus epistemic descriptions of reality (Scheibe, 1973; Primas, 1990; Atmanspacher et al., 2002; Römer, 2006).

A general complementarity between subject and object follows from the generalized notion of observables presented in chapter 3.3: Anything that can be described is the result of an interaction which by necessity is mediated by quanta and to which thus all interacting parts contribute and none of which can be described accurately without an interaction taking place.

In addition to such reductionistic arguments for a generalized applicability of the complementarity principle, there are examples in physics where complementarity seems to be apparent even though it is not directly a consequence of quantum complementarity:

As already mentioned in chapter 2.1 on complementarity, a wave nature has to be attributed to every object in addition to its particle nature according to De Broglie's theory (De Broglie, 1925). For macroscopic objects, admittedly, the wave nature and its probabilistic character are negligible for most practical purposes, firstly because the wavelength is inversely proportional to such an object's (usually) large momentum and secondly because it is very difficult to isolate such objects and thus protect their wave nature from decoherence.[72] Nevertheless, complementarity between wave and particle nature is expected to hold true asymptotically for macroscopic objects and thus theoretical accuracy requires the complementarity principle even for the description of these parts of reality.

Quantum theory and relativity theory could be regarded complementary. At least their mutual exclusivity seems plausible: In relativity theory, objects are entities with well defined boundaries and precise location and momentum while space and time are relative dimensions which change dynamically depending on the frame of reference in which they are measured (e.g. time slows down and space shortens for a fast moving observer relative to a slow moving observer). In quantum theory, conversely, space and time are fixed, absolute dimensions but the 'objects' within it change depending on the frame of reference within which they are described (e.g. a quantum's wave properties are lost when its space-time position is measured). A related duality has been pointed out by John Small (Small, 2006): In quantum theory space-time is fully deterministic and observations on material bodies in space-time have the signature of self-referential computation. In relativity theory, on the other hand, space-time has the signature of self-referential computation and the action of material bodies in space-time is fully deterministic. As Small notes, this duality may have "catastrophic" implications for the current search for a "grand unified theory" combining quantum theory and relativity theory into a non-contradictive self-consistent theoretical framework. Rather, the apparent need for

[72] The most massive objects for which wave nature has been experimentally measured are fluorinated C_{60} ($C_{60}F_{48}$) and modified porphyrin molecules with a plate-like shape ($C_{44}H_{30}N_4$). However, experiments with even more massive objects are underway (e.g. Armour et al., 2002; Marshall et al., 2003).

complementary descriptions may point to the underlying self-referentiality of reality as we can describe it.

The temporal evolution of a system and an information theoretical description of the same system were found to be non-commuting complementary observables (Atmanspacher and Scheingraber, 1987).

Beyond physics, and beyond the natural sciences, there are many pairs of concepts which have been proposed as complementary. These are usually examples of system theoretical 'reasoning by analogy' in the sense that what is proposed is an isomorphy with the situation in quantum physics but not a direct consequence of it. Some of the proposed pairs have had their complementarity backed up formally, others only to a small degree or not at all:

Proposals which have not been subject to extensive formal investigation include first and foremost the ones given by Niels Bohr himself. Bohr was convinced that complementarity is a principle of universal applicability and some of the examples he gave are: definition vs. the usage of terms, clarity vs. truth, love vs. justice (Bohr, cited e.g. by Bernays, 1948), thought vs. emotion (Bohr, 1955, p.159), perception vs. reflection, acting vs. reflecting (Bohr, 1955), physical vs. mental-teleological descriptions of living beings (Bohr, cited by Pais, 1991), different cultures (Bohr, 1963, p. 174-175), intending something vs. being aware that one is intending something (Bohr, 1934, p. 23f) and "the conscious analysis of any concept" vs. "its immediate application" (Bohr, 1934, pp. 23f). An overview and analysis of some of Bohr's examples can be found e.g. in Meyer-Abich, 2004; Pais, 1991; Bernays, 1948 and Bohr, 1999, the latter also providing a comprehensive collection of Bohr's original works relating to the topic of complementarity beyond physics. Unfortunately, in all of his writings Bohr remained rather vague with regard to a definition of complementarity and did not publish any formal analysis of these proposed pairs of words (see e.g. Jammer, 1974).

Other relatively speculative proposals include conscious vs. unconscious processes (Bohr, 1934; Pauli, 1954; Jung, 1969, footnote 130, pp. 229f; Mansfield, 1991; Mansfield and Marvin Spiegelman, 1991), free will vs. causality (Wheeler, 1956), being vs. becoming (Mou, 2001), thinking vs. feeling and intuition vs. sensation (Jung, 1921), male vs. female (Lal, 1966), substantive vs. transitive mental states (James, 1950, chapter 9), bi- or multi-stable states of perception (Plaum, 1992; Kruse and Stadler, 1995; Atmanspacher et al., 2006), therapist vs. client (Kleinberens, 2007), synchronicity (non-causal correlations) vs. causality (Meier et al., 1992, pp. 41f, 57, 176-192), multiple personalities (Jordan, 1947), description vs. interpretation (Lofgren, 1988), science vs. religion (MacKay, 1957; Bedau, 1974; Grinnell, 1986; Reich, 1990b; Derry, 2005; Oliver, 2005), ideal vs. reality, love vs. hate, individual vs. society and connectedness vs. individuality (Walach, 1998), science vs. spirituality (Montalvo, 2004; Walach and Reich, 2005), Christianity vs. Buddhism (De Silva, 1982; Pan-chiu, 2002; Schmidt-Leukel, 2003), divine vs. human nature of Jesus

Christ (Kaiser, 1976; Honner, 1985; Reich, 1990a; Loder and Neidhardt, 1996) and other paradoxes in Christian theology (Bube, 1956).
A relatively large body of literature describes the relationship between subjective consciousness and its quantifiable physiological correlates (or, more generally, mind vs. matter) as complementary (e.g. Edelheit, 1976b; Hoche, 1987; 1990; Velmans, 1991; 1993; Chalmers, 1995b; Velmans, 1995; Primas, 1996; Chalmers, 1997; Walach and Römer, 2000; Velmans, 2002; Atmanspacher, 2003; Nakagomi, 2003; Primas, 2003; Walach, 2005a; Atmanspacher et al., 2006; Atmanspacher and Primas, 2006; Fahrenberg, 2007; Hoche, 2007; Primas, 2009). We will come back to this in chapter 3.4.3.
Other obvious examples might be unity vs. multiplicity, change vs. continuity and substance vs. form. The up to now largest collection of proposals for complementary pairs, to my knowledge, was compiled by Kelso and Engstrøm, 2006. They propose literally hundreds of complementary pairs.

It should be noted that a number of authors, including Lawrence Landau, Hans Primas, Harald Atmanspacher, Hartmann Römer, Harald Walach, Peter beim Graben, Ilki Kim and Günter Mahler, have come to the conclusion that the notion of complementarity can indeed be abstracted from quantum theory without violation of formal logical or mathematical principles (Landau, 1987; Primas, 1996; Kim and Mahler, 2000; Atmanspacher et al., 2002; beim Graben and Atmanspacher, 2006; beim Graben and Atmanspacher, 2009).

The attribution of the word "complementary" to such a large number and wide variety of opposites, however, has not remained unchallenged (see e.g. Alexander, 1956; Feyerabend and McKay, 1958; Barbour and Bailey, 1968; Feyerabend, 1969; Jaki, 1978; Russell, 1988; Sharpe, 1991; Duce, 1996). Critics primarily point out that often either no rigorous enough definition of complementary is used or that the proposed pairs of concepts do not fit such a definition.[73] They warn that the consequently vague handling of the notion of complementarity could prematurely end the search for non-contradictive solutions to apparent paradoxes, and appease conflicts which would lead to progress if they were allowed to be fought out.

These, in my view, are valid concerns that should be kept in mind when working with complementarity and I very strongly support the call for a stringent yet generalizable definition of complementarity. Some elements for such a definition have already been suggested by various authors and I will attempt an initial step towards summarizing them in the next chapter (3.4.2).
I will not in this present study sort through all the above mentioned specific proposals, but I expect that a large proportion of them would fail to meet the criteria for

[73] As S.L. Jaki put it graphically with regard to Bohr: *"Bohr's pairs of complementarity resembled pairs of horns from which one could not even infer unambiguously either that they were rooted in the same head and were thereby truly complementary or that the head itself was real, and even more fundamentally real than the horns themselves"* (Jaki, 1978, p. 205).

complementarity that I will outline. I therefore think that doubts voiced about the adequacy of some of these proposals are justified in a large number of cases.

Others, however, may stand up to more detailed investigation. In fact, a few of the proposed pairs of complementary notions have already had of their apparent isomorphy with the particle/wave complementarity backed up by more or less in depth analysis:

- The applicability of this generalized notion of complementarity to classical dynamical systems has been analyzed in some depth and the description of chaotic systems in terms of Liouville Dynamics and Information Dynamics was found to correspond to a generalized form of complementarity (beim Graben and Atmanspacher, 2006).
- Predictions derived from a model based on the complementarity of elementary cognitive observation processes and the switching process between different representations of a bi-stable stimulus were found to match well with experimental results (Atmanspacher et al., 2004; 2006; 2009).
- Confirmation and novelty have been identified as complementary components of pragmatic information[74] (von Weizsäcker, 1974; Kornwachs and von Lucadou, 1985; Gernert, 2006).
- The relationship between descriptions in terms of structure and function have been shown to correspond very well to complementarity as observed in quantum physics (Pattee, 1988; von Lucadou, 1991a).
- The same can be said for process and substance, based on an analysis by Hartmann Römer (Römer, 2006).
- Gregory Derry gives a relatively detailed analysis of the isomorphy of the relationship between the descriptions of reality given by science and religion and the complementarity between wave and particle (Derry, 2005)

Even though these examples are (to varying degrees) more formally rigorous in asserting complementarity, there nevertheless seems to be no commonly agreed underlying definition of generalized complementarity and no standard procedure for applying such a definition. I consider the development of such a definition of utmost importance for further progress in this field. The completion of this ambitious task is beyond the reach of this dissertation, but I will attempt to outline important elements and possible directions for the formation of a definition of complementarity, and sketch out how it could be applied by analyzing in an exemplary way the relationship between consciousness and matter.

Before doing so, however, I want to mention one further aspect that should not be missing in our assessment of the general applicability of the complementarity principle, namely the fact that strikingly similar theoretical frameworks have been developed or

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[74] Pragmatic Information is a term from information theory which denotes the amount of change that is induced by a signal. It is thus dependent on the context in which it is received. Loosely speaking pragmatic information can be equated with meaning or effect. For example the pragmatic information of a phone call depends on a combination of novelty (i.e. the content is not already known) and confirmation (i.e. the phone call uses a language which the recipient already knows).

discovered again and again throughout history in different disciplines, particularly philosophy and spirituality:

It may be interesting to note in this context that Niels Bohr himself adopted the idea of complementarity from psychology and philosophy, a detail he never publicized himself, possibly in order not to jeopardize the credibility of the concept in the scientific community. Historic studies (Rosenfeld, 1963; Selleri, 1983; Faye, 1991; Plaum, 1992; Faye, 1994) indicate clearly, though, that Bohr got introduced to the use of the word complementarity and the sense in which he later used it in his formulation of quantum theory through the psychologists Edgar Rubin and William James as well as the philosophers Søren Kierkegaard and Harald Høffding. Rubin introduced bi-stable stimuli into psychological research, James first used the term "complementary" to describe the different aspects of personality in patients with multiple personalities (James, 1950, p. 206) and questioned that the object-subject division could be of fundamental nature (James, 1904)). Kierkegaard analyzed prolifically the relationship of "Either-Or" (Danish: "Enten-Eller") (Kierkegaard, 1843). His disciple Harald Høffding, for example wrote: "*In every cognition we can distinguish between a subjective and an objective element, between a knower and the thing known; both terms, however, are only given in mutual relation….we nowhere and at no time possess the pure Subject, with its forms, as an antithesis to a pure object….we really set up an objectively determined Subject (SO) as the reverse of a subjectively determined Object (OS).*" (Høffding, 1905). In addition one could mention Poul Martin Møller, an early nineteenth century writer and philosopher whose novel *Adventures of a Danish Student,* according to Pais (1991), inspired Bohr to his often quoted example of the complementary strategies of two students, one acting and the other one reflecting.

The word "complementarity" may have first been used with this precise meaning by Bohr. Tracing back the origin of the complementarity principle even further, however, it soon becomes clear that the concept of a universal principle which unites opposites without ridding them of their contradiction is no novelty in philosophy, theology and spirituality and may in fact be traced back to the very oldest writings that are available to us today from different cultures. Without being able to go into any adequate detail here I shall at least mention Hegel's "dialectic" (Hegel, 1830), Leibniz's "monads" (Leibniz, 1714; von Stillfried and Walach, 2006a; Walach et al., 2006), de Spinoza's "substance monism with attribute-dualism" (de Spinoza, 1677), Nicholas de Cusa's unification of opposites "coincidentia oppositorum" (de Cusa, 1440; Flasch, 1992), Thomas Aquinas' (1224-1274) "unity of diversity in Christ" (Aquinas, 2002, p. 245-249), Heraclites' (ca. 535–475 BC) "Kalliste Harmonia", the fairest harmony which comes out of discord (Diels and Kranz, 1985, e.g. DK22 B8) and Anaximander's (610-545 BC) "Apeiron" the indefinite, infinite, non-perceivable base of all things out of which reality forms by precipitating contradictory properties (Diels and Kranz, 1985, e.g. DK12 A9; Schäfer, 2004, p.53).
Again, the eastern thought systems offer an equally rich history: In a central teaching of Mahayana Buddhism, the heart sutra, states a relationship between form and emptiness, which appears to be similar to complementarity (Lopez, 1988). Nagarjuna (ca. 150-250),

arguably the most influential Buddhist thinker after Gautama Buddha himself, analyzed the so-called "tetralemma" and showed that all four possible solutions to any paradox describing reality (A is true, B is true, both are true, neither is true) are flawed and the true nature of reality is characterized as "pratitya samutpada", "dependent arising" (Napper, 2003). This analysis has some remarkable analogies to complementarity in quantum physics as pointed out e.g. by Kohl (2005).

Similar claims have been made about related concepts in Jain philosophy, namely "Nayavāda" (the theory of partial viewpoints) and "Syādvāda" (the theory of conditioned predication), both part of "Anekāntavāda" (the theory of non-exclusivity) (Burch, 1964; Matilal, 1981; Kothari, 1985; Mitra, 1986; Jaggi et al., 1994).

Zen master Shih-t'ou Hsi-ch'ien's poem "The Harmony of Difference and Sameness" (ca. 8th century) is an important early expression of Zen Buddhism and is chanted in Sōtō temples to this day (Leighton, 2000).

Advaita (Sanskrit: a = not, dvaita = dualism [75]) is a whole spiritual school (from India) devoted to the non-duality of opposites (in particular of self vs. other and relative vs. the absolute) as its central teaching, with Advaita Vedanta, a branch of Hinduism, as its philosophical arm.

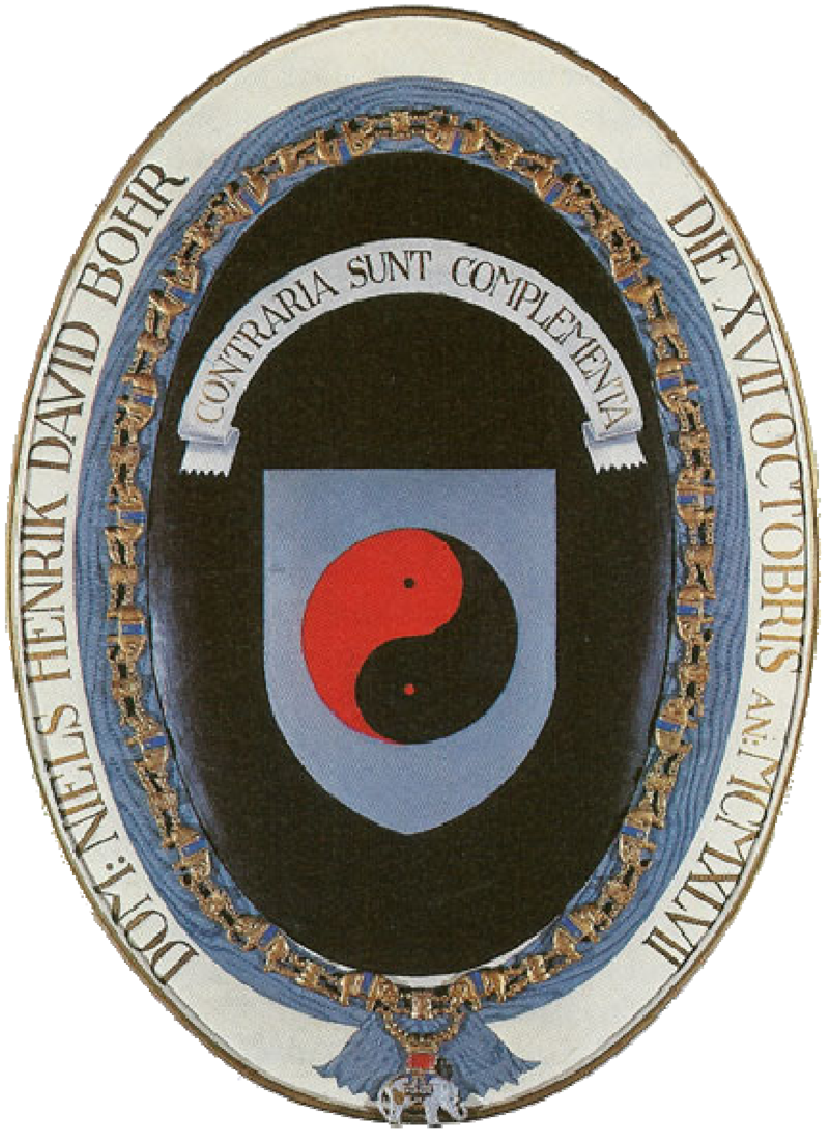
Another, very obvious case concerns the principles "Yīn" and "Yáng"[76] in Daoism and Confucianism (see e.g. Mou, 2001). The earliest writings about their relationship and the relationship between this polarity and the unity in and of all things are probably found in the "Yì Jīng" (Karcher, 2002), whose oldest original dates to the second century and whose origins lie in traditions probably formed several millennia BC (Hertzer, 1996) and the "Dàodéjīng" whose earliest available copy dates to ca. the 3rd century BC (Henricks, 2005). The nowadays well known graphic representation of yin and yang (also called the "Tàijítú", literally: "diagram of the supreme ultimate"[77]) apparently stems from the 16th century (Chunqiu, 2003). Interestingly, when in 1947 Bohr was ennobled with the Danish Order of the Elephant (normally given only to members of royal families and presidents of foreign states) he chose precisely this symbol for his coat of arms (figure 14). The Latin inscription reads "CONTRARIA SUNT COMPLEMENTA" – ("opposites are complementary", my translation). The fact that Bohr saw a symbol from an introspective spiritual tradition to best represent the view of reality which he had come to through experimentation and rationalization, may be interpreted as a further hint to a possible complementarity between science and spirituality.

[75] For definition of dvaita as "dualism" see: Flood (1996), p. 245.

[76] Most Chinese words here are given in the "pinyin-romanization" (see http://www.pinyin.info/).

[77] Translation from http://www.nationmaster.com/encyclopedia/Taijitu.

Figure 14: Niels Bohr's coat of arms[78]



The overall agreement between principles discovered by the study of physical processes and principles discovered by mystical insight has been pointed out by a number of authors, who mostly interpret this fact as circumstantial evidence for the truth and value of mystical experiences (e.g. Capra, 1975; Schäfer, 2004; Zukav, 1979; Laszlo, 2003).

One possible explanation for the appearance of a complementarity-like principle in many religious traditions is that it is an element of the mystical experiences from which spiritual

[78] Retrieved on 10.05.2008 from http://www.nbi.dk/hehi/logo/crest.html, © Niels-Bohr-Institute, Copenhagen.

insights originate. In fact, many of the mystical traditions teach that truth is to be found in the paradox.
For example the Buddhist "Rinzai-Zen" practice called "Koan" entails contemplating a paradox until it disappears as a 'higher' state of consciousness is experienced (Oshima, 1985 and pers. com. 2005).
Mystical experiences in the Christian context can be non-dual, as reflected by the theological term "unio mystica" (Lehmann, 2004) and by the reports given by many mystics e.g. by Teresa of Avila of "spiritual marriage" (Avila, 1577) or by St. John of the Cross' of the "perfect union" (of the Cross, 1586).
Dionysios Areopagitas, one of the most important thinkers of the Eastern Christian Church, whose theology exercised great influence on the mystical tradition of mediaeval Europe, is famous for his remarkably frequent use of antithetic paradoxical terminology for conveying mystical experiences (Alexopoulos, 2006).
Jalal ad-Din Muhammad Rumi, (1207-1273), one of the most famous masters and poets of Sufism (an Islamic mystical tradition) wrote that what humans perceive as duality is in fact a veil, masking the reality of the Oneness of existence (Hakim, 1925).
Also more modern, non-confessional reports of mystical experience report as a central component some form of paradoxical non-duality, as for example Franklin Merrel Wolff's descriptions of "high indifference" and "equilibrium" (Merrell-Wolff, 1973a; b).
In particular the non-dual oneness of subject and object is described as a central feature of many mystical experiences throughout history and in various cultures (see e.g. Forman, 1998).

Another area of scholarship in which we find relatively many recent concepts reminiscent of complementarity is logic. (Naturally, part of them is inspired by the perceived inadequacy of classic binary logic as a foundation for modern science, in particular quantum physics, others are based on independent considerations to advance logic.) I can name but a few of the developments:
Stephane Lupasco, among others, developed the principle of "dynamic opposition" and a "logic of the included middle" (Lupasco, 1947; 1951). In this logic a phenomenon has no reality by itself but only in association with its contradiction, where actualization of one means 'potentialization' of the other.
In the same vein, Joseph E. Brenner's non-propositional "Logic in Reality (LIR)" (Brenner, 2008) attributes probabilities to the opposite values which he regards as categorically non-separable.
Basarab Nicolescu adds to this the idea of "Levels of Reality" (see e.g. Nicolescu, 1998 and Camus et al., 1998) where contradictory descriptions are resolved at increasingly higher levels of reality. Florentin Smarandache's "neutrosophic logic" (Smarandache, 2003) defines indeterminacy as a third variable in addition to truth and falsity.
Helmut Reich proposes relational and contextual reasoning (RCR) (Reich, 1999; 2004), a form of trivalent logic where *"instead of true and false, there are three truth values, namely compatible ("entity" A and "entity" B can be simultaneously present or absent) incompatible (cannot be present or absent simultaneously) and noncompatible (in one context, in one condition A is much more in the limelight, in another B)"* (quoted from Reich, 2005).

Guy Planta describes as "trialogic reasoning" a logic system which includes the possibility for opposites to be transcended (Planta, 1997).
Similar to Lupasco, da Costa and Vernengo (da Costa and Krause, 2001) developed a so-called "paraconsistent logic" which they feel is capable of harboring the phenomenon of complementarity as demanded by quantum physics without leading to the internal logical inconsistencies which necessarily arise in classical logic.

It is of course tempting to speculate, and to some readers it may be intuitively plausible, that the ubiquity of concepts reminiscent of complementarity and the plethora of potentially complementary notions point to a universal applicability of the complementarity principle which goes beyond the attribution of an (infinitesimally small) wave nature to macroscopic objects. Much more work, however, is required in order to make this a convincing case by scientific standards. What will be needed are primarily three things: firstly a precise characterization or even definition of complementarity abstracted from the ideal quantum mechanical case; secondly a rigorous analysis of the proposed complementary pairs in view of this definition; and thirdly, should the definition hold, a solid philosophical framework that allows the interpretation of such analogies in terms of their implications for our understanding of reality. This probably requires substantial joint efforts within the scientific community. For now, and within the scope of this thesis, I can merely sketch in a very preliminary way some contours which I could envision such a definition to take on, apply it in an exemplary way to the so called "mind-body problem" and begin to ponder some of the possible implications and interpretations.

3.4.2 Elements of a definition of complementarity

To begin with let us review some possible characterizations or even components of a definition of complementarity as it can be observed in the relationship between wave and particle descriptions of a quantum. (What follows is an attempt to amalgamate and summarize my own views with definitions and descriptions given by the following authors: Bohr, 1934; MacKay, 1957; Bohr and Noll, 1958; Feyerabend, 1958; McKay, 1958; Bedau and Oppenheim, 1961; Rosenfeld, 1961; Meyer-Abich, 1965; Jammer, 1966; Feyerabend, 1968; 1969; Lindenberg and Oppenheim, 1974; MacKay, 1974; Hitchcock, 1986; Beller, 1992; Kim and Mahler, 2000; da Costa and Krause, 2001; Atmanspacher et al., 2002; Antonopoulos, 2004; Meyer-Abich, 2004; Antonopoulos, 2005; Derry, 2005; beim Graben and Atmanspacher, 2006; da Costa and Krause, 2006; Walach et al., 2006)
It may be important to note that although at various points in this study I use words like "contradiction", "duality" or "polarity" as characterizations of complementarity, these words should not *per se* be understood as elements of a definition of complementarity because they themselves are not precisely defined. I rather want to base the following definition(s) of complementarity on the actual empirical situation in which the wave/particle duality can be observed so that we can ultimately always refer back to concrete observations when we now look for formulations that answer to the question:

what are the characteristics of complementarity as it appears in the case of wave- vs. particle-descriptions of a quantum?

1) What we call complementary, is the relationship between *two* descriptions of a quantum.

Some writers, however, have considered the possibility of multiple elements being in complementarity relationships, called "polyadic" complementarity as opposed to "dyadic" complementarity (e.g. Reichenbach, 1998, p. 159 and MacKay, 1957, p. 390). The situation in quantum physics involves only pairs of descriptions for the wave/particle or the position/momentum dichotomy but there may also be polyadic complementarity between spins along different axes. For now I shall limit the definition to the case of dyadic complementarity because it fits the wave/particle example we have used so far.

2) Both of these descriptions describe one and the same quantum.

As has been pointed out, e.g. by Hitchcock (1986), *"that there are opposites is not the issue, but rather that single things must be described in terms of such opposites."*

3) Both descriptions are needed to fully describe this quantum.

Without both of these descriptive terms, the description is incomplete. Either descriptive term on its own cannot account for the whole range of the observed phenomena associated with the quantum. For example, the particle description cannot explain the interference pattern and the wave description cannot explain the discrete nature of the quantum event. This of course also implies that both descriptions must be true in the same sense of true. It also implies that complementarity descriptions are irreducible to each other.

4) The descriptive terms are incompatible.

This I find the most difficult aspect of complementarity to define. What is the exact nature of this incompatibility? Different formulations have been used to describe it. I think I can discern the following major categories:

a) Incompatibility as the inconceivability of an object to which both descriptions apply fully at the same time.

A different wording of this aspect which is more common in the literature is the following:

> Incompatibility as the logical contradiction which would arise if both descriptors were combined.

This has, for example, been expressed in the following words:

"Complementarity denotes the logical relation […] between concepts which are mutually exclusive, and which therefore cannot be considered at the same time because that would lead to logical mistakes" (Rosenfeld, 1961)

"[Complementary descriptions] are mutually exclusive in the sense that their combination into a single description would lead to logical contradictions." (Jammer, 1974)

The important point here seems to be the concept of a hypothetical 'combination' of the two descriptions which implies both of them being absolutely accurate and real *at the same time*. This is clearly not possible for wave and particle descriptions: either something is in one place only (particle) or it is in many places at once (wave). Attributing to a quantum both the description of absolutely localized and absolutely non-localized at the same time would lead to a logical contradiction within classical bi-valued logic.
For the case of pure wave and particle descriptions of a quantum such a 'combination' of descriptions *at the same point in time* is, however, purely hypothetical anyway, because it never actually has to take place:
Firstly, a quantum, in the moment when it is observed, always only displays pure particle properties (e.g. a definitive singular location), and only from the precise nature of these properties (e.g. the locations of many measured photons collectively displaying an interference pattern) do we in some cases have to infer the necessity to attribute wave properties to the same quantum *at an earlier point in time*.
Secondly, even at this unobserved earlier point in time, any inferred wave or particle properties never actually collide because the degree to which either has to be inferred depends on the conditions under which the quantum is observed. And the conditions (e.g. an experimental setup) in which both wave-properties (e.g. interference) and particle-properties (e.g. point-like position) can be determined or inferred for the same point time *with absolute precision*[79] is not possible (as already discussed in chapter 2.1). As Derry (2005) puts it: *"[…] within the complementarity framework […] logically incompatible views are allowed […] [because] the conditions of observation for the two views are mutually exclusive"*. Accordingly, one could reformulate the above definition of incompatibility in the following way:

b) Incompatibility in the sense that the conditions under which one of the descriptions applies fully and the conditions under which the other applies fully cannot be realized at the same time

The characteristics of incompatibility given so far in a) and b) are the ones used most often in the literature known to me. In my opinion, however, they are not sufficient for a

[79] As also already discussed in chapter 2.1, both descriptions may, however, be applicable at the same point in time with some lower degree of precision. In some conditions, for example, it may be possible and necessary to attribute to a certain quantum an approximate location and some degree of interference. What is not possible, is to create conditions under which precise knowledge of a quantum's position and the observation of complete interference are obtainable at the same time (see e.g. Jaeger et al., 1995).

definition of complementarity. Let me explain this by an example: Imagine standing in a completely dark room and then standing in the same room with the lights on. Here we have two descriptions of the same room: on the one hand a completely invisible room and on the other hand a visible room. These descriptions would qualify as incompatible according to definition a) and b) above: Combining both of these descriptions would lead to a logical contradiction (both statements cannot be true *at the same time*) and the conditions in which either description applies are not realizable *at the same time*. Nevertheless, the incompatibility of the dark room and the lit room is of a different category as the incompatibility of a quantum's particle and wave nature. This is because for the former we can conceive of a higher order (meta-)description which coherently unites both contradictory descriptions into a logically consistent whole. (For example, a person may have entered the room and turned on the light.) Such a meta-description is not possible for particles and waves. There is no smooth way of completely and exhaustively describing the transition from a continuous distribution of probabilities to the discrete actualization of one of them. As Hitchcock (1986) says: *"The unity behind the complementary conceptual opposites is not ultimately susceptible of a rationalistic description. It is a nonrational unity."* I therefore suggest a further characterization of incompatibility:

c) Incompatibility as the inconceivability of an object to which both descriptions apply *even at different times*.

By this I mean the case where we cannot conceive of an exhaustive description, let alone explanation, of the transition from an object manifesting properties which require one description to an object manifesting properties which require the other description. In the case of quanta, for example, we do not know of a possible mechanism which provides a continuous link between a wave of (potentially infinitely many) per se immeasurable potentialities and the measurable actual realization of only one of those possibilities.[80]

d) A further expression of incompatibility is the uncertainty which one of the complementary notions is subject to when the other one takes on a definitive value.

In Heisenberg's reciprocal uncertainty relations we find a mathematical expression which defines the increase in uncertainty of one complementary notion which results when the uncertainty of the other is reduced. As Atmanspacher et al. (2002) explain: *"In ordinary quantum theory, P and Q [position and momentum] are maximally incompatible in the sense that for every eigenstate of Q all values of P are equally probable and vice versa."* Please note that here a distinction between maximally incompatible and incompatible is introduced: the latter would thus designate situations where, given a definite state of one of the observables, the other observable is still unpredictable but not all its possible values are equally likely.

[80] The process of decoherence, as already briefly mentioned, can thus far only provide an explanation for the fact that only discrete outcomes can be observed rather than superpositions of different outcomes. It leaves open, however, the question as to why one *particular* outcome is realized as opposed to any other possible one (see e.g. Adler, 2003, von Stillfried, 2008a)

Either way, we can conclude that incompatibility means that of a pair of complementary notions both cannot take on an arbitrarily precise value at the same time (e.g. beim Graben and Atmanspacher, 2006) or in other words are not "simultaneously decidable" (Strauss, 1975).

In the quantum theoretical formalism this results in non-commutativity of observables. Mathematically this means that the outcome of a multiplication of observables depends on the order in which they are multiplied (e.g. AB≠BA) unlike we are used to from everyday mathematics where the order of factors is not relevant to the outcome (e.g. 2x3=3x2). Physically this means that the sequence in which observables are measured is decisive for the resulting state of the quantum (recall for example the polarization measurements described in chapter 2.2). We can thus formulate:

e) Incompatibility equals non-commutativity which means that the outcome of measuring both complementary observables depends on the order of the measurements.

A last aspect of incompatibility to be mentioned here is the following:

f) Incompatibility applies to descriptions, not to the objects in reality they describe.

This is obvious but important to remember. While we may not be able to imagine an object that combines wave and particle properties this obviously does not mean that photons, electrons and other quanta do not exist. Anyhow, as we have discussed in chapters 2.2 and 3.3 on observables, 'objects' and 'descriptions' are inadequate terminology for quantum physics. Really I should only be talking about observables.

5) Each of a pair of complementary descriptions taken on its own is meaningless and possibly inexistent.

In their abstract form a pure sine wave is absolutely location-less which means it is everywhere equally and therefore indistinguishable from nothing; a pure particle is dimensionless and therefore also indistinguishable from nothing. Apart from that both of these notions imply infinities which have to be considered of unknowable status (see e.g. Popp, 1984, p. 145).

6) The complementary descriptions are needed to mutually define each other.

As already discussed in chapter 2.5, both on the abstract and the practical level one needs defined locations in order to define a wave and one needs a continuum within which to locate a location.
In other words: Supposing we had only the concept of point-like particles, meaning we could only describe the universe as a collection of points, then we would not be able to describe the spatial coordinates of these points because for this we would need a concept

of distance and this one cannot get by accumulating points (as we know even an infinitesimal distance can be divided in infinitely many points). For a complete description of the universe, however, the spatial coordinates of the particles are necessary and we thus require a concept of distance which in turn requires a concept of continuum. The most fundamental realization of the concept of continuum and temporal or spatial distance is an oscillation or, respectively, a wave.
The other way around, a similar dependency exists: The concept of a probability wave in quantum physics was only ever inferred on the basis of the spatial localization pattern of point-like particle detection events. What is more, we cannot even define what we mean by this wave-nature of a quantum without referring to probabilities which again are referring to spatially localized point-like particle detection events.

7) The product of two complementary observables is an action.

In some sense related to the previous point, the combination of both complementary components makes up the quantum. And what is a quantum? Originally it was called the "quantum of action"[81] (Planck, 1920). Basically it is the minimal unit in which change happens. In this sense the product of two complementary observables is considered an action (von Lucadou, pers. comm. 2008).

8) Only one of the descriptions relates to actual observations, while the other is inferred from these observations.

Interestingly, quantum (probability) waves are not directly observable. They have no effect by themselves and cannot be measured. Their existence is however inferred with necessity from the way in which particles are found to behave.

9) Complementarity may be categorized into 'vertical' and 'horizontal' complementarity.

There has been some debate about this issue and to my knowledge it has not been unanimously resolved until now (see e.g. Jammer, 1974, p. 154-6, and Meyer-Abich, 1965, p.103). In my estimation, such a categorization may be possible and useful. For example, a photon's polarizations along different axes may be complementary to each other. These complementary observables are defined on the same logical level and I would thus suggest calling them horizontally complementary. The description of a photon in terms of the observable "polarization" (or "spin") with a definite value and the description of the photon in terms of a wavefunction (a superposition of 'non-existing' potential spin-

[81] The original German expression "Wirkungsquantum" expresses the matter even more tangibly because it conveys the relational character (cause-effect / subject-object) of this action, which in quantum physics is always an inter-action. What is more, the word "Wirkung" can also be found in "Wirklichkeit" (= actuality), thus making intuitively understandable that while potentiality may be continuous, actuality is characterized by quantification of the inter-actions as which it manifests.

values) apply to different conceptual levels and I would thus speak of 'vertical' complementarity.

Concluding, I would like to put into perspective the above effort to define complementarity by the consideration that it may be to some extent undefinable and even unknowable. As Bohr's said toward the end of his life *"I think that it would be reasonable to say that no man who is called a philosopher really understands what is meant by complementary descriptions"* (Cushing, 1994, p. 32).

3.4.3 Analysis of the mind-body problem from the point of view of complementarity

From my point of view, one of the most tempting applications of complementarity concerns the relation between the subjective and the objective nature of systems in general and the relationship between our subjective consciousness and our physical body in particular. This question has been dubbed with different names, for example the "mind-body problem" (Young, 1990) or the "hard problem of consciousness" (Chalmers, 1995b).

It has received sustained attention throughout the history of human thought, in particular since it was conceptualized most prominently by Rene Descartes in the first half of the 17th century as the distinction of "res cogitans" vs. "res extensa", i.e. of 'the thinking substance' vs. 'the substance which extends in space' (my translation) (Young, 1990). More recently, characterization of mental experience has focused not so much on 'thinking', but on its subjective qualitative nature, in other words the experience that it 'feels' or simply 'is' *like* something to exist (see e.g. Nagel, 1974; Chalmers, 1995a; Shear, 1997).

Whatever particular words are used, at the heart of the issue is essentially the realization that subjective experience and objective reality seem to be of fundamentally different quality. As soon as this distinction is made, the question arises of how these categories relate to each other. Our experience clearly tells us that they are strongly related. But how is this possible, given their completely distinct natures?

A number of different avenues have been proposed as possible solutions to this question. They can be roughly classified as "monistic" or "dualistic". Monistic theories see one of the notions as primary and the other as derived from it: In idealism mind is primary and 'brings forth' matter; in materialism mind is a 'product' of matter. In dualistic theories on the other hand, both categories are regarded as primary and separate. A great variety of both monist and dualist theoretical frameworks have been developed which try to solve the puzzle.
I do not want to go into any detail regarding all the intricacies of the historical and recent discourse regarding this question because undoubtedly much literature is available in this

respect. (starting points could be e.g. Young, 1990; Chalmers, 1995b; Fodor, 2006, many editions of the Journal of Consciousness Studies or even the entry on "Philosophy of Mind" on www.wikipedia.org).

For our purpose here it is sufficient to note that up to now none of the theories has led to a wholly satisfying or generally accepted answer. All approaches confront great and thus far unmet challenges: Monistic theories have to explain how it is possible for one substance to bring forth another substance of fundamentally different quality; dualistic theories have to explain how substances of fundamentally different quality can interact and if they cannot, why they nevertheless correlate so closely.

What I would like to consider in the next paragraphs is the possibility that the relationship between subjective conscious experience and objective material reality may be complementary. If this is so, it would make plausible why a unified coherent solution of the paradox has not yet been found. Conversely, it would suggest that it is precisely the paradox which best describes the nature of consciousness in the world.

While I will attempt to examine this proposal in a more detailed and systematic way, I am by no means the first one to suggest that mind (understood as subjective conscious experience) and body (understood as objective material reality) may be complementary in the same way as wave and particle are. Up to now a few authors have explicitly proposed this hypothesis (e.g. Brody and Oppenheim, 1969; Feigl, 1972; Edelheit, 1976b; a; Fahrenberg, 1979; Hoche, 1990; Tang, 1996; Walach and Römer, 2000; Nakagomi, 2003; Walach, 2005a; von Stillfried and Walach, 2006b; a; Walach et al., 2006; Fahrenberg, 2007; Hoche, 2007; Primas, 2007; Walach, 2007b; Primas, 2009).
Max Velmans has also pointed to a similarity with "quantum complementarity" (Velmans, 1991; 1993; 1995; 2002; 2009), but maintained that "psychological complementarity" differs in some important ways (Velmans, 2000; 2009). Thomas Filk and Albrecht von Müller have pointed out similarities between Quantum Physics and Consciousness (Filk and von Müller, 2009) but do not understand consciousness and matter as complementary (Filk, pers. comm. 28.10.2009).

More historically, as to be expected, Bohr himself regarded the physical and the psychological aspect of existence as complementary, as he mentions in the introduction to his first collection of essays (Bohr, 1934). Apart from that, however, other applications of complementarity seem to have interested him more (Bohr, 1999).
Other founding fathers of quantum theory seem to have shared this view (for more detail see e.g. Smith, 2006): Werner Heisenberg for example points out in places that complementarity to him is a compelling analogy. *"How is it possible that part of reality which begins with consciousness be combined with those parts that are treated in physics and chemistry?"* he asks rhetorically, and answers *"Here we have a genuine case of complementarity."* (Heisenberg, 1971, p. 115). However, he did not explicate the issue in much more depth.
Wolfgang Pauli thought along the same lines, but he also did not seem to provide much detail to support this idea, apart from small notes like the following (see e.g. Pauli, 1948;

Atmanspacher and Primas, 2006; Saeger, 2009): *"[P]hysics and psychology reflect again for modern man the old contrast between the quantitative and the qualitative. […] To us […] the only acceptable point of view appears to be the one that recognizes both sides of reality—the quantitative and the qualitative, the physical and the psychical—as compatible with each other and can embrace them simultaneously. […] It would be most satisfactory of all if physics and psyche could be seen as complementary aspects of the same reality."* (Pauli, 1955, p. 207–208)

Carl Gustav Jung made similar remarks throughout his writing. His view, however, includes the idea of a third substance out of which matter and psyche arise or which appears as matter or psyche, depending on the conditions of observation. This undivided and unobservable primordial wholeness he calls "unus mundus" (for an overview see e.g. Shelburne, 1988).
Such a concept has also been used by other authors and is usually referred to as "aspect dualism" or "neutral monism". Sometimes, these terms are used with explicit reference to complementarity or quantum mechanics. (e.g. Atmanspacher and Primas, 1996; Walach and Römer, 2000; Atmanspacher, 2001; 2003; Primas, 2003; Walach, 2005a; Atmanspacher et al., 2006; Atmanspacher and Primas, 2006 and possibly[82] Hiley, 2000 and Bohm, 1990). The original development of aspect dualism or neutral monism, however, occurred long before quantum physics. It was probably first introduced by 17th century Dutch philosopher Baruch Spinoza who viewed "God" and/or "information" as the unifying substance (Stubenberg, 2005). Among others, Ernst Mach (Mach, 1886), William James (James, 1904) and Bertrand Russell (Russel, 1921) adopted and adapted his views. The currently most influential version is probably promoted by Chalmers (Chalmers, 1995b; 1997).
An important difference between aspect dualism or neutral monism and complementarity is that the complementarity does not traditionally include any explicit assumption of some neutral third category. In fact, the justification for assuming such a category in terms of a neutral substance may not be very substantial: As we will see in the following analysis, any neutral category combining consciousness and matter will suffer, in addition to its often acknowledged inaccessibility, from the fact that it is logically inconceivable, just like a combination of wave and particle. In this case, assuming its existence is not justified.[83]

We will now analyze the mind-body dichotomy according to the definition of complementarity which we formulated earlier on the basis of the wave-particle dichotomy. To do so, we have to replace the word "quantum" with a word which unifies

[82] The accounts offered by D. Bohm and B. J. Hiley are of a similar but somewhat different nature. Here, consciousness is seen as the participatory agent in collapsing the unobservable wavefunction into a definite experience. Both are, however, again contained in what is called the "implicate order", a not accessible wholeness (Bohm and Hiley, 1993).

[83] As a last resort, however, we could turn this argument around and say that, since no thing meets these criteria, the only thing which does and thus qualifies as a 'third substance' is 'Nothing'. This may seem no more than a play of words but it opens up an interesting avenue for interpretation, not only of the mind-body problem but also of the particle-wave paradox and of complementarity in general. We shall return to this thought in chapter 3.4.5.

consciousness and body in the same way as the word "quantum" unifies wave and particle descriptions. I suggest the word "individual" for lack of any better ideas and in keeping with the classical Aristotelian solution (Fischer, 2003). Hence:

1) What we call complementary, is the relationship between *two* descriptions of an individual.

This is obvious, we are talking about an individual's physical body and his or her conscious experience thereof.

2) Both of these descriptions describe one and the same individual.

Arguably my consciousness and my body are a unity.

3) Both descriptions are needed to fully describe this individual.

Indeed, something would definitely be lacking from a purely physical description of myself or any other conscious individuals. Suppose I knew every theoretically knowable physical fact about you. I would still not know 'what it is like' to be you. Another often cited example (from Jackson, 1986) is the seeing of a color: On the one hand nothing in my subjective experience can give me a reliable description of the actual physical reality of my body and the world. I might for example be hallucinating or dreaming everything. On the other hand knowing absolutely everything about optics and neurophysiology and the precise state of every atom in my body and the world conveys absolutely no knowledge of the subjective quality of what it is like for me to see e.g. red.

4) The descriptive terms are incompatible.

a) Incompatibility as the inconceivability of an object to which both descriptions apply at the same time. (= Incompatibility as the logical contradiction which would arise if both descriptors were combined.)

This seems like an odd claim at first: Of course mind and body are not incompatible; after all they work for most of us every day in perfect harmony. It is important to remember, however, that this is not the point. Wave and particle also work perfectly for every quantum in the universe. The question is rather, whether we can form a rationally coherent singular description which combines both descriptions. This seems doubtful, as the ongoing and up to now unsuccessful efforts in science and philosophy illustrate. They fail because from a strictly logical perspective there is no conceivable thing or situation to which both of them could be applicable at the same time: there is absolutely nothing physical or matter-like to my qualitative subjective experience and there is nothing mind-like or experiential to be found anywhere in matter. For example, one has spatial extension and mass, the other one does not. Another interesting incompatibility between properties of mind and matter was pointed out by Primas (2009): Mind is a "tensed description, characterized by a privileged position in time, the Now", whereas matter is a "tenseless description, characterized by a homogeneous time".

b) Incompatibility in the sense that the conditions under which one of the descriptions applies and the conditions under which the other applies cannot be realized at the same time.

Indeed, when we observe an individual from the outside it appears as a body, when we observe it from 'within' it appears as conscious experience. We can describe mind as the description of a view from within, the body as the description of a view from without. These angles of observation are maximally exclusive in so far as one is subjective and the other is objective and both can not be realized at the same time. Either I'm inside or outside. A special case to consider is of course the possibility to observe one's *own* body 'from the outside' while experiencing it 'from the inside'. But even in this case, absolute simultaneity is impossible. As Velmans (e.g. 2009, p. 132) points out in his example of a hypothetical "autocerebroscope", which allows one to perceive the very neuronal processes which correlate with ones perception, there will always be a non-zero time lag between the conscious perception of a process and its physical occurrence.

c) Incompatibility as the inconceivability of an object to which both descriptions apply *even at different times*.

Given that the argument under "a)" rules out the logical possibility of both descriptions applying at the same time we now have to assess the conceivability of any object which could at one time-point appear as a body and at another time-point as a mind and a logically coherent description of how and why that transition takes place. I am not sure if this has been tried but I do not have much hope because, as discussed before, the challenge would be to find a possible relationship between two things of such different nature that there is zero overlap: Basically, the problem is that (spatially extended) matter or energy can only exert influence on other (spatially extended matter or energy). A non-material mind is not spatially extending and it can neither be subject nor object of such influence. Equally impossible would be any attempt of explaining how one could completely transform into the other.[84]

[84] These arguments also refute the often advanced idea that consciousness could be an "emergent" property of matter, arising at a certain level of complexity and/or self-organization (for collections of such articles see e.g. Beckermann et al., 1992; Clayton and Davies, 2006). While this may very well apply to certain contents in or forms of consciousness (such as memory, self-identity, self-reflectivity etc.), it can certainly offer no explanation for consciousness per se, this most basic fact that being is 'like' anything at all, the mere existence of subjective qualitative experience. Here the problem is that every emergent

d) A further expression of incompatibility is the uncertainty which one of the complementary notions is subject to when the other one takes on a definitive value.

Does the information we can collect about the mind of a person decrease with the amount of precision with which we can describe his or her body? Probably this relationship cannot be applied with quite the same rigor and absoluteness as in quantum physics. If, for example, I perform an objective observation (i.e. measurement) of my physical body, the probability distribution of my subjectively experienced states of consciousness does not necessarily increase. Conversely, making a very precise introspective account of my state of mind does not necessarily make my body behave more randomly. However, just as in quantum physics we perhaps have to think not so much in terms of *actual* states of mind and body but rather about the amount or accuracy of the *information* that can be obtained about a state. In this sense, the analogy seems to hold: the more precisely I am observing something inside my mind the less aware I may be about my physical existence. Conversely, if I am strongly focused on an external observation I may be less aware of my mental state. To explore the analogy to an extreme, let us see what would be the equivalent of the 'disappearance' of the wave nature of a quantum once its definite location is determined, e.g. by absorption on a photographic plate? When we consider making an absolutely precise observation of a body (e.g. measuring the position of all its atoms) we would have to fixate it and interact with it in such a way that we could probably not avoid killing the person, thereby eliminating any possible information about their subjective experience. Conversely, trying on the other hand to experience the conscious mind in a more and more pure form requires a reduction of physical action and interaction (as it is for example employed by a number of meditative practices). By extrapolation, this could mean that the observation of absolute pure mind would require absolute physical quiescence and isolation, thereby rendering the complementary object of our enquiry, the body, inaccessible to any form of objectification.

e) Incompatibility equals non-commutativity which means that the outcome of measuring both complementary observables depends on the order of the measurements.

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property of a certain level of complexity has in some way to be based on properties of the elements making up the level underneath even though the emergent property itself is not present at that lower level. These lower-level properties have to somehow be related to the emergent property. Consider, for example, the often cited emergent property "liquidity" of water. At a certain level (number of molecules) this property emerges even though it is not present at the level of single molecules. Nevertheless it is based on and can be traced back to the physical properties of these single molecules such as e.g. their geometry and electrical polarity. Such a tracing back is not possible for consciousness. There are no properties of objective physical matter which would allow for subjectivity to emerge at some level of organization or quantity.

Even if we do not go to the extremes of absolutely precise measurements it is clear that we will obtain different results depending on whether we first collect physiological data and subsequently record subjective experience or vice versa, because either will influence the other.

f) Incompatibility applies to descriptions, not to the objects in reality they describe.

As mentioned under "a)" this is true for us, thankfully. Not only do mind and body appear compatible, but even as a unity. This unity of body and mind may not be perceived as such under certain conditions like for example near death experiences, trance, certain psychiatric disorders etc. However, it is usually conceived as possible and the rule rather than the exception.

5) Each of a pair of complementary descriptions taken on its own is meaningless and possibly inexistent.

This point is covered in the next paragraph together with 6).

6) The complementary descriptions are needed to mutually define each other.

Since there is no mathematical formalism for defining mind, there is no such simple way to show this as there is for particle and wave properties. However, it is surely plausible that without consciousness the mere notion of existence would be meaningless whereas if there wasn't anything in existence consciousness would have nothing to be conscious of. This in my view does not rule out (although I doubt it), that both matter and mind could exist independently, just as only waves or only particles might exist, but it renders either description taken by itself meaningless.

7) The product of two complementary observables is an action.

As far as I can see this could with some stretch of the imagination be said about mind and body. Only when both are together, can change be initiated by an individual. What is more, one individual can indeed be seen as the minimal unit in which human action takes place. These vague statements clearly require much more in-depth investigation, though.

8) Only one of the descriptions relates to actual observations, while the other is inferred from these observations.

Does our idea of the existence of a mind of an individual depend on observing the body of that person, in analogy to observing a photon as particle and inferring from these observations its wave-nature? Indeed, all we can ever know about another person's mind is what we can in some way or other measure about their physical presence, be it via the sound waves of the words they say, the electromagnetic activity in their brains, or the physical impact of other forms of behavior. This means, we will never observe someone else's mind directly, but only infer, from the physical information which we receive, that there is an additional nature to that person which is qualitatively different to the information we collect about it. This is different from when we observe ourselves: here in fact the situation is reversed. All our knowledge about our physical body and the physical world is only inferred from our subjective experience. Here we have an important difference to the observations in quantum physics: there, the wave can never be observed or experienced directly. This does not, however, mean that the analogy is imprecise. When talking about observing our conscious experience we are referring to a situation which would be comparable to wavefunctions reporting about their life before measurement. In other words, we have a special access to our consciousness because we actually are one of the entities under consideration, just as, supposedly, if I were a quantum, I might have access to my own wavefunction.

9) Complementarity may be categorized into 'vertical' and 'horizontal' complementarity.

Possibly, complementarity could be seen both on the horizontal axis of mind-description vs. body-description as well as on the vertical axis of dualistic description vs. unified existence.

Summing up this analysis we can see that it may well be possible and potentially instructive to describe the relationship between mind and body as complementary.[85] Several aspects have remained somewhat vague though and possibly more characteristics have to be included into the definition. The possibility of making stronger assertions thus requires a much more in depth analysis but such an endeavor seems promising.

Assuming for the moment that a more and more in depth analysis would reveal a more and more perfect analogy, what would this mean? One interesting aspect of this question is how to interpret an analogy in the first place. Another important aspect is how to interpret complementarity specifically.

[85] If this proposal holds true it is clear that not only the human conscious experience and the human body but subjective consciousness per se and matter in general are likely to be complementary, a proposition which can possibly be best conceptualized as a complementarity between "inside" and "outside". This obviously leads to the postulate of an complementary „subjective" inside to every physical system where an outside can be objectively defined. While I do believe that such a view is justifiable and useful (one of the most appropriate version of it, in my taste, being Ken Wilber's Pan-Interiorism (e.g. Wilber, chapter 14, note 15)) here is not the place to expand on this subject.

3.4.4 What is the use of reasoning by analogy?

Using analogies as a way to discover universal principles, rules and laws is a widely used (albeit often implicit) form of scientific methodology (see e.g. Gloy and Bachmann, 2000; Itkonen, 2005). Nevertheless, it has to be said that reasoning by analogy is a weak form of inductive reasoning and a much weaker form of reasoning than deductive reasoning. This is primarily so because the degree of similarity between two things which are not identical is dependent upon the specific categories of data which a comparison is based upon (see e.g. Juthe, 2005.).

In our case, for example, I have not included specific speeds, masses or sizes into the definition of complementarity. Heisenberg's uncertainty relation coefficient ($\hbar$), for example, specifies the precise amount of uncertainty between position and momentum measurements. Currently, it would seem very difficult to investigate whether the mind-body relationship also obeys precisely the same quantitative uncertainty.

Let us assume, as an optimistic guess, that the analogy does hold true in terms of *qualitative* equivalence even if it does not do so in terms of the precise *quantitative* relationships. In that case, the analogy could still be interpreted as evidence for a principle which is applicable to quanta in one particular way and to human individuals in another way.

Note that here the system theoretical approach of "generalization and re-specification" is applied. It is based on the understanding that a universal principle must not necessarily result in phenomena which are exact 'one to one' mirror images of each other. This is because, in the process of specification, a given universal principle could manifest itself in somewhat different forms, depending on the particular system under consideration. For example, it could be that for the mind-body relationship a different uncertainty relation coefficient applies, thus leading to a quantitatively different, but qualitatively equivalent form of complementarity.

Such reasoning implies, however, that there exist factors which are responsible for the differences. In order to verify the analogy and develop a complete theory, ideally these factors should be identified.
Potential factors might for example be found in the fact that quanta can be indistinguishably identical with respect to certain observables and their causal isolation can be absolute whereas human beings have much more inter-individual variation and much more fuzzy system boundaries. As a result, a general principle of complementarity might, for example, manifest itself in quantum systems in an 'absolute' way and in human systems in a more 'relative' or 'graded' way.

For the sake of following this argument all the way through, let us, as a rather optimistic guess, assume now that the decisive factors of difference between quanta and human individuals can indeed be identified. We could then be led to the question if complementarity can also be applied to other systems. In order to investigate this question, many different systems and pairs of descriptions would have to be analyzed.

Let us further assume that even for those the analogy is found to hold true. What could we conclude from that? Even though such kind of inductive reasoning is always subject to uncertainty (see e.g. Popper and Miller, 1983), we would probably arrive at the prediction that complementarity is a very general, if not universal principle.[86]

This illustrates the merit of investigating analogies in science and the driving motivation behind system theory: The confusing multitude of forms could potentially be reduced to general principles, which can then be adjusted to describe any system by taking into account the relevant factors.

Bohr might have had something like this in mind when he wrote: *"The analogies with some fundamental features of the quantum theory, exhibited by the laws of psychology, may not merely make it easier for us to adjust ourselves to the new situation in physics, but it is perhaps not too ambitious to hope that the lessons we have learned from the very much simpler physical problems will also prove of value in our endeavors to obtain a comprehensive survey of the more subtle psychological questions. […] it is clear to the writer that for the time being we must be content with more or less appropriate analogies. Yet it may well be that behind these analogies there lies not only a kinship with regard to the epistemological aspects, but that a more profound relationship is hidden behind the fundamental biological problems which are directly connected to both sides."* (Bohr, 1934, p. 20–21)

3.4.5 How to interpret complementarity?

If complementarity turns out to be a general or even universal principle but also if it simply remains an indispensable component of quantum theory, the question can be asked: What does complementarity tell us about reality? I would like to point out three possible interpretational routes for complementarity: nothingness, self-referentiality and infinity:

In considering what complementarity tells us about reality one possible starting point is the question: Why does reality require complementarity descriptions? Or in other words: What is it that lies beyond their dichotomy? This question could be considered futile, since, as we have already discussed (e.g. in chapter 3.4.2), the complementary descriptions are incompatible in the sense that there is *nothing* which can unite them into a coherent overall description. This very fact, however, could also point to a potentially important insight when we look at it the other way round: It may indeed be *'Nothing'* which can coherently unite complementary descriptions.

[86] Whether it is a universal principle because it is a fundamental property of the universe or because it is a fundamental property of ourselves and the mechanisms we use for perception and cognition (as e.g. Uri Fidelman seems to suggest (Fidelman, 1987; 1988; 1989)), seems to be another undecidable question.

If we consider for a moment the in itself somewhat paradoxical question of what was before reality came into existence, the only answer that does not lead to the repetition of the same question is ‘Nothing’. If everything came into existence out of nothing then all of existence could reasonably be expected to be constrained to, as a whole, ‘amount to’ or ‘average out to’ nothing. How could it do that more fully than by being composed of complementary aspects, which, in isolation as well as in their hypothetical combination, have to be considered ‘meaningless’, ‘unthinkable’ or ‘impossible’ and thus the closest thing to ‘non-existent’ that we can imagine?

There is, by the way, a substantial amount of scientific literature in physics and cosmology which elucidates the speculation of ‘everything coming from nothing’ and ‘event taking place in nothing’ provides supporting arguments:
As Hans Peter Dürr points out (pers. comm. 2005), it is a valid question to ask ‘where a photon goes’, when, after each half-wavelength, both its magnetic and its electric field pass through zero simultaneously (see Figure 9b). In fact, according to Bernhard Rothenstein the detection probability of a photon is proportional to the square of these amplitudes (Rothenstein, B., pers. comm. 27.02.09), which means that the photon on its path of propagation can be said to effectively pass in and out of existence.
The term “vacuum fluctuation” describes the phenomenon of particle and antiparticle pairs to come into existence spontaneously in what is called “empty space” and usually annihilate each other within a very short time span. Empirical evidence for these fluctuations comes for example from measurements of their impact on energy levels of atoms (e.g. Lundeen and Pipkin, 1981; Barut and Van Huele, 1985) and the so-called Casimir force (e.g. Bressi et al., 2002).
At least since cosmologist Edward Tryon posed the question “Is the universe a vacuum fluctuation?” (Tryon, 1973) an analogous process is widely considered as a potential origin of the universe as a whole (e.g. Vilenkin, 1982 Hartle and Hawking, 1983; Aitchison, 1985; Genz, 2002 Smith, 1988; Hosoya and Morikawa, 1989; Liu and Dai, 2002).
This proposal is given additional plausibility by calculations which estimate that the amount of positive energy in the universe is matched by the negative energy of gravitation thus suggesting that the total energy of the universe may be zero (see e.g. Hawkings, 1988, p. 129, Davis, 1983, p. 31-32, Cooperstock and Israelit, 1995, Tryon, 1984).

Of course the idea of ‘creation out of nothingness’ and ‘existence in nothingness’ is by no means new. In philosophy and theology there is a long tradition of characterizing ultimate reality in terms of the absence of any descriptive features. To name but a few examples: In western philosophy and Christian theology this view is commonly traced back to the tradition of negative theology of Nicholas de Cusa and Master Eckhard and its Neoplatonic roots in Plotinos. More recently, Hegel, in “The science of Logic” defined “Being” (the fundamental unquestionable starting point on which to build his logic) by the expression *“Nothing and not more and not less than nothing.”* (Hartnack, 1998). (Of course, nothing(ness) plays a major role for many other philosophers, too, like for example Leibnitz, Heidegger and Niezsche. For an entertaining foray see e.g. Lütkehaus, 2003.)

An equally long record can be reconstructed in eastern philosophy: E.g. in Hinduism a famous expression of this view can be found in the chant "*neti neti*" in the Upanishads meaning "neither this, nor that" asserting Brahman has no attributes, e.g. He is not real nor is He unreal etc.. In Taoism the first statement of the Dàodéjīng' asserts that anything that can be described is not the Dào. In Mahayana-Buddhism the recognition of the 'emptiness' (shunyata) of all phenomena is considered the 'ultimate insight' into the nature of reality (prajnaparamita) (Doniger, 2006).

Given this long history of 'nothing', it is, however, all the more interesting to note that, just as in the case of complementarity, modern physics may be retracing these old ideas with new accuracy.
For example, in 1981 Stephen Hawking and James Hartle (Hartle and Hawking, 1983) presented a quantum mechanical description of the potential early stages of cosmological evolution called "The wave function of the universe". Zycinski (1996) analyzed this work and its reception and came to the following conclusion: *"[This] proposal was interpreted by many authors as a pattern of cosmic creation from nothing in which no divine Creator is needed. In this approach, physically defined "nothing" was identified both with the empty set of set theory and with metaphysical nothingness. After defining philosophical presuppositions implicitly assumed in Hawking's paper, one discovers that this alleged nothingness has all properties of the philosophically conceived Logos accepted by Hellenic philosophers of the Neoplatonic tradition."*
Influenced by the same tradition, Nicholas de Cusa in his book "De docta ignorantia" formulated half a millennium earlier that on the one hand in God, as highest reality, all opposites coincide (Flasch, 1992) and that conversely, *"the plurality of things arises from the fact that God is in nothingness"*.[87]
This comes very close to my suggestion that complementarity can be interpreted to point to nothingness as the fundamental 'substrate' of reality. This nothingness should not be confused with what is often described as not yet actualized potentiality, as the absence of any-'thing' and thus the potential for everything. It is a much more radical nothingness which could rather be represented by the nonexistent overlap between potentiality and actuality.[88] The understanding of complementarity from quantum physics actually helps greatly to clarify this point. Unfortunately, to my knowledge, this conjecture has not yet been made in the discourse of quantum physics and cosmology. As far as I can tell, the fact that there is no common denominator between wave and particle as well as other fundamental pairs of descriptions of reality has not yet prompted the obvious conclusion that there cannot exist in any rational sense of this word a unified reality underlying these phenomena.

As hopelessly impossible as it is to adequately conceptualize 'nothingness', I nevertheless feel that even the 'thinkable' version of it can help to clarify a number of important issues,

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[87] My translation of "quod pluralitas rerum exoriatur eo quod Deus est in nihilo" (de Cusa, 1440, Book 2, ch. 3).

[88] In other words, "nothingness" as I use the word here, should rather be considered complementary to "existence" which subsumes both actuality (e.g. particles) and potentiality (e.g. waves).

ranging from quantum physics and cosmology to philosophy and spirituality and open an entirely new starting point for considerations about ourselves. I thus very much encourage the pursuit of 'the hard problem of quantum physics': what does a reality look like which unites wave and particle?

Another way in which complementarity might be interpreted in order to provide an idea about the underlying fabric of reality is in terms of self-referentiality: As already mentioned in chapter 2.5 the non-commutative nature of complementary observables can be understood as an expression of the fact that they must fundamentally be one whole, therefore making the outcome of the measurement of either observable dependent on the outcome of a previous measurement of the other. But what does that actually mean? How can we imagine self-referentiality? I personally find that more difficult even than visualizing nothingness. Interestingly, a self-referential origin of the universe has also been found logically plausible in cosmology: According to Gott and Li (1998), for example, *"it is possible that an inflationary universe gives rise to baby universes, one of which turns out to be itself"*, which means, conversely, that it is possible that our universe "is its own mother". It is noteworthy that, with respect to the origin of the universe, self-referentiality is one of the only two logical alternatives to nothingness because it allows dismissing the concept of a beginning by instead proposing a kind of circular infinity. The other alternative is linear infinity which presumes an infinite duration of existence and has also been proposed in cosmology (see e.g. Linde, 1994; Steinhardt and Turok, 2002).

The best way to sum up my musings on the potential interpretation of complementarity could be to say that to me one of the main lessons of complementarity is the insight that any rational approach to reality may be definitively limited by an absolute boundary: Because complementarity is part of reality, any rational understanding and description of reality will either a) be to some extend paradoxical in the sense that mutually exclusive terms are required or b) involve concepts which are impossible to grasp completely by reason, such as nothingness, self-referentiality or infinity because these offer the only way of integrating the mutually exclusive terms.

Given this insight, the hope to establish a logically coherent "theory of everything" should be viewed with caution. In particular the enormous efforts to find or develop a "grand unified theory" which unifies relativity theory and quantum theory come to mind (See beginning of chapter 3.4.1). At least it should be taken into consideration that logical paradoxes might have to be a fundamental part of such a new theory (See also Majid, 1991; Heller, 2004a; b). With regard to the hard problem of consciousness it may be advisable to settle for the unsettling insight that we cannot rationally conceive of a non-paradoxical solution.

This pessimistic estimation does not mean, however, that any insight into the 'unified' nature of reality is impossible. One approach worth considering might be the following: in order to gain a coherent understanding of a reality which presents itself as two irreducible parts of a paradox to the rational mind, it may be helpful to develop 'trans-rational' states of consciousness which manage to fully integrate these parts. Ken Wilber, for one, is of the opinion that the "hard problem of consciousness" is unsolvable to the rational mind and can only be solved by the experience of "satori", a trans-rational state of consciousness (Wilber, 1997, chapter 3 and 11; 2000, chapter 14). Such states have been ubiquitously described in various mystical traditions: Among others (e.g. Wulff, 2000), Stace (1960) has identified as one of the recurring features of mystical experiences that *"[f]undamental opposites appear as unified, laws of logic as abolished, and normal intellectual functions as replaced by a 'higher' mode"*. For this reason, these states have been also been termed "non-dual" or "acategorial" e.g. by Atmanspacher and Fach, 2005; Gebser, 1986 and Taylor, 1984.

In addition to the transcending integration of paradoxical notions, descriptions of such 'higher' states of consciousness often also refer to the experience of the very notions which I have talked above, namely nothingness, infinity and self-referentiality. (For reviews of phenomenological reports and the status of research in psychology of religious experience see e.g. Proudfoot, 1985; Hunt, 2000; Austin, 1998 and Smith, 2008 or the classic James, 1902.)

By making these notions experientially accessible, higher states of consciousness could help us to adequately live in and deal with such aspects of reality which from a purely rational point of view are logically required but at the same time impossible to grasp.

Techniques to induce and train such states have been practiced in most cultures throughout history and are more freely available today than ever before due to the globalization of various spiritual schools and traditions.

As a result of the analysis given in this chapter, I conclude that the theoretical 'hard problems' which humanity's quest for understanding of ourselves and the universe has encountered are not solvable with the means of the rational mind.[89] Therefore an adequate solution can likely only be found on other levels, for example by 'jumping into the heart of paradox', into nothingness, and experiencing unity there. In this sense, spiritual practice can be seen as the radical rational consequence of the current status of the exploration of reality. In my view such practice can with benefit be made use of in the further pursuit of wisdom and real understanding and should be given an adequate place also within the academic system.

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[89] Of course this has been pointed out many times before. It echoes for example Kant's famous observation that *"Human reason has the peculiar fate in one species of its cognitions that it is burdened with questions which it cannot dismiss, since they are given to it as problems by the nature of reason itself, but which it also cannot answer, since they transcend every capacity of human reason"* (Kant, 1781, p.99). What is new about the analysis of such problems in the light of complementarity is that this conclusion is not arrived at by theoretical reasoning only but can also be related to empirical evidence from the very foundations of physics. In addition it not only concerns questions about 'far away' issues such as the origin of the universe but the very nature of every piece of physical reality which we encounter in every moment, including our own bodies.

3.5 Generalized entanglement

One of the central insights from quantum physics is that in addition to the laws of causality there is a non-causal principle at work in shaping our reality, namely through entanglement correlations. This principle was first scientifically formalized in quantum theory but, according to GQT, its applicability is not limited to the quantum realm sensu stricto (subatomic particles, etc.).

Again there are two main avenues of reasoning for such a claim: the reductionistic and the system theoretical approach:

The reductionistic argument is that the entanglement displayed by quanta is of relevance to all objects and systems, since everything is composed of quanta. It is known that individual quanta can remain entangled for long times and over large distances (e.g. Aspelmeyer et al., 2003, Simon and Irvine, 2003) and it has been shown that macroscopic objects consisting of innumerable quanta can be entangled (e.g. Julsgaard et al., 2001; Mancini et al., 2002; Vitali et al., 2007). Nevertheless, as soon as the individual quanta or objects are no longer isolated from interaction with the environment, decoherence begins to take place: the originally entangled quanta will entangle with all the other quanta in their environment (which themselves are entangled with many others, possibly including the whole universe). In this process the original entanglement is not lost, but because (loosely speaking) 'everything is now entangled with everything' any *specific* correlations 'average out' and are no longer detectable. Since the isolation of objects becomes more difficult as they become larger and since such isolation is not expected to occur naturally, there is at the moment a wide consensus in the scientific community that entanglement is not naturally relevant to objects of our everyday experience, unless specifically engineered in such a way. I should mention that there has recently been some literature suggesting possibilities for the natural occurrence of relatively stable entanglement correlations even at macroscopic dimensions (e.g. Mesquita et al., 2005). Up to now, though, these are regarded as neither very likely (see e.g. Davies, 2004) nor potentially effective because of decoherence effects. The effect of entanglement on macroscopic objects and organisms is expected first and foremost at the molecular level (e.g. Ciquan et al., 1990). These can of course, as I have already mentioned several times, be amplified to have macroscopic consequences, but this is different from having macroscopic objects themselves entangled.

The system theoretical approach on the other hand suggests that even macroscopic objects of our everyday experience can be entangled, based on the assumption that some of the principles found to rule quantum-behavior are fundamental principles which also rule other systems, if these are (self-) organized in the appropriate way. In other words, entanglement is seen not as an exclusive property of subatomic and atomic entities but as a principle describing the behavior of systems in general (much in the same way as, for example, the principle of positive and negative feedback cycles occurs not only in neuronal systems but also in ecosystems, the stock market and many other systems (see the according paragraph in chapter 3.1 for references)). Ultimately, this is equivalent to postulating a synonymy of the words 'quantum' and 'system'. This means, in its most radical interpretation, that anything, any quantity that is somehow distinguishable from something else, should be considered a quantum, to which the same principles apply as to photons and electrons.

Two of the main questions which follow upon making this assumption are the following:

- What are the factors that would lead to entanglement within a system ?
- Are there any phenomena which could be instances of generalized entanglement?

In the following, I will chronologically introduce three theories which have postulated that non-local correlations occur in macroscopic systems, namely "Synchronicity", the "Model of Pragmatic Information" and "Weak Quantum Theory". All of them have proposed formulations for the conditions under which systems display generalized entanglement. I will briefly try to extract the essence of these proposed conditions and examine how they compare with the conditions I identified earlier for quantum mechanics. I will then propose a way in which these conditions can be summarized in simple language. Consequently, I will discuss a number of observations which could be interpreted as instances of macroscopic non-local correlations given that their phenomenology corresponds to what would be expected for non-local correlations. Finally I will try to formulate the conditions necessary for an experiment in which generalized entanglement could reproducibly be observed. (In chapter 4, I will then describe two experiments which I conducted in an attempt to realize exactly these conditions.) I will also discuss the possibility that such conditions are impossible to achieve not only in practice but also in principle.

3.5.1 Existing theories of generalized entanglement

3.5.1.1 Synchronicity

To my knowledge, the first theory postulating that non-causal correlations, analogous to quantum entanglement, could also occur in systems not traditionally considered by quantum physics, originated from a collaboration of Psychologist Carl Gustav Jung and Physicist Wolfgang Pauli.[90]

[90] Widely unknown to mainstream science today, Pauli had a very extensive personal and professional relationship with the psychologist Carl Gustav Jung (Atmanspacher et al., 1995; Atmanspacher and Primas, 1996; 2006). Their correspondence stretching over more than 25 years has been published (Meier et al., 1992).

As Jung put it (translation quoted from Walach, 2000):

"An unexpected content which unmediatedly or mediatedly relates to an objective outer event coincides with a common psychological state: this event I call synchronicity. I use the generic term synchronicity in the special sense of temporal coincidence of two or more events, which, however, are not causally related with each other and which have the same or similar content of meaning... Thus synchronicity in the first place refers to simultaneity of a certain psychological state with one or more outer events, which appear as meaningful parallels to the momentaneous subjective state and vice versa." (Jung, 1952, p. 31, p. 26)

Inspired by the observations in quantum physics, Jung proposed in the theory of Synchronicity that events can be non-causally correlated if they belong together in the sense of expressing a common underlying archetype (Jung and Pauli, 1955; Jung, 1973). With archetypes Jung meant ordering principles or patterns which are rooted in what Pauli and Jung call the "unus mundus", an underlying unity of reality in which mind and matter are undivided but nevertheless structured following certain primordial principles (see e.g. Jung, 1969).

While originally synchronicity referred primarily to a non-causal coincidence of 'inner' and 'outer' events in time, the meaning was later expanded, partly as a result of Pauli's input, to include basically any type of (non-causal) correlation between any meaningfully related events (for relevant quotes see e.g. Primas, 1996).

For Jung, one major motivation for developing the theory of Synchronicity was to explain parapsychological[91] phenomena which he had experienced, especially during childhood and youth (Jung and Jaffé, 1963; Wehr, 1985), and phenomena he repeatedly observed in his psychotherapeutic practice which he termed "meaningful coincidences" or "synchronicities".

To illustrate these phenomena, Jung gave several examples, one of which, in his own words *"concerns a young woman patient who, in spite of efforts made on both sides, proved to be psychologically inaccessible. The difficulty lay in the fact that she always knew better about everything. Her*

[91] In this thesis I will use the word 'parapsychological' for a collective of phenomena which have for example been termed telepathy, psychokinesis, haunting, precognition, clairvoyance, extrasensory perception, spirit healing, etc (for an overview see e.g. Irwin, 2004). The word parapsychology was introduced in or before 1889 by Max Dessoir in order to distinguish the rational investigation of such phenomena using only methods which are generally accepted in the scientific community from non-critical engagement with what then termed 'occult' phenomena (Dessoir, 1889; Hövelmann, 1987). Over time, however, this use of the word parapsychology deteriorated as it was adopted by wider circles of society and used for a large range of phenomena. Robert H. Thouless is credited with introducing around 1942 the term 'psi'-phenomena in a renewed search for a neutral term for parapsychological phenomena (Thouless, 1942a; b). I will, however, use the word parapsychology because this is still the common term within the field (i.e. journals, institutes and associations use it to describe their activities) and the meaning of the term 'psi' has meanwhile experienced comparable widening and blurring in meaning. Up to now no new and more suitable terminology has been established in the field. In my view 'causally inexplicable phenomena' or 'causally improbable phenomena' would be a good new characterization.

excellent education had provided her with a weapon ideally suited to this purpose, namely a highly polished Cartesian rationalism with an impeccably 'geometrical' idea of reality. After several fruitless attempts to sweeten her rationalism with a somewhat more human understanding, I had to confine myself to the hope that something unexpected and irrational would turn up, something that burst the intellectual retort into which she had sealed herself. Well, I was sitting opposite of her one day, with my back to the window, listening to her flow of rhetoric. She had an impressive dream the night before, in which someone had given her a golden scarab - a costly piece of jewellery. While she was still telling me this dream, I heard something behind me gently tapping on the window. I turned round and saw that it was a fairly large flying insect that was knocking against the window from outside in the obvious effort to get into the dark room. This seemed to me very strange. I opened the window immediately and caught the insect in the air as it flew in. It was a scarabaeid beetle, or common rose-chafer, whose golden green color most nearly resembles that of a golden scarab. I handed the beetle to my patient with the words "Here is your scarab." This broke the ice of her intellectual resistance. The treatment could now be continued with satisfactory results." (Jung, 1973)

Jung also had in mind phenomena which he called "counter-transference" (Jung, 1946; Kleinberens, 2007). The term counter-transference is nowadays often used to describe the process in which a therapist projects own psychological patterns onto his or her client in response to the patterns that the client projects onto him or her. Jung however also used the term counter-transference to include situations where a therapist consciously experiences mental states like feelings, thoughts and mental images, which turn out to be related to suppressed psychological content of the client of which the therapist had neither direct nor indirect previous knowledge.[92]

Pauli, too, was interested in parapsychological phenomena. In part this had to do with inexplicable experiences of his own[93] (see e.g. Pietschmann, 1995; Enz, 2002, p.115; Rößler, 2007). In addition he thought that these phenomena may provide a good starting point for the development of a complete theory which would unite psychology and physics, an ambition he shared with Jung (Laurikainen and Park, 1989; van Erkelens, 1991).

The analogy between the postulated non-causal correlation underlying "meaningful coincidences" and the non-local correlations of quantum entanglement was often alluded to but not explicated in any great detail by Jung or Pauli. (In this context it should be remembered that at the time when the theory of Synchronicity was formulated in 1952

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[92] Today, just as in Pauli's and Jung's times, the mere existence of the type of phenomena which they called "meaningful coincidences" remains disputed in scientific discourse. We will return to this discussion in more detail. It may be interesting to note here, however, that nowadays there exist whole schools of psychotherapy which use 'counter-transference' in the Jungian sense as one or even the main diagnostic and therapeutic tool (see e.g. Racker, 1957; Petzold, 1980; McLaughlin, 1981; Hübner, 2004; Kleinberens, 2007; Walach, 2007a).

[93] Among them, for example, frequent occasions of surprising and unlikely accidents and malfunctions which seemed to occur in his presence, a phenomenon which led to the famous humorous formulation of the so called "Pauli-Effect", or "Pauli's second exclusion principle": *"It is impossible that a Pauli and a working experimental apparatus are in the same room."* (see e.g. Enz, 2002, p.115, or Meier et al., 1992, p.37).

even the existence of non-local correlations in quantum mechanics was subject to considerable disagreement. Einstein[94] had laid some theoretical foundations in his publication with Podolsky and Rosen (Einstein et al., 1935) but it was only in 1964 that Bell formulated the first inequalities and not until 1982 that their final experimental confirmation was achieved by Alain Aspect and coworkers.

3.5.1.2 Model of Pragmatic Information (MPI)

The next major theoretical development with regard to non-locality as a general feature of reality came from the Model of Pragmatic Information (MPI) which was developed by Walter von Lucadou and Klaus Kornwachs (Kornwachs and von Lucadou, 1985; von Lucadou, 1995; 2006). The MPI uses the notion of pragmatic information in order to specify in more detail the necessary preconditions for the occurrence of non-local correlations in macroscopic systems. Pragmatic information is a term from information-theory which was introduced by E.U. and C. von Weizsäcker (1972; 1974) and further developed among others by C.F. von Weizsäcker (1971; 1985), Gernert (2006), Kornwachs and Lucadou (1985), Atmanspacher and Scheingraber (1992) and beim Graben (2006). It denotes, loosely speaking, the 'amount of meaning of an information' in the sense of the impact of a message upon its receiver. Instead of only measuring the pure information *content* in bits (the so-called Shannon-information[95]) it takes into account contextual information about the receiver of a message. In this way, it can quantify the *effect* a certain piece of information has. The larger the effect, the greater we can consider the meaning of the information.

One way in which pragmatic information has been formally characterized is as the product of two context-variables, namely novelty and confirmation. As an illustrative example, compare the situation of a person reading a newspaper in an unknown language as opposed to reading a newspaper in a familiar language: While the Shannon-information may be more or less equivalent in both cases, the pragmatic information is much larger in the case where this information can actually be interpreted by the reader (= confirmation). In addition, the meaning of this newspaper will be larger the first time it is read (= novelty), compared to the 100th time.

(A possible caveat in this context is that a definition of 'meaning' and/or pragmatic information in terms of the product of novelty and confirmation may be unnecessarily narrow. Actually, a wider definition might be possible, for example in the sense that to the degree that a change in A will lead to a change in B, A has an effect on B, and in this

[94] Einstein and his co-authors were the first to deduce the possibility of non-local correlations from quantum theory, but, ironically, assumed that this indicated an error or at least an incompleteness of quantum theory since *"No reasonable definition of reality could be expected to permit [the reality of a property of one system depend in any way on a measurement carried out at the other system]"* (Einstein et al., 1935).

[95] After Shannon, 1948. According to E.U. and C. von Weizsäcker (1998) Shannon's formula states that information is the negative logarithm of an event's probability and Shannon's co-worker Weaver (1949) stated that: *"Two messages, one heavily loaded with meaning, and the other pure nonsense, can be equivalent as regards information."*.

sense can be said to have meaning for B. Such a concept could more easily be applied also to effects where the terms novelty and confirmation are not necessarily applicable, for example some purely physical effects.)

According to von Lucadou, the amount of pragmatic information corresponds to the degree of organizational closure of a system, because it is the mutual meaning that parts of a system have for each other which unites them into a system and it is the unity of a system that creates the mutual interdependency of its parts. Organizational closure is a concept taken from Varela and Maturana who developed it in their formulation of the theory of autopoiesis (e.g. Varela et al., 1974; Maturana and Varela, 1980). Varela (1981) writes:

"An organizationally closed unity is defined as a composite unity by a network of interactions of components that (i) through their interactions recursively regenerate the network of interactions that produced them, and (ii) realize the network as a unity in the space in which the components exist by constituting and specifying the unity's boundaries as a cleavage from the background."

Based on these theoretical foundations the MPI formulates two fundamental theorems (von Lucadou, 2001b, my own translation[96]):

- First Theorem: Psi-phenomena are non-local correlations in psycho-physical systems which are induced by the pragmatic information produced by the (organizationally closed) system.

- Second theorem: Every attempt to use non-local correlations for signal transmission will make them disappear or change in an unpredictable manner

In the Model of Pragmatic Information von Lucadou thus postulates that the larger the flow of pragmatic information between two subsystems (i.e. the larger the organizational closure), the more these subsystems can be considered as one system and the more non-local correlation will occur between these subsystems (First Theorem). The occurrence of entanglement is however limited to such systems where the non-local correlations cannot be used for transmission of a signal. This second theorem von Lucadou derives from extrapolating the analogy to Eberhard's Principle in quantum mechanics (see chapter 2.3.2) as well as from system theoretical considerations. Namely, he shows that if signal transmission through a system is possible, the system boundaries change and the sender and receiver become part of the system, thereby destroying the organizational closure of the original system. The new system may or may not be conducive to entanglement

[96] The original in German reads as follows:

Erster Hauptsatz: Psi-Phänomene sind nichtlokale Korrelationen in psycho-physikalischen Systemen, die durch die pragmatische Information, die das (organisatorisch geschlossene)System erzeugt, induziert werden).

Zweiter Hauptsatz: Jeder Versuch, nichtlokale Korrelationen zur Signalübertragung zu verwenden, bringt diese zum Verschwinden oder ändert sie in unvorhersagbarer Weise.

depending on the way in which the new part of the system changes the system's eigenbehavior and/or degree of freedom.

Not unlike Jung and Pauli's Synchronicity Theory and the Observational Theories, von Lucadou's model was motivated by the search for a scientific theory which could make sense of parapsychological phenomena themselves and also of their apparent elusiveness under experimental conditions.
In a number of studies (e.g. von Lucadou, 2002; von Lucadou and Zahradnik, 2004) von Lucadou showed that the phenomenology of so-called parapsychological phenomena can indeed be matched closely to this theoretical framework. What is more, this theoretical understanding has enabled the development of practical counseling measures which reliably help people to deal with parapsychological phenomena (von Lucadou, 1997a; b; von Lucadou and Poser, 1997; von Lucadou, 2001a; 2003; Zahradnik, 2007). We will return to a more detailed discussion of parapsychological phenomenology in chapter 3.5.4.

3.5.1.3 Holistic Correlations

In 1996 Hans Primas published an in-depth reanalysis of Pauli and Jung's theory of Synchronicity in the light of the experimental confirmation of EPR correlations and using modern quantum theoretical formalism.

He comes to the conclusion that *"[…] between two kinematically independent subsystems A and B, there can exist holistic correlations if and only if there are incompatible properties both in A and B"* (Primas, 1996, my translation).

Seeing that Primas developed the concept of holistic correlations along the lines of a generalized Bell inequality, I am not sure to what extend this fundamental condition is really necessary for the *occurrence* of holistic correlations or only for their *differentiation* from causal correlations (see also chapter 2.3.2 for a discussion of this distinction).

Anyway, given that the condition is met, these holistic correlations are understood as a general description applicable both to EPR correlations (if it refers to two material quantum systems) and to synchronistic phenomena (if it refers to a mental and a physical system).

The question of whether incompatible properties can be found in mental systems he answers with tentative optimism, referring to Jung and Pauli's concept of quaternity, i.e. a mirroring of the wave-particle complementarity in the relationship between subconscious and conscious.

3.5.1.4 Weak Quantum Theory (WQT)

A further, very detailed investigation of the possibility of abstracting quantum theory to systems in general was conducted by Atmanspacher, Römer and Walach in 2002. Walach was initially searching for plausible explanations of purported effects in alternative medicine, especially homeopathy, and the apparent irreproducibility of these effects in clinical studies. Due to the striking similarity in phenomenology, he expanded his studies to include parapsychology. In their Weak Quantum Theory (Atmanspacher et al., 2002; von Lucadou et al., 2007) the authors show that the principal mathematical formalism of quantum mechanics, including entanglement, can be made generally applicable if some quantitative constants are relaxed which are specific for the subatomic and atomic dimensions, such as Heisenberg's uncertainty relation coefficient "ħ". They come to the conclusion that in any system where a global observable is complementary to local observables these local observables will correlate non-locally. Specifically they state (in Atmanspacher et al., 2002) that:

- Incompatibility and complementarity arise due to the non-commutativity of the multiplication of observables

- Holistic correlations and entanglement arise if for a composite system observables pertaining to the whole system are incompatible with observables of its parts

Although not mentioned in the original publication, the authors, in collaboration with von Lucadou, later added as an additional axiom the limitation that non-local correlations are not suitable to transmit signals. Based on this axiom, they predict that in systems where signal transmission is in principle possible, non-local correlations should not persist (von Lucadou et al., 2007).

While WQT makes very explicit its roots in the established quantum theoretical formalism it is not self-evident how it is to be correctly applied to macroscopic systems. This is to a large extent connected to the question, which we discussed in chapter 3.4, about what exactly constitutes complementarity in a general sense.
An additional challenge arises from the fact that WQT requires global and local observables to be defined which is not entirely straightforward outside of quantum theory *sensu stricto*. There, the combined wave function of the entangled quanta can arguably be defined as global observable whose potentiality is complementary to the actual observed states of the respective individual quanta which constitute the local observables. Alternatively the overall conserved quantity (for example a spin value of zero) could be regarded as complementary to the measurable states of the subsystems (e.g. negative and positive spin values). For macroscopic systems and everyday situations the concepts of global and local observables are less well defined. We will discuss this problem in more detail in the next section.

3.5.2 Comparison with entanglement in quantum theory

In the following I want to analyze how and to what extent generalized entanglement according to these theories is analogous (i.e. isomorphic) to quantum entanglement. While the original concept of Synchronicity seems too vague and I have not understood Primas' re-reasoning well enough to allow for such a statement, both WQT and MPI in my view mirror quite closely the conditions for entanglement as they are found in quantum physics proper. As analyzed in chapter 2.3, two factors are essential for quantum entanglement:

- Firstly, the individual behavior of the quanta under consideration is probabilistic, i.e. has certain degrees of freedom and unpredictability.

- Secondly, their individual behavior has to 'add up' to a certain collective behavior which is determined by an overall quantity that needs to be conserved because the overall system is causally isolated from the rest of the universe with respect to this quantity. The value of the conserved quantity is defined either by the common origin of the quanta or by the result of a measurement to which the quanta contribute collectively but indistinguishably.

As Schrödinger put it: *"The whole is in a certain state, the parts, considered by themselves, are not."* (Schrödinger, 1935a,p.827, my translation).

How, then, are these conditions reflected in MPI and WQT?

In MPI, the two theorems can, in my view, be matched to the situation in quantum theory in the following way:

The second theorem of MPI states that the proposed non-local correlations may not be used for signal transmission. This condition is satisfied only when the entangled events are, taken for themselves, totally probabilistic, i.e. impossible to determine or predict. As soon as they are to some degree predictable one can use them for signal transmission. The higher the degree of predictability, the better they can be used for signal transmission, because fewer events are necessary to achieve a discernible signal/noise ratio. Therefore I take the second theorem of MPI to be a 'degree of freedom'-requirement equivalent to the one apparent in quantum theory.

The first theorem of MPI states that entanglement is induced by the pragmatic information produced in an organizationally closed system. This may appear as a somewhat circular statement, since it is of course the pragmatic information which in the first place links any components together to form an organizationally closed system. What is meant here, however, by organizationally closed systems are systems which behave in such a way as to maintain a continuity of structure and function which is to some degree independent of external influences. This self-referentiality produces new pragmatic information for the components inside the system. As a consequence these systems

display something like a self-organizing and self-regulating activity geared towards a certain continuity and stability of system structure (identity) and system function and dynamics (behavior and development).
Among others, Francisco Varela has analyzed in depth this nature of self-organizing systems, leading to his formulation of the principle of autopoiesis. He pointed out that organizational closure leads to a stability of systems which he called "eigenbehavior", a term originally coined by Heinz von Foerster, (1976), following the quantum theoretical terminology of "eigenvalues". Varela (1981) writes: *"[…] one can […] represent a system as a network of interdependent variables, whose pattern of coherence (in the stable trajectories in their phase space) affords a criterion of distinction. [..] Closure is captured as the fixed-point solutions of such interdependence; such fix-points can be called eigenbehaviors, for they express the invariances specified by the system itself."*
A system's self-generated identity and behavior can thus be seen as quantities which are to some degree invariant and conserved within the whole system (see also e.g. Rocha, 1996 and references therein). Therefore one could see a system's identity and dynamics as analogous to the quantities (i.e. total angular momentum) which need to be conserved in quantum physical entanglement.

To formulate this first theorem of MPI from a slightly different perspective, one could say that in organizationally closed systems, because of their self-referential structure, each component contributes to a collective quality, namely structure and function of the system, and is in turn influenced by this structure and function and thus by all other components of the system. One could say that all of the components of an organizationally closed system share the information contributed by each of the components. In this process the contribution of the individual components becomes indistinguishable, which might indicate a further analogy with the situation in quantum entanglement.

How does WQT correspond to quantum theory? Personally, I find WQT's formulations somewhat harder to match to quantum theory and to interpret in a way which is both generalized and at the same time concrete and applicable and thus accessible to experiments. One main challenge, for example, is to generalize the notions of complementarity and non-commutativity. We could start, however, by adopting Walter von Lucadou's argument that structure (S) and function (F) of a system do not commute, as expressed in the following notation (von Lucadou, 1995):

$[SF - FS] \neq 0$ or $SF \neq FS$

It means that a measurement will result in different outcomes depending if we first measure the structure and then the function or vice versa. This seems plausible. (von Lucadou gives the drastic example of trying to investigate the function of a bird (i.e. its behavior) after first investigating its structure on the anatomy bench.)
One could then try to argue that function is an observable of the system as a whole whereas structure is an observable of its parts, because in order to describe the structure

of a system we have to describe the properties of its individual components, whereas to describe its function we have to refer to the overall result of that structure. If we choose to accept this proposal for global-local complementarity, we basically admit every system which has structure and function and which consists of parts to fulfill the conditions for entanglement as formulated by the WQT, because any such system by definition has a global description which is complementary to the description of its parts. This would on the other hand not necessarily have to mean that all systems should exhibit entanglement: The degree of complementarity depends on the degree of organizational closure since in less organizationally closed systems, structure and function and the properties of the individual parts are more independent of each other. With decreasing complementarity, entanglement should then also decrease.
To sum up, the conditions formulated by WQT can in my view be argued to represent an extremely generalized form of the first theorem of the MPI and the 'conservation-condition' from quantum physics.

What about the other condition, namely the probabilistic nature of the observable under consideration? Here WQT states that quantifiable probability is not among the necessary conditions but a degree of indeterminacy seems to be required:

"As in ordinary quantum theory, the result of a measurement is in general not determined by the state, but notice, that Generalized Quantum Theory, at least in its minimal version presented here, does not associate quantified probabilities to the outcomes of a measurement of an observable A." (quoted from von Lucadou et al., 2007)

3.5.3 Concise formulation

Having looked at existing formulations of generalized entanglement and quantum entanglement, first of all it is obvious that quite a few open questions remain, in particular regarding the precise meaning and applicability of the criteria formulated in WQT. Nevertheless, it appears that at least a certain degree of correspondence among the theories can be established, around the following main ideas:

- The principle of entanglement can be formally abstracted from the quantum physical substrate it was first discovered in and be applied to systems in general.

- Two factors appear particularly necessary for entanglement:

    - Closure of the system as a whole, its isolation with respect to a conserved quantity: a somehow fixed or determined frame or border of the system into which parts of the system have to fit, a global observable, an "eigenbehavior" of the system.
    - Degrees of freedom of subsystems: an unpredictable and as such indetermined behavior of the involved parts of the system.

- The behavior of those subsystems whose properties are of relevance to the overall conserved quantity or quality of the system, will then be individually unpredictable but collectively determined. Thus we will observe them as entangled.

- Entanglement cannot be used to transmit signals.

3.5.4 Possible examples of generalized entanglement

Interestingly, WQT predicts entanglement in an extremely generalized form:

"There is no way to generalize Bell's inequalities up to the general framework of weak quantum theory, and there is no way to argue that complementarity and indeterminacy in weak quantum theory are of ontic rather than epistemic nature. On the contrary, one would expect them to be of rather innocent epistemic origin in many cases, for instance, due to incomplete knowledge of the system or uncontrollable perturbations by observation." (quoted from Atmanspacher et al., 2002, p. 395)

This means that even local (causal) processes can be described in the generalized quantum theoretical formalism and may appear as generalized entanglement only as a consequence of epistemological limitations.

While this is extremely interesting and may possibly turn out to be the more far-reaching discovery, I feel that for most natural scientists at present the main novelty and excitement lie in the possibility of general entanglement in an ontological sense, that is to say in the potential existence of truly non-causal correlations in macroscopic systems. (The authors of the MPI and the theories of Holistic Correlations and Synchronicity do not explicitly consider this distinction but to me it seems clear that they, too, were most interested in this aspect of generalized entanglement.)

In the following, I will thus focus on phenomena where all causal explanations for the observed correlations are as much as possible excluded either through the nature of the phenomenon or through the experimental design.

3.5.4.1 Analysis of parapsychological phenomenology in the light of generalized entanglement

Although the potential applications may be much more far-reaching (see e.g. von Stillfried and Walach, 2006b; a; Walach et al., 2006 and chapter 3.5.4.2), the original conception of entanglement as a general systems-inherent principle in Synchronicity Theory, MPI and WQT was primarily motivated by an effort to find a new approach to the following longstanding dilemma regarding the controversy around anecdotal and experimental data in the area of parapsychology:

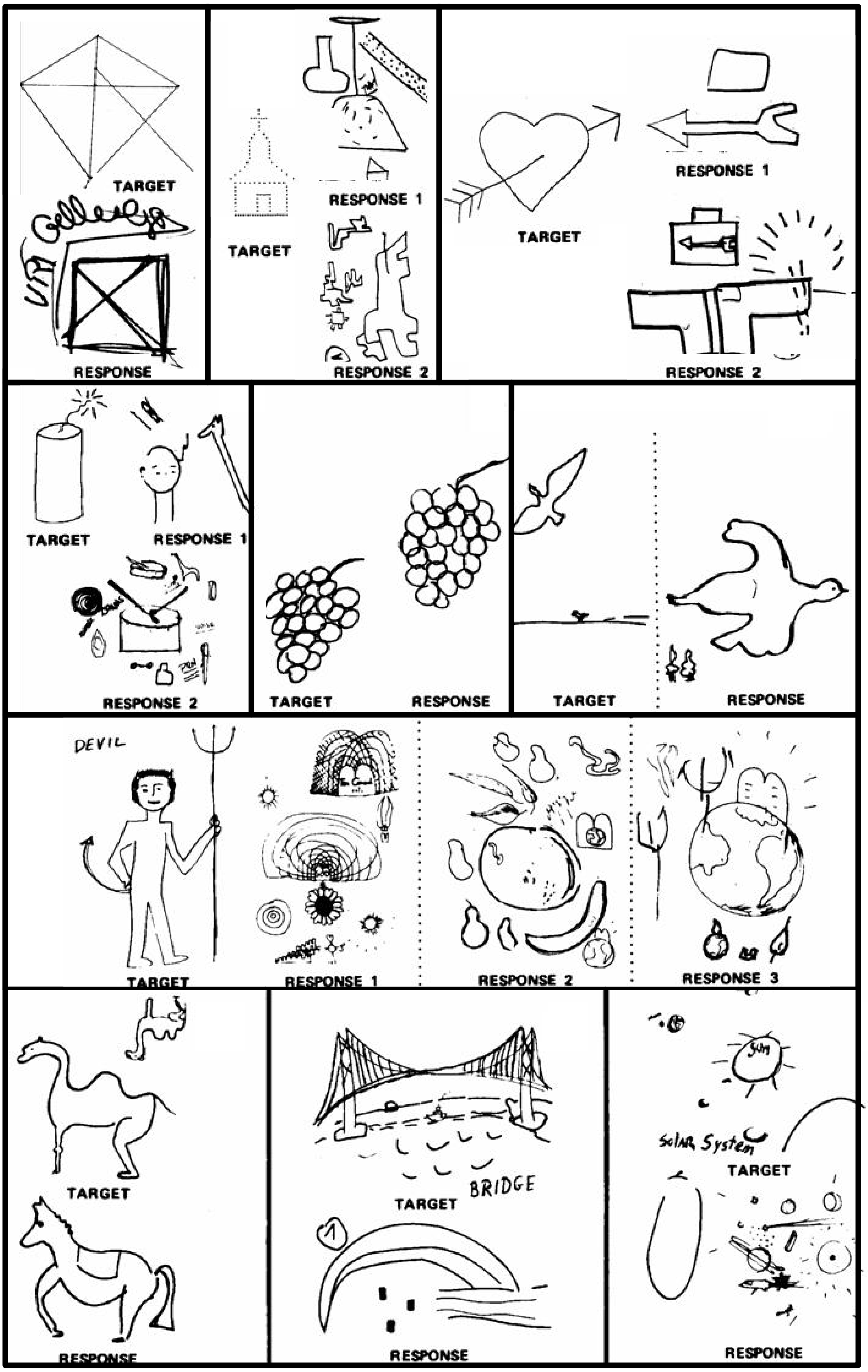
Largely unnoticed by mainstream science, phenomena such as telepathy, psychokinesis (mental influence on physical processes) and precognition (advance knowledge of future events) have been thoroughly investigated for more than a century (for an overview see e.g. Bauer, 1984; Rao and Rao, 2001; Parker and Brusewitz, 2003). Not least due to the high level of skepticism from the rest of the scientific community towards this area, the research was, on the whole, conducted according to quite high scientific standards, especially in more recent decades (see e.g. Mousseau, 2003). The overall result of this research effort is at first sight perplexing: there is still up to now not the slightest sign of a consensus regarding the existence or non-existence of the phenomena in question.
This becomes understandable when looking at the nature of the accumulated evidence: On the one hand, there is a wealth of high quality experiments which make plausible the reality of the phenomena. This is best reflected in the meta-analyses which have comprehensively analyzed all the accessible studies of various experimental paradigms such as psychokinesis (Radin and Nelson, 1989; Radin and Ferrari, 1991; Milton, 1993; Milton and Wiseman, 1999a; b; Storm and Ertel, 2001; Radin and Nelson, 2003b; a; Bösch et al., 2006), telepathy and other types of extrasensory perception (Bem and Honorton, 1994; Standford and Stein, 1994; Milton, 1997; Honorton et al., 1998; Steinkamp et al., 1998), precognition (Honorton and Ferrari, 1989; Steinkamp et al., 1998) and distant intentionality (i.e. mental influence on somebody else's physiology) (Schmidt et al., 2004). All of them except two (Milton and Wiseman, 1999a; b) report an overall effect which is small but statistically significant, in some cases even highly significant.

On the other hand, there is a large body of failed replication attempts and, to date, not a single experimental setup exists which produces stable results and would thus allow reliable replication of the observations. What is more, the effect size seems to shrink with progressing efforts to replicate the effects. Adding to the dilemma is the fact that plausible models of the underlying mechanisms are scarce and the existing ones are often in conflict with established scientific knowledge.

It is beyond the scope of this chapter to review in any more detail the field of parapsychology. Apart from referring to the above quoted meta-analyses, I will thus pick just one example which in my view illustrates the general situation in a particularly drastic way.
In this study, which was conducted by R. Targ and H. Puthoff and their research group at the Stanford Research Institute (Targ and Puthoff, 1974), a participant who claimed to have psychic abilities was isolated in a visually, acoustically and electromagnetically shielded room. After the room had been locked, a "target" picture was produced in a nearby office. The content of this picture was either (a) determined by opening a dictionary arbitrarily and drawing the first word that could be drawn (for Experiments 1-4); (b) prepared independently by scientists outside of the experimental group (following the participant's isolation) and provided to the experimenters during the course of the experiment (Experiments 5-7, 11-13); or (c) arbitrarily selected from a target pool decided upon in advance of daily experimentation (Experiments 8-10).

Under supervision through a one-way monitor, the participant then attempted to draw a "response-picture" which was supposed to resemble as closely as possible the target picture. In 3 of the 13 experiments (experiments 5-7), the participant did not produce a picture. The target and response pictures of all other experiments are presented in Figure 15. (No data was omitted.)

Figure 15: Results of an experiment on extrasensory perception (from Targ and Puthoff, 1974, by permission from Macmillan Publishers Ltd: NATURE, © 1974)



I think it is quite obvious why, on the basis of experimental observations like this, some scientists have become strongly convinced that 'there is something to' the so-called paranormal and have even risked their reputation and careers in an effort to convince others of this matter. And truly, if a person like the one tested here could at liberty reproduce this kind of experiment with the same rate of success for all those of us who need to see with their own eyes, soon only those who refuse to look would be left with doubts.

Such success, however, seems to have remained an unfulfilled hope for this as well as other, similarly remarkable experiments, of which there are a few. The effects have turned out not to be reproducible (Marks and Kammann, 1978b; Marks, 1986) or at least not reliably (Targ et al., 1991; Targ, 1994; Dunne and Jahn, 2003). This fact and the difficulty of developing plausible explanations of the underlying mechanisms have led to sustained discussions rather than a wider consensus regarding the existence or non-existence of the phenomenon (see e.g. the debate in the journal "Nature" (Targ and Puthoff, 1974; Hasted et al., 1975; Taylor, 1975; Marks and Kammann, 1978a; Tart et al., 1980; Marks, 1981; Puthoff and Targ, 1981; Marks and Scott, 1986; Marks, 1986; Targ, 1994), the 'New Scientist'[97] and elsewhere (e.g. Berendt, 1974; Cox, 1974; Randi, 1982).

This situation is typical for the state of parapsychological research regarding various classes of phenomena. While initially rather spectacular observations are reported, the effects seem to fade, disappear or change as soon as replication studies are undertaken.

It is interesting to note that the final evaluation of a 25 year parapsychological research program conducted by the CIA, partially in collaboration with Targ and Puthoff, comes to the same conclusion: On the one hand *"A statistically significant laboratory effort has been demonstrated in the sense that hits occur more often than chance."* On the other hand *"The information provided was inconsistent, inaccurate with regard to specifics, and required substantial subjective interpretation"* (Mumford et al., 1995). In other words, as communicated by the media, *"psychic power is real, but no good for spying"* (Wolf, 1995).

Pratt (1975) summarized the universal loss of psi effects with individual participants as follows: *"We must recognize what has been the most serious limitation on psi research with outstanding subjects. This is the unexplained loss of ability that has always brought their successful performance in the test situation to an end."* (p. 159)

A significant number of authors have meanwhile noted this "reproducibility-problem" as a characteristic feature of parapsychological research (e.g. Bierman, 1980; Braud, 1985; Stevenson, 1990; von Lucadou, 1991b; Batcheldor, 1994; Beloff, 1994; Houtkooper, 1994; White, 1994; Haraldsson and Houtkooper, 1995; Blackmore, 1999; Bierman, 2001;

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[97] Prompted by Hanlon (1974) this took place primarily in the following letters to the editor: 31. Oct. 1975: Gooch, Beloff, Bohm, Hasted; 7. Nov. 1975 November: Dixon, Targ, Puthoff. 14. Nov. 1975: Acker; 21. Nov. 1975: Hazell; 28. Nov. 1975: Creighton, O'Regan; 5. Dec. 1975: Honorton; 12. Dec. 1975: Mott, Otis.

Kennedy, 2001; Atmanspacher and Jahn, 2003; Dunne and Jahn, 2003; Kennedy, 2003; 2006; Walach et al., 2009). Harald Walach (2009) gives a good overview of the "reproducibility-problem" in a number of experimental paradigms in parapsychology and alternative healthcare.

Depending on certain preconception the "reproducibility-problem" is usually interpreted in different ways:
Those who, for whatever reason, feel that the phenomena are real argue that the conditions in the replication studies in some way inhibit the effect. The "psychic" participant might for example get bored or tired by the replication attempts or the skeptical mindset of the investigators could interfere with their abilities. The "psychic" participants themselves often express the conviction that their abilities are 'given to them' only to be used in particular circumstances, for example only to help people, and not for scientific curiosity.
Others, who doubt the existence of the phenomena in question, argue that failed replication attempts simply reveal the truth about the phenomena, namely their non-existence. One possible argument is, for example, that the successful experiments are only due to statistical artifacts: once in a while astonishing results will occur by mere chance, but when more experiments of the same type are conducted, these will average out. Others, in a similar vein, propose that the observed effects are due to publication biases: those studies which show an effect (due to mere statistical fluctuation) have a higher probability to be submitted and ultimately published than all the other 'failed' studies, thereby giving a false impression of the effect size (see e.g. Bösch et al., 2006). Another possible argument is that replication experiments correct initially flawed methodology. In the worst cases, the authors or participants of successful experiments which later fail to replicate are accused of fraud.

Without wanting to enter this discussion on any detailed level it shall suffice to note that all of these explanations have their 'pros' and 'cons' and none are entirely satisfying, leaving important questions open. Expectedly, 'believers' and 'skeptics' have focused on the respective part of the evidence which is in keeping with their own convictions. As a consequence, both sides accuse the other of bias. This can cause personal conflicts which lead to the formation of even more stubbornly divided camps.

Here no new evidence will be provided to tip the scale to either side. In my view, GQT can, however, offer a different interpretation of the phenomena which allows logically consistent sense to be made of *both* sides of the existing evidence, the extraordinary observations and the failure to replicate them. How?

Instead of starting with the question about the existence of the purported phenomena, let us first ask: "If the phenomenon were real, what could the underlying mechanism be?" A thorough assessment of the phenomenology leads to the conclusion that any explanation based on causal mechanisms faces serious challenges: Not taking into account large scale fraud, what causal explanation could there be, for example, for the telepathic-picture-guessing results presented above? Even more difficult to imagine is a potential causal mechanism linking a precognitive dream to the event it foresees let alone the other way around. And how should pure intention be able to causally influence physical processes? While arguments of this sort cannot absolutely rule out the possibility of some hitherto undiscovered or overlooked causal explanation, they do make plausible why it may be worthwhile to also consider thinking along totally different lines. Along with the authors of Synchronicity Theory, WQT and MPI, let us thus assume as a working hypothesis that instead of causal mechanisms there are non-causal correlations underlying this class of causally inexplicable phenomena. Non-causal correlations between random but meaningfully related events could in theory underlie both phenomena of extrasensory perception as well as psychokinesis.[98]

Based upon this hypothesis, we can now formulate a number of predictions: If there are non-local correlations at work in parapsychological phenomena then these should behave according to the same principles as the non-local correlations in quantum physics. We can thus predict that (possibly among other features) such parapsychological phenomena should occur in systems which are characterized by (1) a conserved global variable (whatever that might be) and (2) a high degree of freedom of the corresponding variables in the correlated subsystems. Furthermore (3) it should be impossible to use these phenomena for signal transmission and as such they should occur primarily in systems where this possibility is excluded in principle.

Are these predictions correct? Indeed, there are some indications which could support such a conclusion:

(1) With regards to conserved global variables, we are reminded of the "eigenvalues" and "eigenbehavior" of self-organizing systems as they have been described, for example, in the theory of autopoiesis by H. Maturana and F. Varela (Varela, 1981). We also know that the more organizationally closed a complex system is, the more stable its eigenbehavior will be (Varela, 1981). Walter von Lucadou has demonstrated the applicability of the concept of organizational closure to reports of paranormal and synchronistic phenomena and has shown that their intensity correlates with the level of organizational closure (von Lucadou, 1995; von Lucadou and Zahradnik, 2004; von Lucadou, 2006; von Lucadou et al., 2007). For example, in the case of telepathic or precognitive perceptions, the relationship between the people and/or events involved is often characterized by intensity and importance (close relatives, couples, deaths and accidents). For experimental investigations, those with a high degree of positive personal motivation on the part of

[98] In spontaneous real life situations these two types of phenomena may not even be distinguishable. For it is precisely the nature of a non-causal correlation that makes it impossible to say A caused B or B caused A. It is only when we conduct experiments (originally designed to detect causal correlations) that we introduce such a distinction. We call extrasensory perception those situations where some event is seen as given (i.e. as the predictable ‚independent variable') and the experimental participant becomes conscious of it. In the reverse case, when the participant's conscious intention is seen as a given and some external process enters into correlation with it, we speak about psychokinesis. As we will see, this attempt to 'fix' one side of the correlation may be the fatal flaw of any experimental investigation of generalized entanglement.

experimenters and participants are known to be more successful (Smith, 2003, Honorton et al., 1998, Targ et al., 1991; Heath and Heath, 2003).

(2) With regard to the necessary degrees of freedom in the subsystems, it is of interest to note that many of the paranormal divinatory techniques such as the 'Yì Jīng', Tarot cards, pendulums etc. consist of chance processes of very low predictability. What is more, psychological studies have shown that more 'volatile' states of consciousness (such as trance, deep meditation and dreaming (Kahn et al., 2000)) and less predictable personalities marked by high levels of dissociativity, associativity, absorption, fantasy proneness, and so-called transliminality are associated with a higher prevalence of psychic experiences (see e.g. Rao, 1992; Kennedy et al., 1994; Houtkooper and Haraldsson, 1997; Honorton et al., 1998; Palmer and Carpenter, 1998; Thalbourne, 1998; Lange et al., 2000; Tart, 2000; Kumar and Pekala, 2001; Braud, 2002; Gow et al., 2004; Nelson and Schwartz, 2006; Thalbourne and Maltby, 2008; Thalbourne, 2009).

(3) The prediction that for parapsychological phenomena to occur it should not be possible to use them for transmitting signals is a crucial point in relation to the reproducibility problem. This is because any standard experimental setup, from a system theoretical point of view, actually optimizes the system under investigation for signal transfer: By precisely defining dependent and independent variables and eliminating or controlling for confounding variables, ultimately the state of the independent variable can be predicted from observations of the dependent variable. When, even just in principle, it is possible to influence the independent variable, this is equivalent to being able to transmit a signal. With each replication of an experiment, the uncertainty about the precise relationship between independent and dependent variables decreases and thus its suitability for signal-transfer increases.[99] While this is exactly what one is looking for in scientific experiments dealing with causal mechanisms, it may be a fatal hindrance for all attempts at observing non-causal non-local correlations, because it will lead to a violation of the no-signal transmission condition, i.e. Eberhard's Principle. Thus, the correlations can be expected to break down under experimental conditions, as it is observed in parapsychological research. This process, also dubbed the "decline effect", should take place at the same rate as the potential for signal transmission increases. Von Lucadou has been able to show for some studies that the decrease in effect size is inversely proportional to the amount of pragmatic information that could in principle be extracted from a system and in fact obeys the mathematically determined lower limit (von Lucadou, 2001b; von Lucadou, 2002). Reported patterns of real life parapsychological phenomena also seem to correspond to this limitation (von Lucadou and Zahradnik, 2004).

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[99] For illustration: Consider for example measuring the reaction time of a person (dependent variable) after she has consumed on one occasion coffee and on another beer (independent variable). If a month later you measure her reaction time again, you may from that not be able to predict with certainty if she just had a coffee or a beer, because there are many possible confounding factors (tiredness, weather, medication etc…). If however, you repeat these measurements many times and in addition start controlling for confounding variables, you will soon be able to tell exactly. This means that, in theory, someone else could send you a (one bit) message by deciding what drink to buy that person before she comes to have the measurements taken.

It may be interesting to note in this context that parapsychological phenomena and abilities are often described as erratic and containing an element of vagueness and inaccuracy (see e.g. quotes in Kennedy, 2001; 2003; 2006). They have not allowed people to win repeatedly in lottery or stock market. Often it is only with help of additional information that they can be interpreted correctly.[100]

How then, one may ask, was an experimental proof of the existence of entanglement possible in quantum physics? This has to do with a fundamental difference between the situation in quantum physics and any experiments involving macroscopic systems. In macroscopic systems unpredictability and isolation are only ever possible to a relative degree. Therefore the degree of unpredictability necessarily decreases each time an experiment is repeated, thereby violating Eberhard's no-signal-transmission principle. In quantum physics, on the contrary, one can generate absolutely unpredictable variables and completely isolated systems. The limitations imposed by Eberhard's principle are still visible in the fact that each pair of correlated quanta can only be used for one measurement: After it interacts with the measurement apparatus, its isolation and unpredictability break down and the entanglement correlations are no longer visible. But when a new pair of entangled quanta is generated, their behavior is absolutely unpredictable again.

Summing up, we can say that the view of non-local correlations as general system-inherent processes can offer an alternative interpretation of otherwise hard-to-explain and highly controversial observations, which is grounded in well established scientific concepts, does not contradict existing knowledge and does not require additional metaphysical assumptions. While the similarity between non-local quantum correlations and some so-called paranormal phenomena does not provide further evidence for the existence of the latter, it can make more plausible their existence even in the absence of experimental evidence by giving an explanation for the specific restrictions which apply to their observability as well as indicating ways in which these phenomena can be experienced and dealt with constructively in real life situations (von Lucadou and Poser, 1997; von Lucadou and Zahradnik, 2001). In fact, the lack of experimental replicability of the phenomena in question not only becomes understandable from this perspective, but actually provides additional circumstantial evidence for this view.

[100] With regard to the impressive effects in the earlier mentioned telepathy study, it is interesting to note that the relationship between response and target is not always of the same kind: sometimes they match more graphically (e.g. camel and horse) sometimes more semantically (e.g. fire-cracker and drum). This variability reduces the possibility to reliably transmit a signal from the place where the target is produced to the place where the response is produced because looking at the response does initially not allow a very precise guess about the target. The more replications of the experiment are conducted, however, the more possible this will become (for example by coding a signal as a Morse code, alternating horse-like and not-horse-like pictures). Conversely, the less reliable the phenomenon will have to become.

3.5.4.2 Speculative relevance in other fields

Phenomena associated with spiritual practice

In most if not all mystical traditions and religions of the world there are numerous accounts of occurrences which are in stark opposition to any causal explanation. These range from levitation to telepathy, clairvoyance, prophetic precognition, spiritual healing, apparitions, materialization, dematerialization and many more (for some reports see e.g. Mensching, 1957; Keller and Keller, 1968; Ward, 1987; Houston, 1994; Hanauer, 1997; Harris, 1999; Targ and Katra, 1999; Wallace, 2003; Gitt, 2005; Herbers et al., 2005; Vellenga, 2007). While it is beyond the scope of this dissertation to go into any details of this subject matter, it shall simply be noted, for completeness sake, that with the potential existence of generalized entanglement in mind one can no longer exclude with any certainty the reality of these phenomena. For example, since spontaneous non-causal spatial displacement of macroscopic objects can only be considered extremely unlikely but not absolutely impossible (see chapter 3.2), a discussion of levitation, materialization etc. has to focus on plausibility rather than the often voiced argument regarding impossibility of existence due to violation of established scientific knowledge. This estimation of plausibility is an extremely difficult task firstly because very little definitive understanding of generalized entanglement is available let alone quantitative understanding of the factors involved. Secondly, cases differ greatly and always have to be regarded with all their individual peculiarities. It may, however, be interesting to note that in general the psychological changes aspired for on a spiritual path could, from a system theoretical point of view, be considered to be conducive to the occurrence of macroscopic entanglement phenomena. For example, the development of a strong and steady intentional orientation, coupled with a relaxation of control and a readiness for unexpected things to happen could be seen as allowing for global eigenbehavior and local unpredictability. The uncritical engagement with and for other people as well as the willingness to merge with higher causes and the wish to transcend ones limited viewpoint may in addition be associated with ways of engaging with systems in an immersive and participatory, rather than distanced and observational way.

Finally it can be noticed that there are some characteristics of these phenomena, which appear characteristic for generalized entanglement. For example, it is almost considered common sense that these kind of phenomena cannot be subjected to scientific let alone experimental study, an estimation which is confirmed by the reports of some scientists who have tried (e.g. Chari, 1959; Osis and Haraldsson, 1979; Haraldsson, 1987; Thomas, 1989; Wiseman and Haraldsson, 1995; Haraldsson and Wiseman, 1996; Haraldsson and Baba, 1997). At the same time, these investigations also resulted in some reasonably well documented case-studies of spontaneous occurrences which do not allow to dismiss the phenomena altogether too easily. This is reminiscent of the situation in parapsychology and analogue reasoning may apply.

Symbols and Rituals

Since, according to GQT, non-local correlations are essentially the result of relations within and boundaries around systems we could also say they are the result of the distribution of meaning within reality.

In countless ways throughout history have humans created rituals and symbols by attributing to certain actions or things a certain meaning.

In addition to the usually unquestioned psychological effects (autosuggestion, social bonding etc.) such behavior may thus also lead to the formation of systems and system dynamics which are conducive to the occurrence of non-causal correlations.

For example: If, for whatever reason, an ordinary stone is being attributed with curative powers by someone this stone will become more important to this person. This means, that any change in this particular stone (e.g. its destruction) will cause a greater change in the person than a change to any other less important object. From a purely system theoretical point of view, a system has thus formed including those who attribute the meaning and the object of the meaning attribution.
According to my interpretation of GQT, variables of subsystems of this system with sufficient degree of freedom will now non-locally correlate in such a way as to conserve the global system parameters characterizing this system. Given that one defined global quality of the system is the facilitation of healing, this may indeed occur through unpredictable events within the subsystems, in particular the largely chaotic and thus quasi-unpredictable system of human physiology.

Possibly W. Pauli had a similar understanding when he wrote *"What I have in mind when I talk about the new idea of reality I would try to call the idea of the reality of symbols."*[101]

Effects in complementary and alternative medicine

Interestingly, the area of research into complementary and alternative medicine (CAM), which has received growing interest in the last decades, seems to be encountering a situation similar to parapsychology (Walach, 2005b): Individuals report substantial benefits from alternative methods such as homeopathy and the CAM market is booming (even though people are often paying out of their own pocket, since CAM is not covered by most health insurances). At the same time, scientific proof of efficacy is largely lacking. Individual studies have detected promising effects of various CAM treatments, but these effects are often not reproducible except for a general placebo effect. What is more, many of the effects seem very hard to explain even theoretically by any causal mechanisms.

[101] In a letter to Markus Fierz 8. Aug. 1948, my translation. The German original reads: *"Was mir unter der neuen Wirklichkeitsidee vorschwebt, möchte ich versuchsweise nennen: die Idee der Wirklichkeit des Symbols."*

How, for example, could a homeopathic remedy possibly have a specific causal effect if due to the typical dilution procedure it does not even contain a single atom of the substance it was originally prepared from? By and large, the same reasoning as for parapsychological phenomena can be used in dealing with these effects. For more detail, in particular regarding the way in which homeopathy can be seen as isomorphic to quantum entanglement see e.g. Schlitz and Braud, 1997; Walach, 2000; 2001; Milgrom, 2002; Hyland, 2003b; a; Milgrom, 2003b; a; Walach, 2003; Dossey, 2004; Hyland, 2004; Kennedy, 2004; Smith, 2004; Baumgartner, 2005; Hankey, 2005; Lewith et al., 2005; Milgrom, 2005; Schmid, 2005; Walach et al., 2005a; Milgrom, 2006; Weingärtner, 2006; Hankey, 2007; Dossey, 2008; Hankey, 2008.
A very interesting study was recently conducted by Anja Matschuk (2010) on the phenomenology of clairvoyant 'readings' in therapeutic settings. Qualitative analysis revealed a close match with predictions derived from the Model of Pragmatic Information and Weak Quantum Theory. As mentioned earlier, Thorsten Kleinberens (2007), too, showed in a different context that a therapists' extrasensory perception of conscious content belonging to the client displays characteristics which would be expected based on WQT and MPI.
A widespread therapeutic and consultative technique which seems to capitalizes strongly on (extra)sensory phenomena which are difficult to explain causally, is the so called constellation work. The potential relevance of quantum physical concepts, in particular entanglement, for the theoretical understanding of the underlying mechanisms, has been noted by several authors (e.g. Boulton, 2006; Schneider, 2007; Mahr, 2008). Due to the simplicity of the method and the frequent occurrence of causally inexplicable phenomena, constellation work might be a good field for empirical research on potential macroscopic entanglement correlations.

Evolution

Some authors have voiced doubts whether a mechanism composed solely of random mutation and environmental selection would have been able to produce the complex and varied biosphere that we encounter today, given the observed rates of mutation and the time available for evolution (e.g. Moorhead and Kaplan, 1967; Gould and Eldredge, 1977; Cairns-Smith, 1982; Hoyle and Wickramasinghe, 1982; Hartl et al., 1985; Bradley, 1988; Hall, 1988; Ankerberg and Weldon, 1994; Behe, 2001; McFadden, 2001).

From a system theoretical perspective, there may, however, be a possible explanation of how systems can evolve into seemingly very unlikely states in relatively short time span. Ecosystems are composed of subsystems of more or less co-dependent and interacting species and environmental parameters. One could argue that, if non-local correlations do occur as a result of systems closure, random environmental changes and random mutations might in fact correlate in such a way that a given global observable is conserved. Possible candidates for such a global observable may be, on the individual and species level, survival and reproduction and on the ecosphere level maximal energy use, which in turn may be connected to a global observable of the physical universe, namely entropy maximization. This would match with recent proposals in eco-system thermodynamics (see e.g. Schneider and Kay, 1993; 1997; Toussaint and Schneider, 1998; Virgo and Harvey, 2007).

Alternatively or additionally, autopoietic system dynamics may be seen as producing eigenvalues which could serve as the conserved global quantities.

The binding problem

This problem in neuroscience relates to the open question of how the brain, which processes different aspects of a stimulus (e.g. color, shape and movement) in different areas of the cortex at different times (e.g. due to different lengths of signaling pathways), can facilitate a unitary perception of this stimulus (e.g. a red ball flying towards me). How are the different stimulus-aspects bound together during or after processing?

The currently most favored hypothesis states that those neurons involved in processing different aspects of one stimulus fire in synchronous rhythms, thereby somehow identifying themselves as belonging together (Singer, 2007). Empirical data for this hypothesis is ambiguous but overall supportive (e.g. Shadlen and Movshon, 1999; Thiele, 2003; Singer, 2004; Palanca and DeAngelis, 2005). Either way, the question remains, how the neurons become synchronized in the first place.[102]

Potentially (generalized) entanglement could provide a possible approach to this question.
Firstly, there are proposals of actual quantum mechanical entanglement occurring at relevant temporal and spatial dimensions because of a shielding from decoherence by microtubules (e.g. Mavromatos and Nanopoulos, 1998; Hameroff, 2007) which others, however, dispute (e.g. Tegmark, 2000).
Secondly, the brain has been described by a few authors as displaying system theoretical analogies to quantum systems although this, too, is not common ground (e.g. Vitiello, 1995; Pessa and Vitiello, 2004; Behera et al., 2006; Marcin, 2009). It has also been noted specifically that particular neural networks, with different topologies, can be regarded as quantum states (Altman et al., 2004).

Other biological processes

A few authors have shown that if organisms could base their decision making upon correlated chance events, this would result in a much increased efficacy (Josephson and Pallikari-Viras, 1991; Brukner et al., 2005; Summhammer, 2005; Bovino et al., 2007).

[102] Leaving aside for the moment the much more fundamental question of how an ensemble of neurons firing in synchrony could be related to a subjective experience of unity of perception (see chapter 3.4.3 on the mind-body problem).

While these authors assume that actual entangled quanta are necessary for such a process to take place, generalized entanglement could be understood to predict that such correlations can also take place without involving quantum mechanical entanglement in the strict sense. Generalized entanglement would thus provide a general coordination mechanism in addition to causal interactions. It could potentially explain how coordinative processes take place be it in large scale or widely separated ecosystems or also on small scales such as the detection of extremely diluted molecules by corresponding receptors.

3.5.5 Implications for possible experimental designs

Based on the theoretical understanding of generalized entanglement developed above (see summary in chapter 3.5.3) I will now outline the conditions which should be fulfilled in an ideal experimental setup, designed to detect generalized entanglement.

The following factors seem essential to me:

a} A organizationally closed system that is subject to a conservation law, which may also be the systems own self-referential structure and/or dynamic, i.e. an eigenbehavior.

b} The possibility to observe subsystems of this system which are related to this eigenbehavior, i.e. those subsystems which in some way contribute to the quantity or quality to be conserved. If there is entanglement it will be between those.

c} At the same time, the relevant subsystems and their properties or behavior must be in principle unpredictable, which also means they must be impossible to manipulate.

c'} If, however, someone or something is able to predict or manipulate these components and their properties, even just in principle, this person or object has to be regarded as part of the system under study and must thus fulfill conditions *a}* and *b}*

d} It must be possible to distinguish correlations caused by entanglement from causal correlations and mere chance correlations.

For a successful experimental proof in the conventional sense *a}, b}, c}* and *d}* need to be fulfilled for the first experiment and all replications. My suspicion at the moment is that in any one experiment it is only ever possible to simultaneously satisfy *a}, b}* and *c}* but not *d}* or alternatively *a}, b}, c'}* and *d}* where *c'}*, however, gives a new meaning to *a}, b}* and *d}* because it introduces my first-person subjective experience and behavior as a central factor.

To illustrate how I arrive at this suspicion, I will explore three different possible approaches for observing generalized entanglement, while keeping in mind the conditions I have arrived at through the theoretical analysis so far:

1) As the experimenter, I could choose an organizationally closed system (*a*} is satisfied) of which I had no previous knowledge and which has developed without any influence from my side. In this way the development of the system and its observables are unpredictable to me and beyond my influence (*c*} is satisfied). (For example, I could choose a family system.) I then probe the system for correlations. I will naturally find a lot of correlations between observables which also seem to conserve a whole systems property (*b*} may be satisfied). (For example, one of the couple specializes in raising children while the other one specializes in earning money, a combination that may optimally 'con-serve' the system's function of reproduction.) But, unfortunately, I cannot decide with certainty whether these correlations are non-causal or purely accidental or based on causal interaction between the system's components. In the case of human systems I could let the system-components themselves report to me any correlations they experienced which they consider meaningful and unaccounted for by causal mechanisms (for example telepathic experiences). I cannot, however, decide if their judgment is correct nor can I calculate significance levels for the reported events (*d*} is not satisfied).

2) I can then decide to observe the organizationally closed system (i.e. the above family) more closely, possibly without interfering with the organizational closure or only to a small degree (*a*} may still be satisfied). I can then identify observables of the subsystems which stand in relation to an observable of the systems as a whole and which correlate reliably (*b*} is satisfied). I could then, by repeated observation, statistically distinguish these correlations from mere chance correlations (*d*} would become satisfied). However, as soon as I understand the nature of their correlation (i.e. what global observable is being conserved and how), there comes a problem: if there is, even only in principle, the faintest possibility of manipulating these observables their unpredictability is no longer given (*c*} is not fulfilled). This means that I could use the correlations for signal transmission which in turn is equivalent to the notion that I have become part of the system. Hence *c'*} is required.

3) I must thus accept the fact that the original organizational closure has been disrupted and I have become part of the system or rather a new system has formed. In order to be able to observe entanglement correlations this new system has to again fulfill conditions *a*}, *b*}, and *c*}. This means that there must be a global eigenbehavior of the system, to which some of the parts are relevant, and the behavior of these parts must be autonomous, unpredictable and independent from the environment outside of the system. Notice that I, the experimenter, have now shifted from an exo-perspective to an endo-perspective (see Atmanspacher and Dalenoort, 1994; Primas, 1994; Atmanspacher, 1996; Rössler, 1998), or even more drastically, I have fused with the previous object of my investigation. What I will experience as part of this new system will depend entirely on the system and my role within in. If my behavior and the system as a whole are conducive to

entanglement correlations I may experience or observe them.[103] But since that means that I need to be ‘co-creative’, in the sense that, for example, my own behavior must be unpredictable and independent from the outside of the system and primarily serve the systems global eigenbehavior, I have lost all attributes that make me a serious researcher in the eyes of today’s science. Objectivity, falsifiability and reproducibility of my observations are no longer given. When I report my experiences from the endo-perspective of a system to another scientist, he or she can only investigate my claims using the approaches 1), 2) and 3) outlined here, with the same result.

Essentially, I have arrived at a very pessimistic view about the possibility to prove the existence of parapsychological phenomena reproducibly, in the sense that today’s scientific paradigm defines ‘prove’. It seems very likely to me that if the phenomena exist, they are to some extend based on non-causal mechanisms, i.e. non-local correlations. Such correlations can only occur in conditions where they do not, even in principle, allow for signal transmission and thus do not violate space-time continuity (see chapter 2.3.2). In quantum physics this condition is fulfilled when the value of the entangled observables is absolutely unpredictable, as for example in the EPR experiment described in chapter 2.3.1. In macroscopic reality, this unpredictability is limited due to decoherence and the ‘averaging’ of the probabilistic behavior of the innumerable quanta involved in macroscopic systems (chapter 3.2). This is not so much a problem in unique and spontaneous real life situations, where the remaining unpredictability can successfully prevent signal transmission. When we attempt, however, to simulate such a situation as an experiment we will always run into the difficulty of being capable, at least in principle, to manipulate and predict the respective observables. Especially when the same experiment is repeated several times the predictability increases to the level where signal transmission is in principle possible.[104]

Maybe at this point a reminder would be helpful, of what exactly constitutes a signal transmission and what does not. The decisive point is not that there should not be a reliable correlation between the two entangled variables. This is, after all, the case in quantum physics, where the entangled observables match with unfailing accuracy: After measuring the state of one of a pair of entangled quanta one knows with absolute certainty the state of the other. This perfect correlation is, however, confined to *within* the entangled system. The measurement outcome is absolutely unpredictable because it does not correlate with anything *outside* of this system. A signal transmission, in the sense in which I use the word here, only occurs if an *external* receiver can obtain information about

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[103] This may also be part of an explanation of the often reported non-classical “experimenter effect“: There is some indication that the outcome of parapsychological experiments depends to some degree on the experimenters, in particular their beliefs about the existence of the phenomena in question and their intention in conducting the experiment. (For an overview see e.g. Wiseman and Schlitz, 1997; Palmer, 2002; Smith, 2003). If a system is formed with the intention to disprove the existence of non-local correlations therein, this is going to be (at least part of) the system’s eigenbehaviour and vice versa.

[104] Theoretically, even the most minute deviation from absolute unpredictability can be accumulated to a usable signal to noise ratio.

an *external* sender *via* the entangled system. This implies that the sender exerts some kind of influence onto (part of) the entangled system or is at least able to predict its behavior.

There are only two ways in which we can exclude the possibility of exerting an outside influence onto a system or predicting its behavior: one is leaving it alone and the other one is becoming ourselves part of the system and taking care that our behavior is ruled only by system-internal factors. The latter approach may be the most promising for anyone who authentically wants to find out about the existence of non-causal phenomena (compare e.g. Kennedy, 2000) but both ways do not lead to observations that can be reliably replicated in the sense that they would amount to a scientific proof.

As things can go, I came to these conclusions only after I had spent much time and effort conducting experiments in the hope to develop an experimental paradigm where non-local correlations in macroscopic systems could be reliably observed. My supervisor Harald Walach and I had some ideas, based on our theoretical understanding at the time, of how it might be possible to create an experimental situation that fulfils all the requirements for generalized entanglement and at the same time circumvents the no-signal-transmission principle.
From my current point of view, as outlined above, these experiments were probably doomed to fail from the beginning. And indeed, nothing in the results points to the occurrence of any non-causal correlations.
Nevertheless, in the following chapter I will report in detail on the experimental work conducted in this context, including the rationales which led to the different setups and a discussion of their shortcomings as I see them now. I hope that describing them here may least prevent others from repeating my mistakes and at best inspire some better ideas in the readers.

4. Experimental approaches to testing GQT with regard to entanglement

4.1 Entanglement through 'indistinguishability'?

4.1.1 Introduction and rationale

The first experimental set-up to investigate the hypothesis of systems inherent non-local correlations was inspired by the findings of a large meta-analysis of double-blind randomized placebo controlled clinical trials (RCTs)[105] which indicated a high correlation ($r = 0{,}78$; $p < 0{,}001$)[106] between effect sizes in treated ("verum") and untreated ("placebo") collectives of participants in (Maidhof et al., 2000; Walach et al., 2005b). Even when a number of possible confounding factors are taken into account, the correlation appears robust. Given the momentary lack of alternative explanations the authors hypothesized that generalized entanglement might have occurred between verum and placebo groups due to their systemic organization and in this way be responsible for the observed correlation.

From the perspective of Weak Quantum Theory (WQT), verum and placebo groups could indeed be seen as subsystems of a larger system, namely the entire clinical trial. One can further speculate that the specific allocation of either a verum or placebo treatment to members of each group might be considered local observables pertaining to the subsystems and, accordingly, the blinding of the entire trial might be considered a global observable pertaining to the system as a whole. These local and global observables could then be regarded as complementary because they can not both be realized at the same time with arbitrary precision in the same person. If these assumptions were correct, WQT would predict entanglement to occur between the subsystems, i.e. the verum and the placebo group, which could account for a correlation between placebo effect sizes and verum effect sizes.

In the analogous quantum physical situation, entanglement arises in a system where the wave function (global observable) is complementary to the measured states of the

[105] Double blind randomized placebo controlled clinical trials (RCTs) are the currently most widely used format for pharmaco-medical studies. It entails splitting a certain group of study participants randomly into two groups. Participants in one group are then administered the pharmaceutical to be tested (the so-called verum-treatment) while the other group is administered an indistinguishable treatment that, however, lacks the crucial pharmaceutical ingredient (the so-called placebo-treatment). Since the treatments are indistinguishable, neither the participants nor the doctors know whether they are administering a verum or placebo treatment (hence the name: double-blind).

[106] Here, 'r' is the so-called Pearson correlation coefficient. It can range from 1 to -1 and indicates the strength and direction of a correlation between two datasets. The value of 'p' indicates the expected fraction of α-errors (false positives) committed when rejecting the null hypothesis (in this case the null hypothesis states that the two datasets do not correlate).

entangled quanta (local observables), because the former is a superposed probability distribution and the latter are discrete states.

Another way in which this experimental situation can be regarded analogous to quantum physical systems displaying entanglement is that it induces a certain degree of indistinguishability between the subsystems, through the blinding procedure.

In order to experimentally investigate the hypothesis that the systemic organization of randomized controlled clinical trials (RCTs) leads to entanglement between the verum and placebo groups, a biochemical *in vitro* model-system was designed which from a system theoretical point of view corresponds to an RCT but can be implemented at much smaller financial and logistical expense and allows for more exact replication experiments.

4.1.2 Pilot experiments

4.1.2.1 Material and Methods

Initially, we used bacterial cell cultures (*Pseudomonas putida,* ATCC 27853[107]) which would be treated with a growth-inhibiting 'verum'-solution (e.g. an antibiotic) or an ineffective 'placebo'-solution which was indistinguishable from the 'verum' solution to the experimenter. However, preliminary experiments soon revealed that the bacterial growth rates varied strongly from culture to culture (as determined by microscope cell counts and ATP concentration measurements after 4h and 8h incubation in LB medium[108] at 37°C) so that in order to conduct an experiment which would be statistically sensitive to potentially small effects we would have to use an unrealistically high number of cultures.

In an effort to further refine the experimental system we then chose an enzyme reaction in which luciferin is oxidized in the presence of the enzyme luciferase and adenosine triphosphate (ATP). In the oxidation process a photon is emitted (Figure 16). This particular reaction was chosen because the reaction rate can be measured without having to interfere with the reaction itself by monitoring photometrically the emitted photons, thus limiting the disturbance of any hypothetical organizational closure. Another advantage of the luciferase reaction is that it is frequently used in research and thus a large body of experience exists and the complete enzyme system can be conveniently purchased as a readymade kit. *ViaLight Plus* from Cambrex, Belgium was chosen after comparing it with similar kits (*KinaseGlo*, Promega, USA, and *ViaLight MDA*, Cambrex) because it had the additional advantage of a stable reaction rate over a relatively long time.

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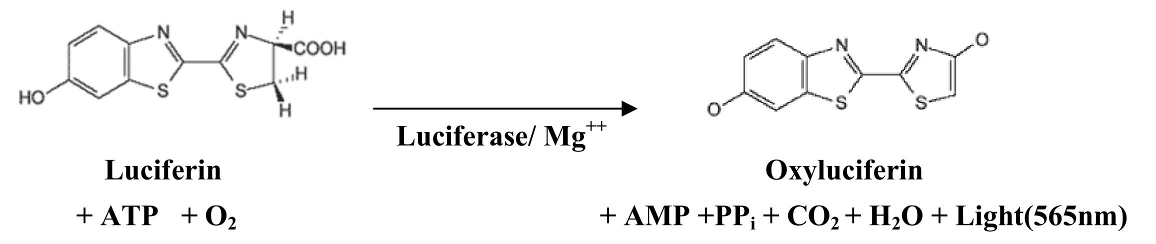
[107] *P. putida* is a very common non-pathogenic soil-bacterium; ATCC stands for American Type Culture Collection, which is a provider of standardized microbial strains and cell lines, the number identifies the exact strain.

[108] LB medium stand for Luria-Bertani medium or lysogeny broth, which is a most frequently used growth medium for bacteria, containing yeast extract, trypton and salt.

Figure16: Equation for luciferase reaction



(PP_i= inorganic phosphorus, AMP= adenosine monophosphate, Mg^{++}= magnesium ions)

This luciferase reaction can be inhibited by a number of molecules which are structurally similar to ATP, because these molecules also bind to the binding site of ATP on the luciferase enzyme (competitive inhibition) or potentially to other areas (allosteric inhibition) (Ugarova, 1989). A number of substances were tested and Adenosin monophosphate (AMP) was selected for highest and most precise inhibition effects.

In our experiments we thus used the addition of aqueous AMP solution as the experimental condition (i.e. the ‘verum’) and the addition of an equal volume of distilled water as the control condition (i.e. the ‘placebo’) because these liquids cannot be distinguished by an experimenter without technical aid, as confirmed in a forced choice trial.

On eight so-called multi-well-plates (*96-well LIA plates* from Greiner Bio-One, Germany) each well was loaded with 50µl buffer solution and 50µl of 5µM aqueous ATP (Sigma-Aldrich, Germany) solution. Subsequently either 50µl of 1mM aqueous AMP (Sigma-Aldrich, Germany) solution or an equal volume of double distilled water (ddH_2O) was added. Finally 50µl of the reaction solution containing the luciferase enzyme was added to start the reaction.

In order to minimize variability due to variation in reaction times, the experimental procedures were scheduled as accurately as possible for all wells so that all wells were roughly ‘in phase’: Buffer was added at time (t)=0, ATP solution at ca. t=12min, AMP solution or water 50µl at ca. t=1h 50min, luciferase solution at ca. t=3h10min.

The plates were then placed on a stirring table for 1min at 130rpm in order to assure thorough mixing of the reaction components. After storage in darkness for 12mins for elimination of plate-inherent luminescence[109] the photon emission from the wells was measured for 1sec per well in a luminometer (*ViktorLight* from Wallac, Finland, now

[109] Apparently the plastic plates absorb and re-emit energy from sunlight and laboratory lighting which leads to auto-luminescence (after-glow) of the plates.

PerkinElmer, USA) at ca. t=3h26min (Measurement M1). As an additional option to gain more information, the measurement was repeated at ca. t=20h (M2) and t=96h (M3).

Wells where any irregularity occurred (e.g. contamination or spillage) were recorded and later excluded from analysis.

In order to avoid classical experimenter effects (e.g. subconscious pipetting or handling bias) 'Placebo' and 'Verum' solutions were transferred simultaneously using a 12-channel electronic pipette (*Research* from Eppendorf, Germany) from a 'master plate' where on one half of the plate each well was filled with 250µl of aqueous AMP Solution ('verum') and on the other half of the plate each well was filled with 250µl of water ('placebo'). Half of the plates were loaded from master plates where the experimenters knew which side contained the 'verum' and which side contained the 'placebo' (We shall call this the 'distinguishable condition'). The other half of the plates where loaded from master plates where the experimenters did not know which side contained the 'verum' and which side contained the 'placebo' because the solutions had been randomly labeled by a person who was not involved with the rest of the experiment and the solutions cannot be distinguished visually or otherwise. (We shall call this the 'indistinguishable condition'.) This and all subsequent handling of the distinguishable and indistinguishable plates happened in an alternating way in order to minimize variance between both groups by spreading the influence of any temporal effects as evenly as possible over both groups.

There were hence four different conditions in this experimental setup as illustrated below: The reactions with 'verum' or 'placebo' in the 'distinguishable condition' (V and P) and the reactions with 'verum' or 'placebo' in the 'indistinguishable condition' (Y and X) (Figure 17).

Figure 17: Schematic representation of 96-well plates in pilot experiments (X and Y represent the unknown reagents in the indistinguishable condition, V and P stand for 'Verum' and 'Placebo' in the distinguishable condition.)

X	X	X	X	X	X	Y	Y	Y	Y	Y	Y
X	X	X	X	X	X	Y	Y	Y	Y	Y	Y
X	X	X	X	X	X	Y	Y	Y	Y	Y	Y
X	X	X	X	X	X	Y	Y	Y	Y	Y	Y
X	X	X	X	X	X	Y	Y	Y	Y	Y	Y
X	X	X	X	X	X	Y	Y	Y	Y	Y	Y
X	X	X	X	X	X	Y	Y	Y	Y	Y	Y
X	X	X	X	X	X	Y	Y	Y	Y	Y	Y

V	V	V	V	V	V	P	P	P	P	P	P
V	V	V	V	V	V	P	P	P	P	P	P
V	V	V	V	V	V	P	P	P	P	P	P
V	V	V	V	V	V	P	P	P	P	P	P
V	V	V	V	V	V	P	P	P	P	P	P
V	V	V	V	V	V	P	P	P	P	P	P
V	V	V	V	V	V	P	P	P	P	P	P
V	V	V	V	V	V	P	P	P	P	P	P

After collection of the measurement results the experimenters were unblinded and the conditions were labeled as follows:

Indistinguishable 'Verum'= V_I, Indistinguishable 'Placebo'=P_I, Distinguishable 'Verum'= V_D, Distinguishable 'Placebo'= P_D

4.1.2.2 Analysis

Since previous experiments with psycho-physical systems have sometimes shown no changes in the mean of outcome variables but did instead show significant changes in the variance of outcome variables it was decided in these experiments to include both mean photon counts and variance of photon counts in the formulation of the null hypothesis.

Our null hypothesis (H_0) was that no significant differences will be detected between the indistinguishable condition and the distinguishable condition, with respect to these measures:

H_0: $V_I = V_D \wedge P_I = P_D$

Our primary hypothesis (H_1) was that any potential entanglement in the indistinguishable condition would lead to a convergence or divergence of reaction rates or variances:

H1: $V_I \neq V_D \vee P_I \neq P_D$

The Levene F-test was chosen for comparison of variances[110], and the Student *t*-test was chosen for comparison of means. Significance levels for both tests were calculated 2-tailed, because H_1 is not a directed hypothesis (i.e. it would have to be rejected if mean or variance in one of the groups were significantly higher *or* lower than in the other group). The *t*-test was carried out for homoscedastic or heteroscedastic samples[111] depending to the results of the Levene F-test.
In addition, the Brown-Forsythe test for equality of means (Brown and Forsythe, 1974) and the Welch t-test were performed, which are known to be less sensitive to differences in sample size and variance. The difference between the outcomes of the various tests was negligible (see appendix 3).
Both the outcome measures as well as the statistical tools for analysis had been decided upon in advance, before conducting the experiments.

Calculations were carried out using *SPSS* and *Excel* Software.

4.1.2.3 Results

There were N= 432 reaction-wells per condition (V_I , V_D , P_I , P_D) totaling 1728 wells (18 96-well plates). Each well was measured at 3 measurement time points M1, M2 and M3. Due to spillage and technical pipetting problems, some wells had to be excluded from the analysis. The following reaction rates were measured (Table 3):

[110] The Levene F-test (Levene, 1960) is a version of the F-test which is less sensitive to deviation of the samples from normal distribution. It is, however, like the original F-test (e.g., Bortz, 1993, p. 140), itself based on the assumption of equal variances and may thus be sensitive to unbalanced designs (e.g. unequal sample size) as has been pointed out for example by Glass et al. (1996). Since this is not always fulfilled for the data under consideration here, the differences in variance should a priori be given less weight of consideration than the differences between means. In the individual cases the samples should at least first be checked for deviation from a normal distribution using the Kolmogoroff-Smirnoff test (e.g. Sachs, 2004, p. 379).

[111] Theoretically the *t*-test is based on the assumption that both the sizes and the variances of the two samples are the same. (Normal distribution is only required for small samples.) In practice it is robust as long as either of these assumptions hold (especially for sample sizes of >30) but it can produce incorrect results if both are violated (Ramsey, 1980). Since differences in sample size are an issue with the data at hand, we used the result of the Levene F-test to test for equality of variances. If the variances were found to differ significantly (heteroscedastic), an according correction of the *t*-test was undertaken (Bortz, 1993, p.133; Clauss and Ebner, 1972).

Table 3: Observed photon emission in pilot experiment:

	Condition	N	Measured photon emission (counts per minute): Mean	Std. Deviation	Std. Error Mean
Measurement M1:	**P(D)**	400,00	81175,69	5604,50	280,23
	P(I)	366,00	81030,38	5974,38	312,29
	V(I)	370,00	33569,63	1333,93	69,35
	V(D)	401,00	33254,54	1871,90	93,48
Measurement M2:	**P(D)**	282,00	26161,84	3407,78	202,93
	P(I)	246,00	25408,82	3241,94	206,70
	V(I)	250,00	18291,68	1065,78	67,41
	V(D)	281,00	18630,57	1627,05	97,06
Measurement M3:	**P(D)**	282,00	6475,32	1067,01	63,54
	P(I)	198,00	6060,16	869,79	61,81
	V(I)	202,00	1282,49	398,86	28,06
	V(D)	281,00	1429,59	566,64	33,80

The statistical analysis gave the following results (Table 4): (For conciseness, only a summary is given here, more complete data is provided in Appendix 3)

Table 4: Statistical analysis

	Comparison of variances **Levene F-Test** *Significance p	**Comparison of means** **Student T-Test** *Significance p (2-sided)
Measurement M1		
V_I vs. V_D	0,78	0,73
P_I vs. P_D	0,08	**0,01**
Measurement M2		
V_I vs. V_D	0,45	**0,01**
P_I vs. P_D	0,57	**0,01**
Measurement M3		
V_I vs. V_D	0,91	**0,00**
P_I vs. P_D	**0,04**	**0,00**

*Rounded to two decimal places, statistically significant values are marked **bold.**

4.1.2.4 Discussion

On the basis of these results the null hypothesis would have to be rejected and the hypothesis that the reaction rates differ depending on whether the allocation of reagents is known to an experimenter, is supported. There are, however, a number of alternative explanations which need to be considered.

- V_I and V_D and P_I and P_D, respectively, ended up on different sides of the plates in the randomization process. This means that the difference between distinguishable and indistinguishable condition could be fully or partially due to a position effect. Indeed an influence of the position of a well on the plate on its reaction rate can be detected (One-way ANOVA, Significance for M1: $p=0{,}069$; for M2: $p=0{,}015$; for M3: $p<0{,}001$). Potential explanations for such a position effect could for example be small variations in pipetting volume between the left and the right channels of the 12-channel pipette or a non-uniform temperature distribution in the luminometer.) A clear separation of a potential effect of indistinguishability and a potential effect of position is not possible with the available data structure. In order to eliminate this and similar potential source of errors we decided to introduce a permutation protocol for the main experiment.

- Due to some spillage and technical pipetting problems a number of wells had to be excluded from analysis. Since different plates and different numbers of wells were affected for the different conditions, the observed effects may potentially be due to the excluded wells. In order to explore this consideration further, a post-hoc reanalysis of the data was performed including from all measurements (M1, M2, M3) only those wells which where also still included in the third measurement. (This was called the "Minimal complete dataset".) The reanalysis resulted in an overall reduction of significant differences between means and an increase in significant differences between variances (Table 5).

Table 5: Statistical analysis of the post-hoc selected "minimal complete data set":

	Levene F-Test Significance p*	**Student T-Test** Significance p (2-sided)*
Measurement M1		
V_I vs. V_D	0,55	0,26
P_I vs. P_D	0,14	0,91
Measurement M2		
V_I vs. V_D	**0,04**	0,20
P_I vs. P_D	**0,03**	**0,02**
Measurement M3		
V_I vs. V_D	0,91	**0,00**
P_I vs. P_D	**0,04**	**0,00**

*Rounded to two decimal places, statistically significant values are marked **bold.**

While it is difficult to gauge the underlying mechanisms (statistical or otherwise) that led to these changes it becomes clear that the data is to some degree sensitive to selection. In order to achieve a setup that does not produce complications of this kind, it was decided to make use of an automated pipetting robot in the following main experiment.

- Even though care was taken to avoid that the experimenters introduce a subconscious bias into the experiment, this possibility could not be ruled out completely. For example we could have unintentionally pipetted slightly more reagent into the distinguishable plates, which would have resulted at least partially in a similar effect as observed. This potential source of a false positive result will also be excluded by the use of a pipetting robot.

- If the data is taken to reflect a true effect which is not due to artifacts such as the ones discussed above, then there are a number of open questions such as why the difference in reaction rates increases with time and why the reaction rates in the distinguishable condition were almost always higher than the indistinguishable condition.

4.1.3 Main experiments

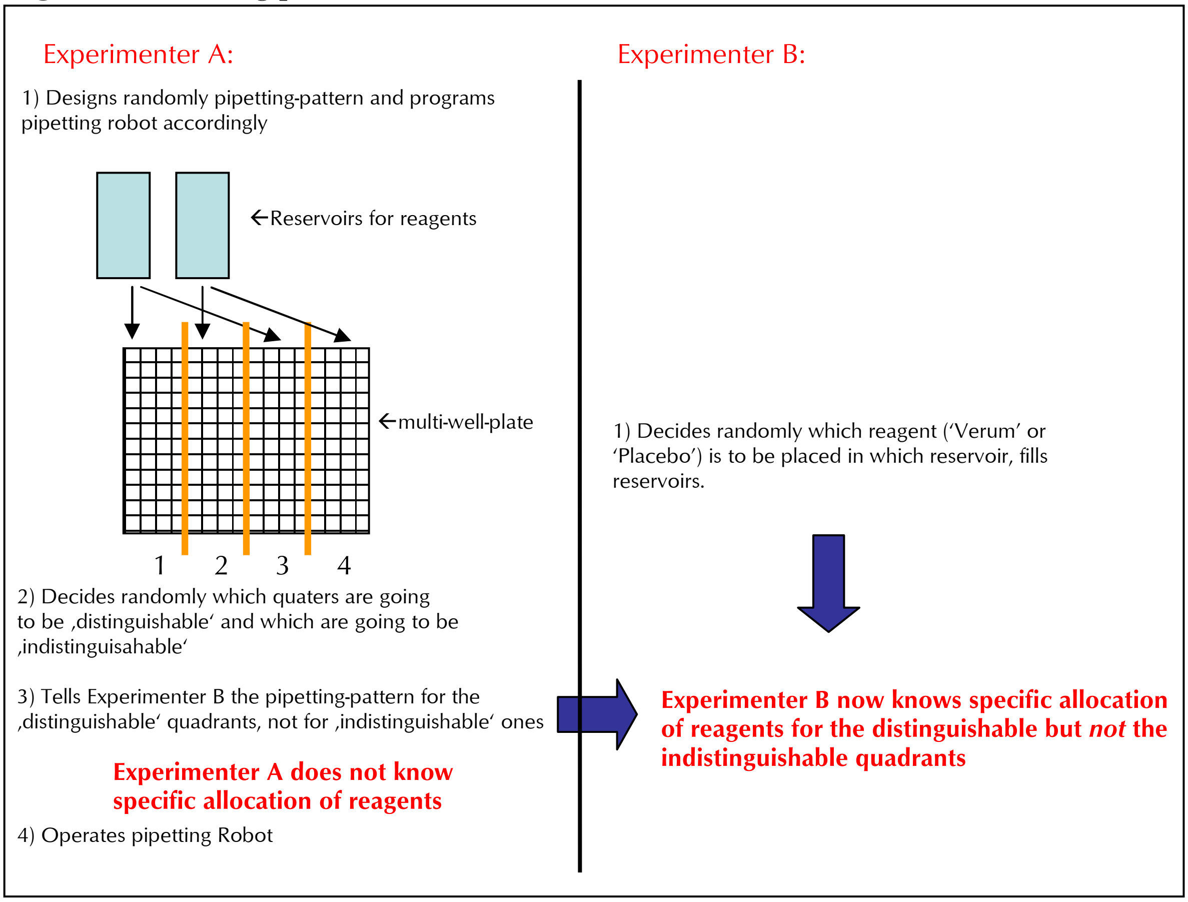
4.1.3.1 Material and Methods

Based on the experience gained from the pilot experiment some changes were introduced for the main experiments:

This time we used eight 384-well plates (*LIA* plates from Greiner Bio-One, Germany) increasing the total number of wells to 3072 while allowing for faster handling.
In order to eliminate the possibility of a classical experimenter effect, to reduce spillage and to further increase accuracy, pipetting was executed using a programmable pipetting robot (*EPmotion 5070* from Eppendorf, Germany).
Each well was loaded with 10µl buffer solution and 25µl of 5µM aqueous ATP solution. Subsequently either 25µl of 1mM aqueous AMP solution or an equal volume of double distilled water (ddH_2O) was added. Finally 25µl of the reaction solution containing the luciferase enzyme was added to start the reaction.

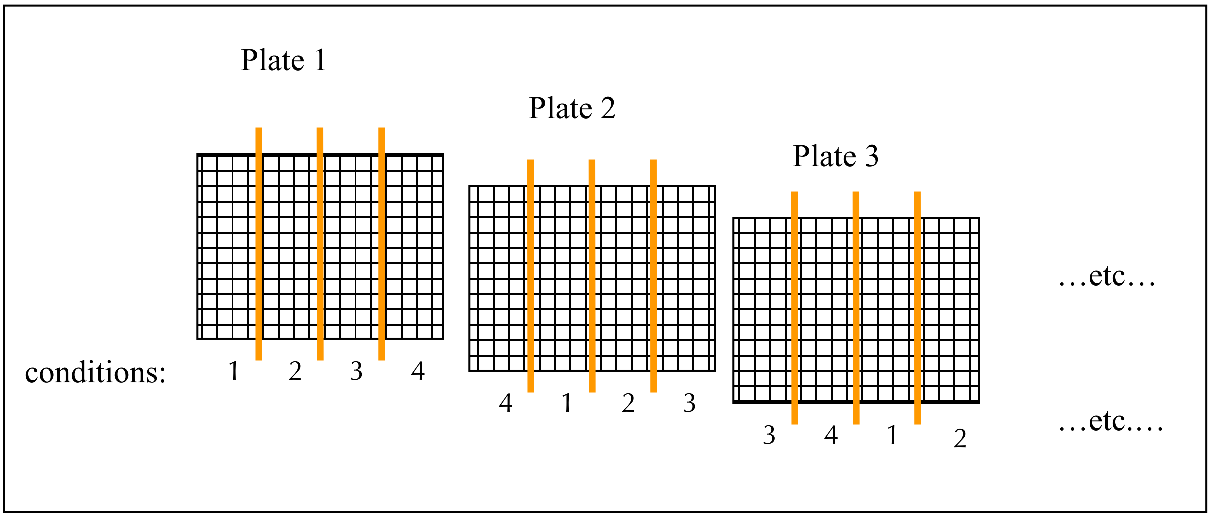
In order to assure blinding of the experimenters, the plates were first divided into four quarters. Then the assignment of reservoirs of the pipetting robot to the individual wells in each respective quarter was decided randomly (via coin throw) by one of the experimenter (experimenter A) while the assignment of AMP solution and water, respectively, to the reservoirs was decided randomly by another experimenter (experimenter B). Therefore only for those wells where the assignment is revealed by experimenter A to experimenter B the specific allocation of 'verum' and 'placebo' treatment is known, for the other wells the experiment is blinded, i.e. the groups are indistinguishable (see figure 18).

Figure 18: Blinding protocol



In order to reduce the probability of an α-error (false rejection of H_0) induced by experimental artifacts, great care was taken to eliminate the possibility of systematic variations accumulating throughout the experiment. In order to avoid placement and timing effects, the quarters were permutated. In each experiment (consisting of eight 384-well plates) each of the four conditions (distinguishable/ indistinguishable, 'verum'/'placebo') thereby came to be located in each of the four quarters twice (see figure 19).

Figure 19: Permutation protocol



Again, care was taken to assure approximately equal handling times for all plates. The plates were placed in a Luminometer (*CM Ultra* from Tecan, Germany) at ca. 25min after initiation of pipetting. There they were temperated to 30°C while being shaken at 100rpm for 16min and then left to settle for 8min. The reaction rates were then determined by measuring the light emission at 565nm from each well for a period of 1sec relative to a background reading of an empty plate. Photon emission was measured twice with a 5min interval in order to check for temporal variability of the reaction rate.

To increase the reliability of the data and reduce the possibility of unjustified rejection of the null hypothesis, so-called "running controls" were conducted. These are experiments with the exact same setup except for the factor which is considered decisive in H_1. In the case presented here that means the entire experiment is repeated but the blinding procedure is omitted. Therefore all effects which are due to whatever experimental or statistical artifacts should continue to show up, while any effects due to the blinding procedure should disappear. [112]

[112] Running controls, also called systematic negative controls, are the most comprehensive way to distinguish varying effect sizes from accidental fluctuations. This methodology has been increasingly promoted recently for the study of controversial phenomena (e.g. Walleczek et al., 1999; Hintz et al., 2003; Jonas and Chez, 2003; Yount et al., 2004). While in principle I support this call and suggest employing it also in less disputed areas, it should be noted that from a system theoretical point of view an experiment

The entire experiment, including running controls, was then repeated in order to produce two identical datasets (to be called Experiment-1 / Control-1 and Experiment-2 / Control-2) which would allow developing post-hoc hypotheses after analyzing the first of the datasets and then testing them on the second dataset.

4.1.3.2 Results

The following reaction rates were measured (Table 6):

Table 6: Observed reaction rates in main experiment (in photon counts per minute):

	Condition	N (wells)	Mean counts per minute	Std. Deviation
Experiment 1:	**P(D)**	768	742504.57	66539.78
	P(I)	768	744849.31	67667.83
	V(D)	768	212412.25	8915.96
	V(I)	768	211940.42	8860.75
Running Control 1:	**P(D)**	768	701601.40	96654.30
	P(I)	768	702708.69	97028.51
	V(I)	768	181541.37	7526.35
	V(D)	768	181565.36	7408.69
Experiment 2:	**P(D)**	672	894724.11	91085.51
	P(I)	672	894447.22	96965.88
	V(I)	672	231620.80	14278.32
	V(D)	672	231270.98	14587.46
Running Control 2:	**P(D)**	672	390809.72	36735.02
	P(I)	672	389780.17	36818.65
	V(I)	672	108178.89	7460.16
	V(D)	672	108302.29	7769.59

with running controls may not be the same as an experiment without running controls and may thus not be useful for the study of systems-inherent phenomena.

Like in the pilot experiment, means were compared using the Student's t-test; variances were compared using the Levene-F test. Statistical analysis of the data revealed no significant overall differences between means and variances of reaction rates under blind and open conditions as shown in table 7 (For more detailed results and statistical analysis see appendix 4).

Table 7: Overview of the statistical analysis of results of main experiment:

	Comparison of conditions	**Comparison of variances** **Levene F-Test** *Significance p	**Comparison of means** **Student T-Test** *Significance p (2-sided)
Experiment 1:	**P(D) vs. P(I)**	0.40	0.49
	V(D) vs. V(I)	0.89	0.30
Running Control 1:	**P(D) vs. P(I)**	0.98	0.82
	V(D) vs. V(I)	0.55	0.95
Experiment 2:	**P(D) vs. P(I)**	0.15	0.96
	V(D) vs. V(I)	0.77	0.66
Running Control 2:	**P(D) vs. P(I)**	0.88	0.61
	V(D) vs. V(I)	0.35	0.77

*Rounded to two decimal places

There was no statistically significant difference between the two measurement time points at 5min apart, indicating relatively stable reaction rates.

Since the reaction rates decreased markedly over time (probably through spontaneous oxidation of luciferin at room-temperature) the variance over the whole experiment was quite large, which of course affects the sensitivity of the t-test and F-test. It was thus decided post-hoc to additionally calculate these tests on a plate by plate basis. Since each experiment consisted of 8 (7) plates with 2 conditions to be compared (V_I vs. V_D and PI vs. P_D) this entails 16 (14) calculations per experiment (details not shown). The t-test proved significant in the following cases:

For experiment-1: 2 of 16 comparisons
For control-1: 0 of 16 comparisons

The F-test proved significant in the following cases:

For experiment-1: 1 of 16 comparisons
For control-1: 1 of 16 comparisons

Only in for the comparison of means there was a difference between experiment and control condition. This trends, however, was not repeated in the second data set, where the t-test proved significant in the following cases:

Experiment-2: 3 of 14 comparisons
Control-2: 3 of 14 comparisons

And the Levene F-Test proved significant in the following cases:

Experiment-2: 1 of 14 comparisons
Control-2: 3 of 14 comparisons

4.1.3.3 Discussion

On the basis of the above analysis the null hypothesis cannot be rejected, thus indicating that the blinding procedure did not have a significant impact on reaction rates.

There are a number of technical and theoretical limitations regarding this experiment which need to be taken into account:

- The risk of falsely rejecting the null hypothesis (β-error) is very small, due to the large power of the presented experiment. For example, for an assumed effect size of 0.2, which is generally considered small (Cohen, 1988), the probability of a β-error is only p=0,025 with regard to the comparison of means by the t-test.
  Nevertheless, the possibility cannot be excluded that the effect we were looking for is of even smaller magnitude (see e.g. Bösch et al., 2006). In that case, obviously, we might have missed it here. If, for example, we assume an effect size

of d=0.1 the probability of a β-error probability regarding the t-test is already p=0,5. (Power calculations were carried out in GPower 3, following Faul et al., 2007).

- A major point of criticism of the main experiments could be that for logistical reasons the measurements were collected only at one relatively early time-point (<1h) even though the pilot experiments had shown more significant deviations at later time-points (20h and 96h). This should have been avoided and would be a worthwhile improvement in future experiments. Nevertheless, for a small number of plates a continuous recording of reaction rates was conducted up to 35h after pipetting. No replicable kinematical patterns were discernible in these measurements, neither for experimental nor control conditions: Both under control and under experimental conditions significance levels increased in some cases and not in others (data not shown).

- Another, more general criticism can be voiced regarding the attempt to recreate in system theoretical terms the kind of RCTs which, in the above mentioned meta-analysis, displayed a correlation between verum- and placebo effect sizes: In these studies a range of verum effect sizes correlated with a range of 'placebo' effect sizes. In our experimental setup there was no range of 'verum' effect sizes because we did not apply different 'dosages' of AMP. We were thus focusing only on a potential effect of a given 'verum' effect onto a 'placebo' effect, which we hypothesized to depend on the blinding of the experiment. Strictly speaking this hypothesis is already a step further ahead of the hypothesis that there are verum-placebo correlations at all, which could have and should have been tested separately or by expanding the experiments to include different concentrations of inhibitor.

- Even more generally, there is justification for questioning the existence of a real verum-placebo correlation in the data analyzed in the initial meta-analysis of RCTs (Maidhof et al., 2000; Walach et al., 2005b). There, the authors correlated the full effect in the verum group with the effect in the placebo group. To be precise, however, the full effect in the verum group has to be regarded as composed of the placebo effect which is active in both groups and the pure verum effect which is specific to the verum group only. If the placebo effect is large enough relative to the pure verum effect, the observed correlation may simply be a covariation: The size of the placebo effect in the placebo group then obviously correlates with the size of the placebo effect in the verum group plus the pure verum effect. In order to avoid mistaking such a co-variation for a correlation, first the pure verum effect has to be calculated by subtracting the unspecific placebo effect from the total effect size in the verum group. Then the calculations should compare the pure verum effect with the placebo effect. This turns out to be more difficult than it sounds, though, because there is a ceiling effect: The full effect in the verum group can never exceed 1 (i.e. 100% healing) and thus a placebo effect > 0,5 by definition entails a pure verum effect < 0,5 and vice versa. In this way an artefactual inverse correlation is created. To date I have not found out a satisfactory way to solve this problem. The only, admittedly crude, possibility is to exclude all studies where either the placebo effect or the pure verum effect exceed 0,5. In the thus limited dataset the initially observed correlation disappears almost completely ($r = 0,05$; $p = 0,28$).

- Furthermore, the system theoretical categorization of indistinguishability und specific allocation as complementary global and local observables may, with hindsight, not be justified. On the one hand it is certainly true that knowledge of the specific allocation and blinding may be regarded as mutually exclusive in that they cannot be realized at the same time in one individual. On the other hand, these descriptors are not really needed to describe one and the same thing. They are more likely describing the states of different experimenters. Thus blinding can also not be seen as a global observable pertaining to the system as a whole but rather should be regarded another local observable describing the state of an experimenter.

- This leads to the question whether in this experimental system there is any global observable which could function as the conserved global system variable, basically binding the individual reactions together. (In other words: how is condition *a*} satisfied? See chapter 3.5.5.) From my current point of view the only somewhat promising global system property would be the systems purpose, which is arguably linked to the intention of the experimenters. From this point of view the experimental setup then resembles a classic psychokinesis experiment, where some physical process is supposed to be influenced by a participant's intention. As discussed in chapter 3.5.4.1 and 3.5.5 such effects, even if they occur, cannot be expected to be reliably reproducible.[113] Since in this experiment my intention was very strongly only to produce significant results if they were also reproducible, it would not have served to promote the occurrence of any non-local correlations.

[113] A decline effect has to be expected due to the violation of Eberhard's theorem: If the correlations were stable, a signal transmission could no longer be excluded in principle since the reaction rates would give clues about the experimenter's intention. Thus any such correlations would have to be destabilized in further repetitions of the experiment.

4.2 Entanglement through 'correlation-triggered feedback'?

4.2.1 Introduction and rationale

Given the limitations of the experiments considered above in chapter 4.1, I next wanted to try a very different approach to designing an experimental system that would fulfill the requirements formulated by GQT for generalized entanglement, and thus allow its validation or falsification.

This second approach was inspired by one of the most thoroughly investigated parapsychological phenomena which we hypothesized to be a potential candidate for generalized entanglement, namely the mental influence on physical processes, so-called psychokinesis (PK). In particular we were interested in PK on random physical processes. Historically the study of psychokinesis began with field investigation and case studies of relatively massive purported phenomena such as haunting events and séance-room table levitation (Crookes, 1889; James, 1896; Richet, 2003). While attempts to replicate such phenomena under controlled laboratory conditions have been conducted repeatedly since then, this branch of research has always been relatively small compared to another branch that started in the 1930s and 1940s (Rhine and Rhine, 1943): Inspired by claims of casino gamblers, experiments were devised where participants tried to mentally influence the throw of dice (For an overview of results of these experiments see e.g. meta analysis by Radin and Ferrari, 1991). The advantage of this paradigm was that it made statistical analysis much easier and allowed comparison against easily definable controls. With the development of appropriate technology, the dice were in the early 1960's replaced by so-called 'random event generators' (REG)[114]. REGs use unpredictable physical events such as radioactive decay or electronic and thermic noise to generate a random sequence of outputs, for example in form of numbers or bits. As already mentioned in chapter 3.5.4.1, the influence of human or animal intention on REGs was confirmed as a small but statistically highly significant effect by a number of meta-analyses of the published literature (Jahn et al., 1987; Radin and Nelson, 1989; Radin and Ferrari, 1991; Atmanspacher et al., 1999; Jahn et al., 2000; Radin and Nelson, 2003b; Bösch et al., 2006). Nevertheless there is continued debate about the existence of psychokinesis. Primarily this is due to the small overall size of the effect. As Bösch (2006) and others (e.g. Scargle, 2000) argue, such a small effect can in principle be explained by publication bias. In addition there is a severe lack of replicability (Schmidt, 1987) as is typical for all of the so-called psychic phenomena (Blackmore, 1999; Kennedy, 2001; 2003). The meta-analyses also reveal a trend for effect-sizes to decrease with increasing trial size and length.

From the perspective of understanding the psychokinetic effect as a non-local correlation between the intention of the experimental participant and the random process, this seems understandable: If the correlation were reliably replicable it could, in principle, be used to

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[114] Also often called 'random number generator' (RNG).

transmit a signal. Since this would violate space-time continuity, as expressed by Eberhard's theorem, the correlations have to break down and the psychokinetic effect must disappear. (The observed patterns of decreasing effect sizes are more or less in agreement with von Lucadou's proposed "decline effect" (von Lucadou, 2002).)

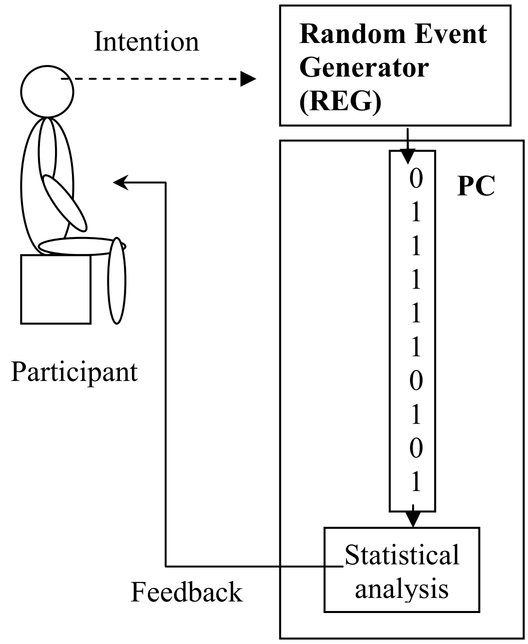
Based on this theory-inspired hypothetical understanding of PK, I had an idea about how to possibly circumvent this problem. Accordingly, in the experimental setup which will be reported next, the following modifications were implemented: Instead of using only the output of a random event generator (REG) as the dependent variable, I chose to measure the *correlation* between the behavior of an REG and some quasi-unpredictable physiological variable of the participant. This novel set-up I called the 'correlation-triggered feedback' approach.[115] In this way, I hoped, no signal could be transmitted from the participant to the REG solely via a non-local correlation, since for an observer of the REG output no deviation from random behavior would be detectable: In order to detect any such deviations, both the output of the REG as well as signals from the participants had to be collected. This is only possible by classical information transfer, thus excluding the possibility of information transfer at speeds greater than that of light. (For a detailed description of the classic as well as the novel set-up, see Figure 20 a) and b).)

[115] Although this modified set-up constituted an unprecedented experiment, I want to acknowledge that, as I only found out later, Hagel et al. (2002; 2004) had already used a setup which is comparable except it did not incorporate a 'true' REG (based on strictly unpredictable quantum-processes) but rather so-called 'pseudo-REGs' (based on oscillators).
Parallel to but independent of my work Tilman Faul and Matthias Braeunig also developed a set-up which in my understanding is comparable except for the difference that in their system the pulses directly sample an analog random process rather than sampling digital bits which themselves are being generated by sampling an analog random process at a fixed frequency. In their experiments no significant non-causal correlations were observed either (personal communication, 2007).

Figure 20: Traditional and modified PK experimental setup

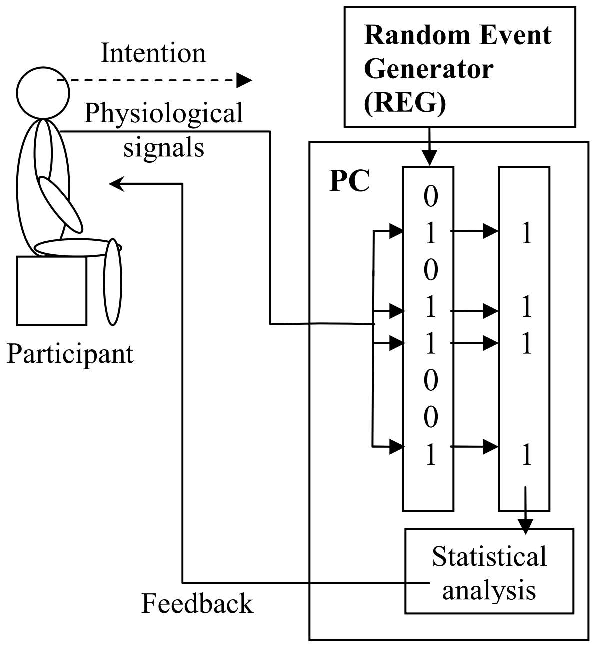
a) Setup of traditional PK-experiment: direct feedback

An REG produces a random signal. A personal computer (PC) records it as a string of random binary digits (bits) and performs a statistical analysis, indicating any deviations from chance behavior. According feedback is then presented to the participant.
The participant now directs his or her intention to change the behavior of the REG in a certain way (here e.g. "more 1's").
In this setup, the intention of the participant could be inferred by observing the REG behavior. If the PK effect were stable, in this way a signal could be transmitted. Assuming the PK effect is based on non-local correlations, this signal transfer would violate space-time continuity. Therefore, as the potential for signal transfer increases over time, the correlations would hence have to break down.



b) Setup of modified PK-experiment: correlation triggered feedback

Here additional signals coming from the participant (e.g. via measurements of some physiological processes like heartbeat etc.) are fed into the PC. The PC uses the timing of these signals (I call them 'sampling pulses') to select individual bits out of the REG data stream. The statistical analysis is then performed on the selected bits only and indicates the level of correlation between both streams of data.
In this setup, because the precise timing of the physiological signals varies quasi-randomly, no information about the intention of the participant can be detected by observing only the REG. Only after the (causal) signals from the participant are received, can any deviations from chance expectancy be detected. In this way, we hoped, any transfer of signals is limited to the classical speed limit of the speed of light and can thus not violate space-time continuity.



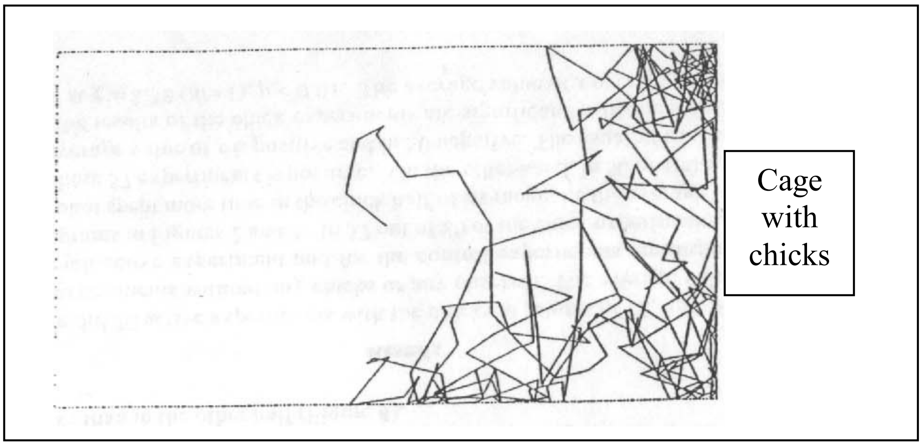
Intention and motivation of the experimental participants are of fundamental importance for such an experiment. This is true from a system theoretical point of view (only if the REG behavior has meaning for the participant, will they form an organizational closure) and has been confirmed in experimental practice (Kanthamani and Rao, 1972; Kennedy, 1995; Braud, 2002; Heath and Heath, 2003). Unfortunately, the psychology of human motivation and intention is relatively complex and difficult to control unambiguously. For example, if participants are asked to mentally influence the behavior of a random event generator they may, even if consciously directing intention towards this task, subconsciously try to avoid successful performance if it would e.g. contradict their world view. Interestingly psychokinesis and other psi-studies have repeatedly detected a so-called "sheep-goat effect", namely outcome differences between participants who in principle believed in the possibility of the task at hand ("sheep") and those who did not believe ("goats") (see e.g. Palmer, 1971; Troscianko and Blackmore, 1982; Brugger et al., 1990; Schlitz et al., 2006). What is more, "goats" are frequently shown to achieve so-called "psi-missing" effects, leading to significant PK effects opposite to the direction set by the task (e.g. significantly less 0's instead of significantly more 0's) (Rhine, 1969; Child and Levi, 1979; Kennedy, 1979; Harley, 1989).

Given these complications I planned to conduct the experiment with animals as participants, where the intention of the animal could be extrapolated relatively straight forwardly from its biologically determined instincts. Animals have been used in PK research before with mixed results which overall compare well with human PK experiments[116] (Levy and André, 1970; Schmidt, 1970; Watkins, 1972; Schmidt, 1974; Braud, 1976; Edge, 1977; Schmidt, 1979; Edge, 1982; Chauvin, 1986; Peoc'h, 1988; Johnson, 1989; Green and Thorpe, 1993; Peoc'h, 1995; 2002; Bedford et al., 2005). Usually these experiments are constructed in such a way that animals are given positive stimuli (e.g. warmth or food) and/or negative stimuli (e.g. electric shocks) the rate of administration of which is controlled by the REG output. I was in particular inspired by the work of René Peoc'h (1988; 1995; 2002) where young chicks were imprinted[117] on a moving robot, which was steered by an REG. In his experiments he observed that in the presence of imprinted chicks in a cage, the robot would move significantly more often in the vicinity of the cage than under control conditions (in the absence of chicks). When the robot was illuminated, even non-imprinted chicks appeared to attract the robot, but only in the dark (see Figure 21).

[116] Of course all the effects observed in these studies could be as well ascribed to the experimenters, in particular when taking into account the possibility of a non-local mechanism.

[117] Imprinting denotes the process during which chicks and other birds learn to recognize their mother in the first days after hatching. If during this time the chicks are presented with appropriate objects instead of their mother, they will develop a comparable attachment to these objects (Bateson, 1966), as was most famously demonstrated by the young geese following Konrad Lorenz around after having imprinted on his rubber boots (Lorenz, 1937). In my view, imprinting could be seen as the formation of a particularly strong organizational closure.

Figure 21: Observation in an REG experiment, adapted from a figure from Peoc'h, 1995, exemplifying the itinerary of an illuminated REG-controlled robot in the dark in presence of chicks off the right hand side of the area. Under control conditions (in the absence of chicks) the robot would spend on average equal times in the left and right hand side of the area (data not shown).



Peoc'h's experiments, too, seem to have encountered difficulty with reproducibility (e.g. Johnson, 1989; Jahn et al., 2007; Jahn et al., 2008) which could be attributed to the set-up being designed along the lines of Figure 20a. I hoped to overcome the potential limitations inherent in that design by modifying the experiment in analogy to Figure 20b.

4.2.2 Material and Method

4.2.2.1 Outline

Thus, as a modified replication of Peoc'h's approach, I intended to have a mobile robot be steered by the REG output in combination with sampling pulses from the chicks themselves. These sampling pulses were supposed to be derived from a digital camera recording the position of the chicks within the cage. If a correlation between REG data and the digital camera data were to be found by the statistical analysis, the robot would move closer to the cage, otherwise in the reverse direction. Unfortunately, when the experiments were supposed to take place in early 2006, the global epidemic of avian influenza A/H5N1 led to official regulations making experiments with chicken and other birds impossible at the University of Freiburg.

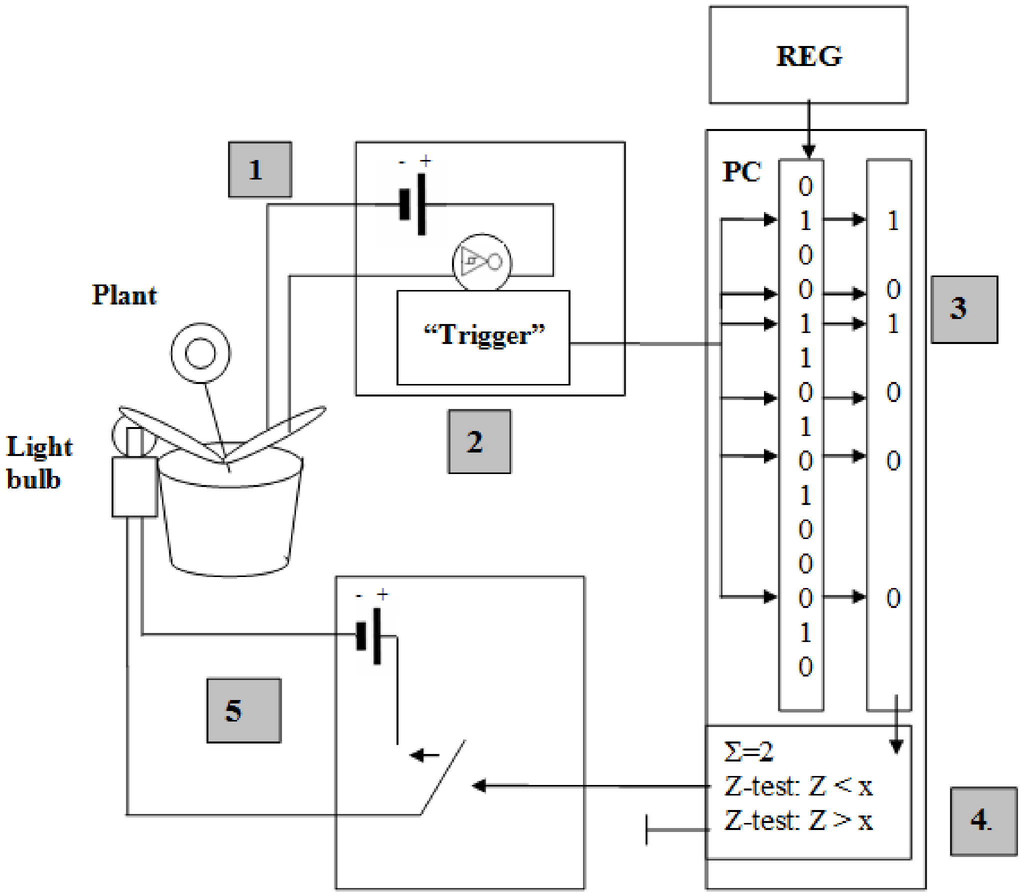
I thus decided to contend with an analogous experimental setup involving plants, which was originally intended only as a preparatory experiment to test the hard- and software. Only very few plant-PK experiments have been conducted (Edge, 1977; Edge, 1982; Odier, 1997), giving mixed results comparable to other PK studies. I was therefore aware that relying solely on plants would give a very weak basis for deciding between different possible interpretations of potential negative results: Do plants e.g. not possess PK capability or were they just not able to apply it in this experiment? Therefore, in spite of the before mentioned problems of human psychology, the experiments were conducted with human participants as well, where there was at least a comparative possibility for interpretation, because humans are generally considered reliable agents of PK in the parapsychological literature and a lot of experimental data has been accumulated.

In these experiments feedback was given via a light bulb which, depending on its positioning, could provide positive feedback to the plant in form of light or negative feedback in form of excessive heat.

The signal from the plant and human participant consisted in an electrical pulse the exact timing of which depended on the electrical resistance of one of the plant's leafs (for details see figure 22 and appendix 5). Both plant and human tissue conductance are know to vary considerably in short term fluctuations and long term shifts (e.g. Boucsein, 1992; Volkov and Brown, 2006). In contrast to the more predictable conductance changes in reaction to stimuli, these more autonomous variations occur in a quasi-unpredictable way. This was an important consideration in the rationale for this experiment, because loosely speaking any correlations between two random sequences can only be detected when both sequences are known, thus our hope of preventing any possible signal transfer in this experiment.

My null hypothesis stated that significant correlations between the physiological (plant and/or human) signal and the REG output will not be observed more often than statistically expected by chance. My working hypothesis stated that depending on the type of experimental setup (positive or negative feedback) there would be a significantly stronger or weaker correlation between the two data streams, resulting in above chance occurrence of positive feedback and below chance occurrence of negative feedback.

Figure 22: Schematized description of experimental setup



Schematized Function (more detailed description in Appendix 5)**:**

[1]: At the interface between the organism and the personal computer [PC] an increasing voltage is generated and applied to the plant (and/or human) via electrodes.
[2]: As soon as the electrical current flowing in the circuit exceeds a certain threshold, an electronic 'trigger' is released and a 'sampling-pulse' is sent to the parallel port of the PC. Thereby the voltage drops and then starts to rise again until the next 'sampling-pulse' is generated. The intervals between the pulses depend on the conductivity of the biological tissue and thus vary quasi-unpredictably.
[3]: Whenever a sampling-pulse is registered by the PC, the software selects the next incoming bit from a stream of bits which are generated by a random event generator (REG) and recorded by the PC via the serial port.
[4]: After a preset number of bits has been selected in this way, the software performs a statistical analysis of their selection. If a certain preset deviation 'x' from chance expectancy is exceeded, the PC sends a signal to a relay switch.
[5]: When the relay switches to ON, the predetermined feedback is applied for a set amount of time. (Here, for example, negative feedback in form of excessive heat to the leaf.)

4.2.2.2 Hardware

The REG was a widely used commercially available random number generator (ORION, Netherlands) based on white electrical noise from two independent analogue Zener diodes. The randomness of this REG has been successfully confirmed using the generally accepted test suites compiled by Marsaglia (1995; 2002). The serial port of a standard personal computer (PC) was used to power the REG and to record its output.

The interface controlling sampling pulse generation and feedback application were constructed in collaboration by Prof. Johannes Hagel at the Institute for Psychophysics in Cologne, Germany (Details can be found in appendix 5).

The light bulb used for feedback was a 60 Watt neodymium bulb[118] (EGB, Germany).

4.2.2.3 Experimental participants and conditions

Experiments were conducted using plants (*Primula vulagaris*) under conditions of positive feedback (lighting in an otherwise dark but ventilated container) and negative feedback (heat from light bulb destroying leafs). Plants were connected to the sampling pulse device via custom made non-invasive clip-electrodes.

Furthermore, some experiments were conducted with human participants, who were connected to the sampling pulse device via hand held electrodes either on their own or in series with the plant. Participants were myself and selected members of the research group who were given instructions to mentally prevent the plant from destruction or, in the experiments without plants, to mentally cause the light to come on as often as possible or as rarely as possible.

In all experiments sampling pulse frequency was tuned to be smaller than the REG output frequency by about one order of magnitude or more in order to assure a high independence between both data-streams and thus to make signal transfer impossible.

Control conditions were realized by experiments where the plants were either shielded from the impact of the feedback or replaced by resistors or oscillators.

[118] Neodymium bulbs produce a spectrum of light which is more suitable for plants than normal artificial light, with more red and blue and less yellow wavelengths.

4.2.2.4 Software, data processing and statistical analysis:

The software was run on MS Windows 95 operating system to allow for accuracy in measuring time intervals. In later versions of MS Windows the access to a systems-clock is apparently less precise (Hagel, pers. comm., 2006).

The source code for the most important parts of the software programmed specifically for this experiment can be found in appendix 6.

Here I merely give a schematic overview of how the data was processed.

The REG output was sent to the serial port of the computer in form of ca. 960 random bytes per second. The bytes range from 0-255. Once a sampling-pulse coming from the plant and/or human organism is received at the computer, the software (corr.c, see appendix 6) selects the next byte arriving at the serial port and assigns the value 1 if the byte is ≤ 127 and the value 0 if the byte is >127. Each value of 1 or 0 is called a 'period'. Periods were then subjected to an X/OR transformation[119], which ensures that the probability of a period '1' and the probability of a period '0' are precisely equal at 0,5.

A sequence of 'n' periods is called a 'trial'. For each trial a so-called 'cumulative difference' (cd) was calculated by adding 1 for each period labeled '0' and subtracting 1 for each period labeled '1'. For each trial then a value 'sig' was calculated as $(cd/\sqrt{n})$. If the absolute value of 'sig' (called 'asig') was larger than a certain predefined value (called 'sigmax') it was called a 'correlation'. The cumulative difference (cd) will be binomially distributed around a mean difference of 0. Therefore the probability of a trial producing a cd which will result in asig > sigmax (let us call this cd(corr)) can be calculated in the following way:

1) We determine cd(corr):

$Cd(corr)/\sqrt{n} > sigmax$
$Cd(corr) > sigmax*\sqrt{n}$

That means we derive cd(corr) by calculating $sigmax*\sqrt{n}$ and then rounding the result to the next larger possible cd (this will be an even number for trials with an even number of periods, odd number for trials with an odd number of periods).

---

[119] X/OR transformation means that every second period is inverted to the opposite value. This procedure ensures equal distribution of 1s and 0s even if the REG were biased (Marsaglia, 2003).

2) We then determine the probability of a trial producing a cd ≥ cd(corr):

Since both positive and negative 'sig' can result in 'asig' > 'sigmax' the doubled cumulative binomial probability function calculates the probability value for a trial producing a cd≥cd(corr), which we shall call P:[120]

$$P = 2\left(\sum_{j=k}^{n}\binom{n}{j}p^j q^{n-j}\right)$$

(where k =mean+cd(corr)/2; and p=q=0,5 the probabilities for 0's and 1's)

A number of trials N (called 'ndurch' in the program corr.c) were included in one 'run'. Thus each run will contain a number of correlations which is called 'ncorr' which should be binomially distributed with a maximum at NP under the null-hypothesis.

3) Given that we have defined a directed hypothesis in advance, we can now calculate the probability ('p') of a run to contain ≥ ncorr or ≤ ncorr, depending on the direction of the hypothesis, under the null-hypothesis. This p-value will indicate the likelihood of falsely rejecting the null-hypothesis.

For illustration, let us assume the following example:[121]

An experiment consisting of 1 run (R=1) is to be conducted, where the run shall consist of 100 trials (N=ndurch=100) with 101 periods (n=101) each.[122] Each of these trials will

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[120] The software as seen in appendix 6 actually uses a different method to calculate a value called 'pcorr' which is supposed to reflect the probability of a trial producing a cd ≥ cd(corr): For binomial distributions with large n and probabilities not too close to 1 and 0 (npq ≥ 9) the binomial distribution can be approximated with a normal distribution (Pratt, 1968; Sachs, 1982). Therefore the software z-transforms the distribution of cd(corr) (cd(corr)/n) and then calculates p(corr) using the function erf(z) (Abramowitz et al., 1965). The erf(z) function integrates the normal distribution:

$$\operatorname{erf}(z) \equiv \frac{2}{\sqrt{\pi}}\int_0^z e^{-t^2}\,dt.$$ where t=0…z.

However, care has to be taken that, since the binomial distribution is discrete, for comparing it with a continuous normal distribution the individual values of cd have to be regarded as midpoints of intervals (bins). Thus the z-value to be chosen for reading the probability of obtaining at least a certain value of cd has to be the average between that value of cd and the next lower possible value of cd. This is not done in the program corr.c.

Therefore, the normal approximation was calculated by the software for the purpose of a rough estimation only and did not enter into the actual statistical analysis of the data, where only the direct calculation of P via the binomial distribution was used as described above.

[121] Using the data from an actual experiment, data file khw83, see appendix 7.

[122] The number of periods chosen should be chosen so that erf(z)=erf(d/√n) ≠ P because in that case the decision of the software based on erf(z)>P would produce an artifact by not taking into account the case

thus have a certain cumulative difference (cd) with a potential range from -101 (only 0's) to 101 (only 1's). Under the null hypothesis, cd is expected to be binomially distributed around a mean of 0. Suppose that 'sigmax' was set to 1,940323. This means that all trials resulting in a cd > (sigmax*√n=1,940323*√101= 19,50000481) would be counted as a correlation. Since the closest possible cd is 21 (61 periods of '0' and 40 periods of '1' or vice versa), cd(corr)= 21.

The probability (P) of any given trial counting as a correlation will thus be

$$P = 2\left(\sum_{j=k}^{n}\binom{n}{j}p^{j}q^{n-j}\right) \text{ (where k=61, p=q=0,5 and n= 101)}$$

=0,046044067

This was calculated using MS Excel.[123]

We would thus expect the number of correlations per trial (ncorr) to be binomially distributed around a mean of N*P= 4,6044067.

Assume that we observed 11 correlations in this run. Given a directed null-hypothesis (e.g. "A given run will not produce more correlations than expected by chance") we can say that the probability to observe a run with 11 or more correlations is p=0,006408815 (this was calculated using MS Excel[124]). This means we can reject the null-hypothesis with an alpha error of less than one percent, thus indicating a highly significant deviation from what we would expect if the null-hypothesis were true.

4.2.3 Results

In pre-experimental test-runs the apparatus consisting of hard and software (without any organisms connected to it) was shown to function properly and to produce normally distributed random data without significant statistical deviations.

Frequency analysis of the sampling-pulses revealed strong variability of frequency over up to one order of magnitude (data not shown). This variability is likely due to the above mentioned variance of conductivity of the plant and human tissue because when biological tissue was replaced with electrical resistors, the variability of sampling-pulse frequency disappeared almost completely.

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where erf(z)=P. This means for example that if z is a whole number n should not be a square number. In addition the values have to be chosen so that 'standard deviation' << 'mean' by at least a factor of 10 in order to allow for reliable statistical analysis.

[123] In German notation:
=2*(BINOMVERT(40;101;0,5;WAHR)) or =2*(1-BINOMVERT (60;101;0,5;WAHR))

[124] In German notation: =1-(BINOMVERT(10;100;0,046044067;WAHR))

The complete data analysis of the experiment was performed only after the experiment was concluded, so as to prevent optional stopping[125].

The experimental runs were analyzed with unidirectional (one tailed) tests, given that a directed working hypothesis was, at least implicitly, always defined (i.e. less negative and more positive feedback).

An unforeseen problem was the treatment of control runs where plants were either replaced by resistors or oscillators: In contrast to experimental runs and control runs with plants, no directed hypotheses were defined because these control runs were not attributed to specific experimental runs. It was thus unclear how the control runs should be analyzed. For comparability, it was decided to analyze each control run twice with a one tailed test in each direction.

In total, 89 runs were conducted with an overall non-significant result as shown in Table 8 (A detailed list of experimental conditions and the according outcomes is given in appendix 7):

Table 8: Overview of outcome of all runs:

	Total number of runs	Of which significant ($p \leq 0{,}05$, one tailed)
Experiments with plants	48	1
Experiments with human participants	9	1
Experiments with humans and plants	2	0
Control experiments with plants (directed null-hypothesis)	14	0
Control experiments* (undirected null-hypothesis)	64*	2*

* 32 actual runs were conducted which were then analyzed with two opposite one tailed tests.

The total number of significant runs is not significantly larger or smaller than to be expected under the null hypothesis both in controls ($p>0{,}3$) and in experiments ($p>0{,}3$).

All in all, the null hypothesis was thus confirmed in the experiments reported here: No above chance deviations from randomness were detected.

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125 "Optional stopping" is a frequently voiced counter argument regarding psi experiments: The idea is that by stopping an experiment when the results are significant and continuing it when they are not, significant results are more likely to be due to chance fluctuations.

Of course the way in which the statistical analysis was performed is not the most sensitive thinkable. It was decided upon in advance, however, with the intention to conservatively screen for strong effects only.

There was no significant decline in effect sizes of individual runs over the course of the entire study ($r = 0.053$, $p = 0.27$).

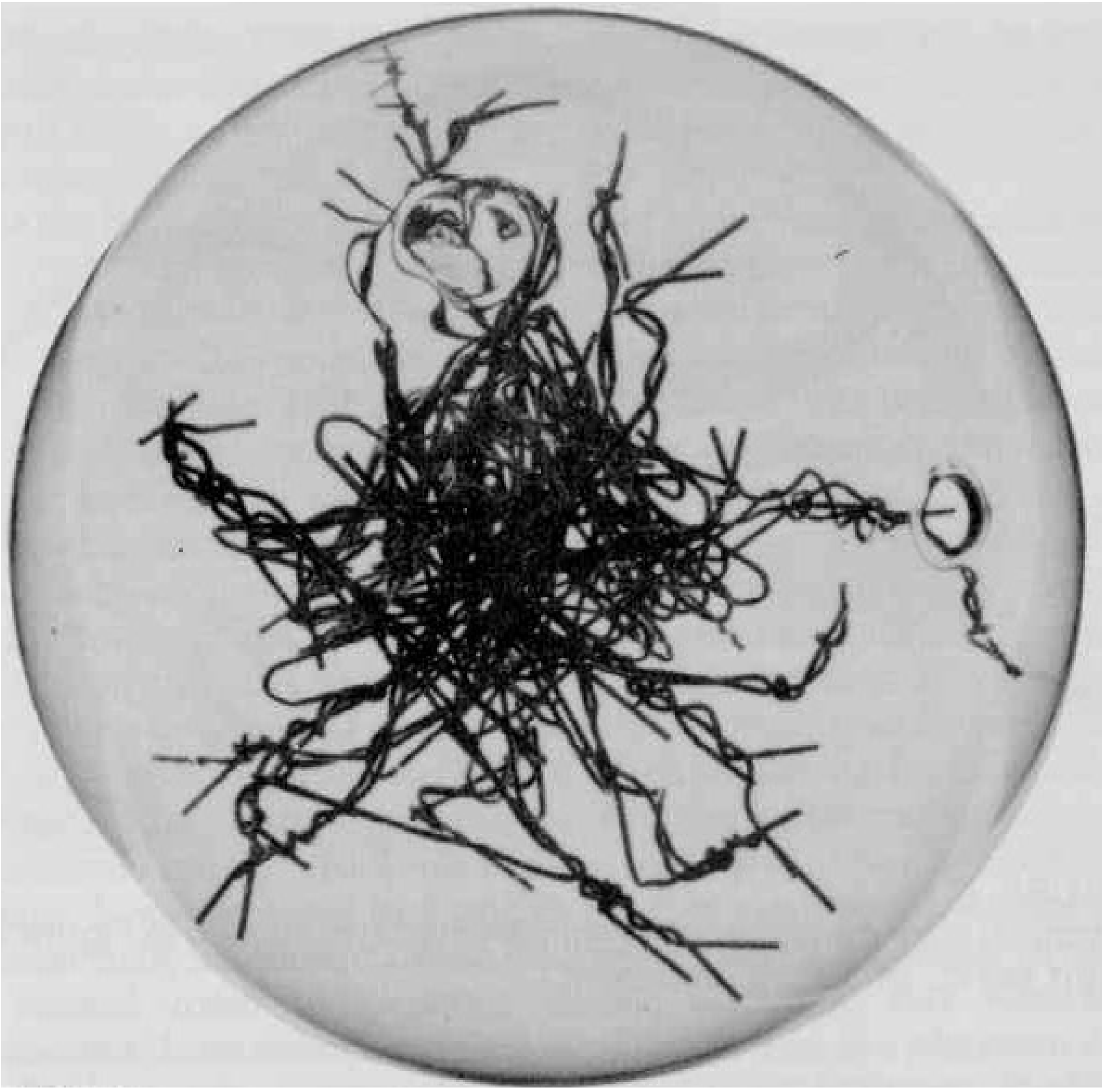
4.2.4 Discussion

Generally speaking, there exists a fundamental asymmetry between positive and negative results. While confirmation of hypotheses will result in more certainty about our models of reality, results which do not fit the hypotheses are open to a wider range of interpretations. One possible interpretation of the negative results in this study is of course that PK does not exist. Another class of possible interpretations retains the idea that PK exists, but that the experimental system developed here was not suitable to either its occurrence or its detection. Both interpretations can be drawn based on the available data and no logically binding preference can be established for either.

If PK does not exist then this study reports one of the many experiments revealing this state of affairs. Since the probability of getting it published is small, certainly lower than for a comparable experiment with a positive outcome, its future may also provide an example of the publication bias at work, which could explain to a large extent the existing collective of data seemingly pointing to the existence of a PK effect (see e.g. the analysis by Bösch et al., 2006).

If PK does exist, I failed to observe it in the experiments described above. This could either be because the statistical power of the study was not high enough to detect the effect or because no effect took place. Regarding the former, it has to be said that the statistical analysis used here may not be the most sensitive thinkable, in particular as a result of its layered structure. This, however, I found preferable to the risk of detecting false positives. Regarding the possibility of no PK occurring even if it exists, this could be due a large variety of reasons, for example faulty experimenting, unsuitable experimental subjects or the particular kind of experiments not being suitable for PK to occur, at least not in the parameters which were defined as outcome criteria. Thus, the assumption that PK exists but was not observed in this study invariably provokes questions regarding the precise reason(s) why that could have been so. In this way, new hypotheses might be generated, which could again be tested and thus lead to better understanding of the phenomena after all. Let us therefore explore this interpretation a bit further. Before doing so let us ask, however, on what rational grounds anyone could be drawn to the opinion that PK exists but was not be detected in this experiment? One could refer to the collective data available from PK experiments and assume that the amount of hypothetically conducted but not published studies is unrealistic (four unpublished studies for every published study according to the calculations by Bösch et al. (2006)). One may also be taking into account results of research on other psychokinetic effects which exhibit an even higher level of improbability and therefore seem almost inexplicable by statistical fluctuations, such as metal deformation phenomena like the one depicted in figure 23 (for other examples see e.g. Brookes-Smith, 1973; Hasted, 1976; 1977; Hasted and Robertson, 1979; 1980; Hasted, 1981; Schmeidler, 1982; Beloff et al., 1996; Bugaj, 1996; Heath, 2000; Heath and Heath, 2003; Houck, 2003).

Figure 23: From Hasted (1976): A glass sphere of 131mm diameter with one 8mm diameter hole was filled with common paperclips made of nickel-plated steel. The paperclip scrunch was produced by eleven year old Andrew G, in about thirty minutes without the help of tools. According to the author, "an impossible task".



Faced with such reports one is only left with explanations in terms of fraud or undiscovered methodological artifacts. If one does not deem those plausible, one arrives at the conclusion that PK occurred in some instances but did not occur, or at least was not observed, in the experiments reported here.

What, now, could have been the reasons for this? Of course, many different considerations could be voiced with respect to the possible limitations of this experiment and the observed outcome. I shall only touch upon a number of points which seem the most important ones to me.

For this purpose I will base my thinking on the hypothesis that PK is an instance of generalized entanglement. As we have seen, this hypothesis is theoretically possible, because (as discussed in chapters 2 and 3.2) there is a fundamental probabilistic degree of freedom even in macroscopic physical systems which means that they could enter into non-causal correlations. Such an approach seems more plausible to me than the search for any explanation based on potential causal mechanisms, because the purported phenomena do not seem to obey causal principles in a number of ways (compare e.g. Schmidt, 1993). For example, the effects in general do not seem to drop off with distance or physical shielding, nor can they be avoided by separation in time (see e.g. Schmidt, 1987). Assuming, therefore, that PK is based on non-local correlations, I will now, with hindsight, explore the most severe limitations of the conducted experiments in relation to the necessary conditions for entanglement which I have identified meanwhile.

The first crucial factor that needs to be realized for generalized entanglement is that the different systems under investigation (here the REG and the plant or human organism) must be subsystems of a larger system. One way in which this can be assessed is by the amount of 'meaning' the subsystems have for each other in a very general sense of the word: To the extent that a change in subsystem A causes a change in subsystem B and vice versa they form an overall unity.
In the experiment this condition was fulfilled only partially in the sense that, on the one hand, depending on the feedback the plant's leafs will dry out or not and the experimental participant will feel that he or she achieved their task as intended or not. It cannot be supposed, on the other hand, that what happens to the plant or the human being has more of an impact on the REG than other events happening in its proximity.

The next requirement is that there is a global fixed observable, a global eigenbehavior of the system as a whole. As discussed earlier, it seems to me that one good way to conceptualize this global observable could be in terms of the intention, motivation or purpose of the overall system.
In this respect there is a hierarchy of intentions. On one level, the purpose that characterizes the system could be seen in the motivation of a plant to survive or of a human participant to achieve his set task. On a super-ordinate level, however, the purpose of the entire setup is clearly to produce replicable evidence for non-causal correlations, for that was my intention as the experimenter. As a general remark on meaning and intention in an experimental setting it should be said that it is very difficult to artificially create real meaning and authentic intention and one can suppose that the intentions created within the context of an experiment will, in general, be of less importance to the experimental system as a whole than the intention of the experimenter who created the

entire system in the first place.[126] It may be relevant in this context to point out that my clear motivation for all of the reported experiments was to only observe phenomena that would later be replicable by anyone, given the appropriate technology, independent of their attitude. This could be a difference to the intention of experimenters in other PK experiments where the primary objective was possibly to record the phenomenon at all cost. For me this seemed not desirable at all, having read a few of those sad and sometimes terrifying accounts of scientists who lost all reputation and credibility because the results they published were not replicable by other researchers.

This brings us to the next requirement and, in my view, the most fundamental of the potential limitations of the reported experiment. GQT predicts that in order for entanglement to occur and be replicable, it must be in principle impossible to use it for transmitting a signal. As we have discussed, this requirement is fulfilled in quantum physics by the fact that the individual observables of the entangled quanta are absolutely unpredictable.[127] In the macroscopic setting described here, however, there is no absolute unpredictability except in the quantum processes sampled by the REG. Due to decoherence and averaging, all other processes are to some extent predictable and their unpredictability is comparatively small. For the same reason, regarding any macroscopic system there exists in principle the possibility for us to exert an external causal influence with an at least to some degree predictable effect. This too, may be an important limitation for entanglement to occur, since it may mean that the system under consideration is not isolated with respect to the entangled parameters. As we know, in quantum physics this leads to an immediate loss of the entanglement correlation to decoherence.[128]

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[126] Regarding the experiment at hand, of course the most immediate question could be to what extent a plant can be at all expected to have an intrinsic motivation for survival or to what extent such a motivation is e.g. present only in "higher organisms". But even with human participants there are fundamental difficulties: for example, if it were really the participants' *authentic* intention to have the light 'off' more often than statistically expected, he or she could simply unplug the light bulb. Why don't they do it? Because implicitly their intention is also to please the experimenter by adhering to some artificial rules set up for the experiment. Some experimenters have tried to tackle this problem by providing authentically positive or negative feedback to study participants (like financial rewards or physically unpleasant stimuli). But there again, it may be of more relevance to the overall purpose of the system if an experimenter authentically wants to reward certain achievements or whether he actually has the intention to disprove the phenomena in question. And physically unpleasant stimuli could be avoided more *authentically* by participants by deciding not to take part in the study.

[127] As Bell's inequalities prove (see chapter 2.3.2.1), there is either no property of a quantum that determines the outcome of its interaction with the measurement apparatus or this outcome is predetermined collectively through the properties of not only the entangled quanta but also the quanta in the measurement apparatus and anything that had a causal influence on the latter, including the decisions of the experimenters and the position of all visible matter in the universe, should the experimenter choose to make the filter settings depend on it. This means there is either nothing to predict or in order to predict it we would have to know everything without changing it in the process which is in principle impossible.

[128] Suppose a pair of entangled quanta as described in chapter 2.3.1: After some predictability of one quantum's future behavior has been gained through the first measurement process, the original entanglement correlation will be no longer discernible in a second measurement, because it has now entangled with all the quanta in the measurement apparatus and its causal environment.

Due to this *in principle* ability to partially predict and manipulate the properties of at least one of the subsystems in this experiment, a non-local signal transmission could be possible as soon as entanglement between the subsystems occurs reliably. For illustration, let us explore a hypothetical version of the plant-REG experiment where entanglement occurs as a perfect correlation between sampling-pulse and REG behavior:[129] Let us suppose the system is programmed in such a way that as soon as a deviation from a perfect correlation between the time of arrival of the sampling-pulses and the value of the thus selected bits is detected, a negative feedback will be initiated. Now, assuming that the purpose of the system is to avoid such negative feedback, entanglement would non-causally correlate the REG's quantum process and the process that times the sampling-pulse in such a way as to conserve this overall purpose (i.e. the global system eigenbehavior). In this way a perfect correlation would arise, meaning that every time the sampling-pulse from the plant reaches the computer, the next bit that will be sampled from the REG has the same value, say a "1". The computer will analyze the selected bits, discover the perfect correlation and thus not initiate the negative feedback. Suppose now that we somehow influence the timing of the sampling-pulse (for example by applying a strong electromagnetic field). If we were, for example, to produce a stable frequency (say 1Hz) for this pulse, then someone else, given sufficient time and computing power, would be able to detect this frequency by solely observing and analyzing the output of the REG (i.e. without directly observing the pulse). In this way a signal would have been transmitted.

When designing the experiment, I did try to eliminate the possibility of signal transmission by external causal influence on the sampling-pulse: The sampling-pulse varied quasi unpredictably due to the underlying chaotic physiological processes, and an *actual* signal transfer was therefore impossible. This, however, is not enough: According to my current understanding of the theoretical framework, the mere *in principle* possibility of signal transfer would violate space-time continuity and thus prevent non-local correlations from occurring. Therefore, in this experiment, additional modifications were introduced as a further effort to make signal transfer impossible (detailed in figure 20): The 'correlation-triggered feedback' method meant that in contrast to traditional REG-PK experiments, a hypothetical observer of the REG in these experiments, even if he does not need knowledge of the sampling-pulse to detect the hypothetical 1Hz frequency, can nevertheless not detect it *before* the pulse arrives because only those bits which will be sampled by it, will correlate with it. It was my hope that because of this limitation no actual violation of space-time continuum might occur because it is as if a 'bottleneck' was installed, slowing down the non-local correlations to the speed of the causal process with which the sampling-pulse is transported to the REG. This can be seen as analogous to a situation in quantum physics, called "quantum-teleportation", where large amounts of

[129] The argument remains the same for non-perfect correlations, this exaggeration is used only to make the central issues more evident. Basically the only difference for a non-perfect correlation would be that the signal-to-noise ratio of any hypothetical transmission of information via the correlation would be smaller.

information (i.e. signals) *can* be transmitted via entanglement correlations but only with the help of an additional classical channel and thus limited to the speed of this channel (see e.g. Barrett et al., 2004; Riebe et al., 2004). Since in these setups seemingly the signal-transmission-prohibition is not violated, I had hoped that the 'correlation-triggered feedback' setup could similarly satisfy the no-signal-transmission requirement and thus allow for the occurrence of generalized entanglement correlations. This did not turn out to be the case. As said before, there may of course again be many reasons for this failure, including the possibility that PK does not exist at all, let alone generalized entanglement. For the moment, however, let us remain with the hypothesis that generalized entanglement does exists and follow it all the way through, in order to see why the modification I introduced could not have led to the occurrence of replicable macroscopic non-local correlations, even if they actually exist:

As I said, a hypothetical observer of the REG (let us call him Bob for now) could receive a signal from the experimenter (let us call her Alice) by way of discovering in the REG's behavior the frequency pattern which she imposed on the sampling-pulse. As a result of the above mentioned modification introduced in this experiment, he could not do so *before* the pulse arrives because only those bits which will be sampled by the pulse correlate with it. However, he does not need any *information* carried in the pulse to detect the frequency pattern. In this fact, one might, with hindsight, already see an indication that this modification might not be sufficient to create the conditions for macroscopic entanglement: In quantum physics, every signal transmission using entanglement (as for example in the case of quantum teleportation) needs additional information to be transmitted causally (just like the sampling-pulses in the experiment here) but this information also *has* to be *used*. *Without* it, an observer *cannot* extract from the observations of only one subsystem the information someone else may want to send from another subsystem via the entanglement correlation (see e.g. Riebe et al., 2004; Sherson et al., 2006).

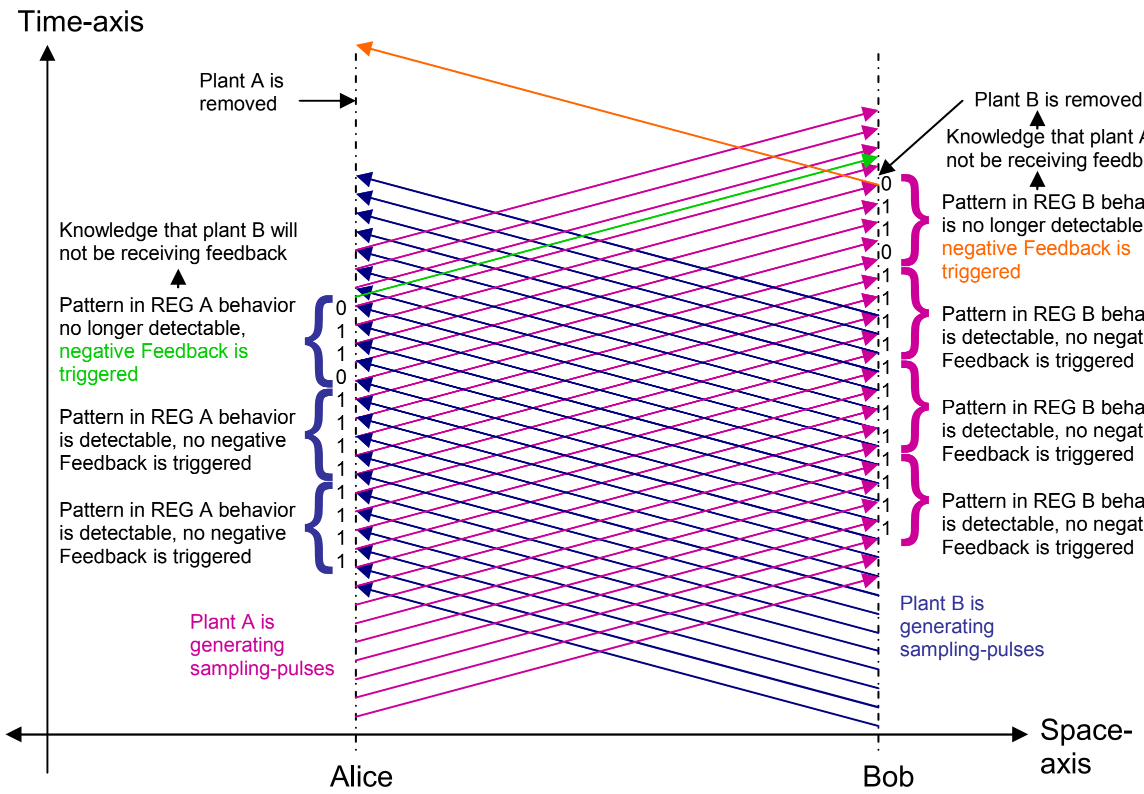
As explained in chapter 2.3.2, the 'signal-transmission prohibition' serves as a protection of space-time continuum which would get disrupted by faster than light signal transfer. This disruption becomes most visible when so-called "intervention paradoxes" or "vicious circles" arise. With hindsight, it seems to me that the modifications introduced in my experiment were not sufficient to *in principle* exclude the possibility of precisely this happening. Let us continue analyzing the hypothetical experiment to illustrate how. One way in which a violation of space-time continuity could take place is the following: Suppose that the hypothetical observer of the REG (his name still being Bob) has detected in the REG output the 1Hz pattern of '1s' which is due to the entanglement correlation which occurs due to the system's overall purpose and the way in which Alice has manipulated one side of this correlation, namely the sampling-pulse.[130] If Bob now

[130] In fact, for this experiment we could even allow Bob to analyze the bits selected by the sampling pulse, in which case he can detect the perfect correlation even without any manipulation of the sampling pulse by Alice.

suddenly notices that the correlation pattern disappears, he can infer that by the time the negative feedback arrives at the other subsystem, this other subsystem no longer attributes the same meaning to the feedback (otherwise the correlation would continue unchanged). So he knows something will have happened there (for example the plant will have been removed from the proximity of the bulb etc.).

Possibly, this in itself would already comprise a violation of space-time continuum. However, an even more obvious violation in form of an intervention paradox could in principle arise. To see how, we need to simply assume that Alice and Bob have an additional experiment running in parallel, with exactly the same setup, except that here Bob is the one observing the plant and manipulating the sampling-pulse while Alice is observing the REG. Bob, upon discovering the change in behavior in the REG that he is observing, could now introduce some change regarding his plant which will be visible to Alice as a change of behavior of her REG at a time *before* any change has actually occurred on her plant (see figure 24 for a space-time diagram of this situation).

Figure 24: Set-up for a potential intervention paradox using two entangled systems (This diagram can be seen as a two-dimensional analog to the light-cone diagrams in figure 11 and 12, with all spatial dimensions collapsed onto one axis.) Detailed explanation follows in the text below.



The situation portrayed in figure 24 above is as follows: Alice and Bob are located at distant points in space. Alice has access to plant A and can observe REG A. Bob has access to plant B and can observe REG B. The arrows represent causal influence propagating with (maximally) the speed of light. REG B is now being sampled by sampling-pulses coming from plant A. If during each sampling interval (indicated by curly brackets) the correlation pattern (as symbolized by only 1s) is detected in the raw RNG data or in the sampled bits, no feedback is initiated. As soon as the correlation pattern disappears (symbolized by a mix of 1s and 0s), feedback is initiated. This would indicate that the system has changed in such a way that feedback avoidance is no longer necessary to conserve its overall purpose. This could for example be the case when, by the time the now initiated feedback reaches the position of Alice (tip of orange arrow), plant A has been removed from the bulb so that the feedback is no longer negative. As soon as Bob notices such a change in the output of REG B, he can now for example remove his plant B from the bulb. As a consequence the behavior of REG A will change at the time when the presently arriving feedback for plant B was decided upon (base of green arrow), that means *before* Plant A is removed.

When we now assume that Alice and Bob could also be robots which just execute certain commands instead of making supposedly free willed decisions, the *in principle* possibility of an intervention-paradox will become clearly visible: Robot Bob has detected a change in the REG he is observing. This serves as a command to remove his plant from the bulb. As a result robot Alice detects a change in her REG. For her this serves as a command to make sure her experiment continues unchanged. In this case there will not be a change in the REG which robot Bob is observing, hence he would not be commanded to change his experiment which would then leave the REG which robot Alice is observing unchanged which for her could be the programmed command to at a certain time remove the plant from the bulb which in turn would change the REG which robot Bob is observing and so on and so forth. This is a slightly less cruel version of the intervention paradox of someone traveling back in time to prevent his birth which means he will not exist so he cannot travel back and prevent his birth so he will be born and travel back to prevent his birth and so on and so forth.

The interesting property of this kind of causal loops or intervention-paradoxa is that nothing ever happens because whatever happens prevents itself from happening. Seemingly, space-time continuum and in that sense the logical consistency of actual reality is quite fundamental and well protected against self-referential loops. Whatever would form such a loop will just not happen.[131]

Regarding the experimental investigation of non-causal correlations, it therefore seems as if the signal transfer prohibition must be equated with a prohibition to observe anything else but absolutely unpredictable events when observing only one of the entangled subsystems in isolation.[132] Conversely that means that whenever unpredictability is compromised, entanglement cannot subsist. Since unpredictability is never absolute in macroscopic systems and will decrease with replications, systems producing reproducible entanglement correlations may be in principle unachievable.

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[131] What is very perplexing to me is that this is the case even though, as we have discussed earlier (chapter 2.5), the very structure underlying our reality seems to be just that: completely selfreferential (and possibly: nothingness). So the special thing about the reality that is happening seems to be that it does not allow the loop to close which would force it not to happen. According to Small (2006) the way in which the loop is prevented from closing could be described either as space-like separation of events (as formalized by relativity theory) or by the impossibility of an infinite amount of change to happen within a finite period of time (as defined by the 'quantum of action' in quantum theory). In other words, time and space, i.e. dimensionality, is what prevents reality from 'not taking place' even though it ultimately cannot be taking place. So maybe we could say that causality is what is taking place and selfreferentiality or non-causality is what 'is'.

[132] This gives an interesting paradoxical perspective on quantum unpredictability, since it means that it is the very conservation of the continuity of space-time and causality which does not permit us to find anything continuous (in the sense of predictable, property-like) when we observe a quantum in causal isolation.

If this analysis is correct, its logical consequence for any attempts to produce replicable experimental evidence in parapsychology is fatal. Normally, as I said towards the beginning of this chapter, the understanding of why an experiment did not produce the expected results can and should lead to new experiments in which the decisive parameters are corrected accordingly. The analysis of the negative results of this study, however, have, at least for the time being, not led me to the development of new testable hypotheses but rather to the realization of the potential impossibility of *any* viable experimental setup. We are thus presented with a theoretically very interesting situation: Generalized entanglement is a logically possible and, given the circumstantial evidence, even plausible phenomenon. Objective experimental proof of its existence, however, must be regarded impossible, due to the above theoretical considerations.

Interestingly, already Pauli and Jung discussed a mutual exclusivity and possible complementarity between "synchronistic" events and statistical experimental methodology, meaning that the latter become inapplicable in the context of the former and vice versa (see quotes in Atmanspacher and Primas, 1996; Primas, 1996).

This does of course not mean, however, that it must be impossible for anyone to witness such events. It just means, as discussed in chapter 3.5.5 that in order to do so, one has to personally interact and in some sense 'become one' with the system, and this excludes independent experimental manipulation or objective observation from the outside.

What is science supposed to do with such a phenomenon? Should we limit science to a methodology referring only to objectively provable matters and thus let go of the ambition for an all encompassing scientific view of reality? Or should we sacrifice the certainty brought about by the superiority of 'objective proof' over 'subjective experience' and in turn receive holistic understanding? In some way it should come as no surprise to see that the concept of generalized entanglement probes the limits of the current experimental paradigm, which, after all, has been developed for identifying stable local-causal relationships in the world. Generalized entanglement, in contrast, denotes a (complementary?) type of non-local, non-causal relatedness. It thus makes sense that it may also require a different (complementary?) experimental paradigm, based more on subjective and engaged experience rather than objectively distanced observation.

5. Conclusion and Outlook

Due to the lack of unambiguous experimental evidence, the conclusions that can be drawn at the end of this work are based primarily on logical reasoning and intuitive plausibility. From the point of view of an experimentalist this may be disappointing. Since, however, even these unproven and possibly unprovable conclusions seem to have potentially far reaching implications, I will state them here anyway:

- It seems plausible to me to postulate that some of the fundamental principles of reality as discovered by scientific exploration, based on objective measurements, are isomorphic to fundamental principles which spiritual exploration arrives at, based on subjective experience.
    - One of the most central of these common principles is the 'unity of opposites' that is described by complementarity.
        - Applying generalized complementarity can help to better understand the structure and cause of longstanding theoretical problems such as the mind-body problem. It does so without getting rid of but rather by highlighting the irresolvable contradictions between the opposing concepts.
        - In this way, complementarity indicates a definitive limit for any rational understanding of reality in the sense of a comprehensive and logically coherent explanatory framework.
        - It may, however, be possible to transcend these limitations in non-dual or acategorial states of consciousness which have to be considered trans-rational in the sense that they can be experienced but not conveyed through language or logic nor be imagined.
        - Practices that facilitate such states of consciousness should be explored as potentially helpful means to developing a more complete understanding of reality and thus allow for more adequate engagement therewith.
    - Another such a common principle, in my opinion, is non-locality.
        - Theoretically, the principle of non-causal correlations can be applied not only in quantum physics but to systems in general.

- If such generalized entanglement can really occur, it may mean that, in addition to our causal actions, the attribution of subjective meaning could decisively influence a system's behavior.

- The hypothesis that parapsychological phenomena are based on non-causal correlations, provides an explanation which is logically consistent, in good agreement with circumstantial evidence and in keeping with established scientific knowledge. There is thus no justification for statements claiming that parapsychological phenomena "can't be" or "would contradict science".

- If this hypothesis is correct, however, there is reason to believe that no experimental proof of these phenomena can be expected, even if they are real. Experimental evidence will fail in particular with regards to replicability and independence of the experimenter.[133]

- Instead it seems likely that the possibility to observe non-local correlations in everyday systems is dependent on the subjective stance of each individual and the way in which he or she thus enters into relationship with the system.

- This, in consequence, would mean, that for science to be able to investigate reality comprehensively, participatory first person engagement has to complement objective observation, at least with regard to systems capable of meaning generation.

- Further, it may mean that if more people were to relate in a more conducive way to themselves, their environment and to reality as a whole, non-causal correlations would occur more frequently, more reliably and with larger magnitude.

- Thus developing a strong common intention and at the same time allowing for individual freedom may be a precondition to allow system dynamics emerge which optimally suit this intention. This could be seen as a guiding principle in the development of human society and its integration within the larger system of this planet. It can also be a guiding principle for achieving personal goals that are in harmony with the collective.

[133] While this could justify the conclusion that further experimentation is not warranted, I would not like to propose that. My analysis may be wrong and in that case a replicable experiment might be developed. If, on the other hand, my analysis is correct it will be supported by more experiments which initially show highly improbable outcomes and subsequent replication failure (such as the ones outlined e.g. in Walach et al., 2009).

- Spiritual practices could be understood as, among other things, creating the conditions for such non-causal coordination and thus increase in synergy between individuals and the totality.

- The investigation of the potential occurrence of non-causal correlations in all kinds of systems in various areas of research could lead to deeper understanding of how these systems work (e.g. disease and healing, evolution, brain-function etc.).

Obviously, there are a large number of open questions and interesting further issues to explore. In the following I will outline the most central ones in my current estimation:

- When describing the generalization of entanglement to macroscopic systems I equated the "eigen-behavior" of these systems with the global observable of quantum systems which is subject to conservation-laws. This is a large leap of faith and more in-depth analysis should be conducted in order to justify or dismiss it.

- Since macroscopic phenomena are never in principle entirely uncontrollable, I reasoned that any non-local correlation involving macroscopic events would, to some extent, amount to a potential or actual signal transmission and can thus not be stable. However, I have only shown this conclusively for the setup used in my experiments here. It remains necessary to develop a more comprehensive theoretical proof for this reasoning that applies to all thinkable setups. In doing that, we might also discover setups where this problem could be circumvented, although I doubt it.

- Reliable statistical calculations should be undertaken to examine the question whether the evolutionary development of species can or cannot be reasonably explained by the effects of independent random mutations over the available periods of time. To my knowledge such calculations are very difficult and have not been conducted to any large extent. Nevertheless efforts should be made because this could serve as a further piece of circumstantial evidence for or against the occurrence of non-causal correlations between unpredictable events in systems with a strong organizational closure.

- With regard to generalizing complementarity, its defining characteristics should be worked out in more detail using quantum physics as the defining case and reference point.

- An in-depth analysis should be undertaken of the potential complementarity inherent in conceptual opposites such as e.g. determinism / indeterminism; mind / body; science / spirituality; quantum theory / relativity theory; etc..[134]

- A number of philosophical and spiritual concepts which appear similar to complementarity should also be investigated in more depth to find out if this similarity amounts to a substantial isomorphy and if shortcomings of such concepts can be understood better in the light of complementarity

- Ways for effectively communicating the concept of complementarity and enabling individuals to develop a complementaristic view of reality and themselves should be explored.

- Applying complementarity to oneself may help to constructively integrate apparently conflicting aspects of the internal psyche (such as male/female aspects etc.) as well as providing a constructive framework for handling external conflicts. These potentially salutogenetic effects should be investigated. I suspect that such indirect, secondary effects of GQT related concepts may even turn out to be more accessible to experimentation and quantification than the existence of the concepts themselves.

- This is true also and in particular for generalized entanglement. Here different therapeutic methodologies involving what appear to be non-causal mechanisms could be studied not so much in terms of investigation the these mechanisms themselves but rather the effectiveness of the treatment as a whole as subjectively experienced by the clients.

Given the considerable potential for deeper understanding and reconciliation both on a theoretical academic level as well as on a personal and interpersonal level, I consider it worthwhile to pursue this research further.

[134] It is important that the application of complementarity should not prevent contradictions to be explored to their very extremes but rather support this activity by providing a framework in which this can happen constructively.

6. Acknowledgements

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Finally I want to acknowledge the primroses that I killed in the course of the REG experiment (ironically in order to prove a hypothesis based on the premise that meaning is a notion that can be applied to them). May their sacrifice ultimately lead to greater wisdom and happiness of all beings everywhere.

7. Appendix

7.1 Appendix 1 (Calculations for Bell Inequality)

Overview of all possible outcomes of the EPR experiment described in chapter 2.3.2.1 for all possible combinations of filter settings and photon instruction sets.

	Photon A	**Photon B**
Instruction set	[α+ β+ γ+]	[α– β– γ–]

Filter setting F_A	**Filter setting F_B**	**Photon A**	**Photon B**	**Photons A and B behave differently**
α	α	+	-	Yes
β	β	+	-	Yes
γ	γ	+	-	Yes
α	β	+	-	Yes
α	γ	+	-	Yes
β	α	+	-	Yes
β	γ	+	-	Yes
γ	α	+	-	Yes
γ	β	+	-	Yes

	Photon A	**Photon B**
Instruction set	[α– β– γ–]	[α+ β+ γ+]

Filter setting F_A	**Filter setting F_B**	**Photon A**	**Photon B**	**Photons A and B behave differently**
α	α	-	+	Yes
β	β	-	+	Yes
γ	γ	-	+	Yes
α	β	-	+	Yes
α	γ	-	+	Yes
β	α	-	+	Yes
β	γ	-	+	Yes
γ	α	-	+	Yes
γ	β	-	+	Yes

	Photon A	Photon B
Instruction set	[α− β− γ+]	[α+ β+ γ−]

Filter setting F_A	Filter setting F_B	Photon A	Photon B	Photons A and B behave differently
α	α	-	+	Yes
β	β	-	+	Yes
γ	γ	+	-	Yes
α	β	-	+	Yes
α	γ	-	-	No
β	α	-	+	Yes
β	γ	-	-	No
γ	α	+	+	No
γ	β	+	+	No

	Photon A	Photon B
Instruction set	[α+ β+ γ−]	[α− β− γ+]

Filter setting F_A	Filter setting F_B	Photon A	Photon B	Photons A and B behave differently
α	α	+	-	Yes
β	β	+	-	Yes
γ	γ	-	+	Yes
α	β	+	-	Yes
α	γ	+	+	No
β	α	+	-	Yes
β	γ	+	+	No
γ	α	-	-	No
γ	β	-	-	No

	Photon A	**Photon B**
Instruction set	[α– β+ γ+]	[α+ β– γ–]

Filter setting F_A	**Filter setting F_B**	**Photon A**	**Photon B**	**Photons A and B behave differently**
α	α	-	+	Yes
β	β	+	-	Yes
γ	γ	+	-	Yes
α	β	-	-	No
α	γ	-	-	No
β	α	+	+	No
β	γ	+	-	Yes
γ	α	+	+	No
γ	β	+	-	Yes

	Photon A	**Photon B**
Instruction set	[α+ β– γ–]	[α– β+ γ+]

Filter setting F_A	**Filter setting F_B**	**Photon A**	**Photon B**	**Photons A and B behave differently**
α	α	+	-	Yes
β	β	-	+	Yes
γ	γ	-	+	Yes
α	β	+	+	No
α	γ	+	+	No
β	α	-	-	No
β	γ	-	+	Yes
γ	α	-	-	No
γ	β	-	+	Yes

	Photon A	Photon B
Instruction set	[α− β+ γ−]	[α+ β− γ+]

Filter setting F_A	Filter setting F_B	Photon A	Photon B	Photons A and B behave differently
α	α	-	+	Yes
β	β	+	-	Yes
γ	γ	-	+	Yes
α	β	-	-	No
α	γ	-	+	Yes
β	α	+	+	No
β	γ	+	+	No
γ	α	-	+	Yes
γ	β	-	-	No

	Photon A	Photon B
Instruction set	[α+ β− γ+]	[α− β+ γ−]

Filter setting F_A	Filter setting F_B	Photon A	Photon B	Photons A and B behave differently
α	α	+	-	Yes
β	β	-	+	Yes
γ	γ	+	-	Yes
α	β	+	+	No
α	γ	+	-	Yes
β	α	-	-	No
β	γ	-	-	No
γ	α	+	-	Yes
γ	β	+	+	No

7.2 Appendix 2 (Entanglement overview)

Selection of experiments demonstrating entanglement involving various observables, various types and numbers of quanta and various methods of preparing and measuring entanglement.

Correlations between photons that are stronger than those predicted by classical physics were actually already observed by Chien-Shiung Wu and Irving Shaknov in 1950 (Wu and Shaknov, 1950). They carried out experiments in which an electron collides with a positron to create positronium, which is a short-lived state in which the electron and positron are bound together. This state then rapidly decays to produce two gamma-ray photons. Due to conservation of angular momentum, these photons have spins pointing in opposite directions.

The earliest experimental confirmations of the non-local nature of these correlations in Bell's sense were achieved by so-called atomic cascades (e.g. Freedman and Clauser, 1972). There, a suitable atom, for example a calcium atom, is put in an excited state by submitting it to electromagnetic radiation at suitable frequency which gets absorbed by the atom. When the exited atom then spontaneously decays back to the ground state the previously absorbed energy is emitted in form of two photons within a very short time. Due to the law of conservation of angular momentum their polarizations must be symmetric if they are emitted in opposite directions from the same calcium atom. The outcomes of polarization measurements on emitted photons which are appropriately selected according to their emission time, wavelength and direction of propagation are therefore non-locally correlated.

Polarization of photons is not the only observable which can be non-locally correlated in entangled quantum systems. The before mentioned down conversion sources can for example also produce photons in states exhibiting non-local correlations between observables other than polarization. An interesting case considers pairs of photons where each photon has a probability of being emitted 'at two different times'. Here, the relevant observable is the time of emission of the two photons of the pair, and the conjugate one is the energy (wavelength) (see Franson, 1989; Kwiat et al., 1993). Corresponding experiments have been carried out (e.g. by Brendel et al., 1992; Brendel et al., 1999). Another scheme considers the directions of emission as observables (Horne et al., 1989): each photon of an entangled pair involves two different directions of emissions, strongly correlated to two directions of emission for the second photon. An experiment of this type has also been carried out (Rarity and Tapster, 1990). Moreover, one can, transform polarization-entangled states into momentum or energy-time entangled states (Kwiat, 1995; Zukowski and Pykacz, 1988). In addition, photons have been entangled with regard to their position (Irvine et al., 2005)

The findings regarding entanglement have been confirmed experimentally to hold true in an analogous fashion also for other quanta such as electrons (e.g. Chtchelkatchev et al., 2002), neutrons (Lamehi-Rachti and Mittig, 1976; Hasegawa et al., 2003), atoms (e.g.

Riebe et al., 2004; Rowe et al., 2001; Barrett et al., 2004) and combined systems of atoms and photons (Blinov et al., 2004; Sherson et al., 2006). Nowadays, entanglement between up to five photons (Zhao et al., 2004) or eight ions (Häffner et al., 2005) has been reported. Using already entangled particles one can entangle large collectives of atoms, given that these are in coherent states (Julsgaard et al., 2001). In this way some thousand neutral atoms in a so-called cluster state have been entangled (Greiner et al., 2002). Even macroscopic objects such as mirrors have been successfully entangled with quanta (Mancini et al., 2002 Vitali et al., 2007).

A very interesting thought experiment (Elitzur et al., 2003) highlights the meaning of 'non-local' as independent of space *and* time by proposing a time-reversed entanglement scenario, where two atoms become entangled through interaction with two photons from *independent* sources which only become entangled *afterwards* through a Bell measurement.

7.3 Appendix 3 (Data for indistinguishability experiment: pilot study)

7.3.1. Statistical analysis of 'indistinguishability' pilot study

Measurement at time point 1: 'Placebo'

Group Statistics

	Condition	N	Mean	Std. Deviation	Std. Error Mean
measured photon emission (counts per minute)	P(D)	400,00	81175,69	5604,50	280,23
	P(I)	366,00	81030,38	5974,38	312,29

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
measured photon emission (counts per minute)	Equal variances assumed for t-test	0,08	0,78	0,35	764,00	0,73	145,31	418,39	-676,03	966,64
	Equal variances not assumed for t-test			0,35	746,62	0,73	145,31	419,58	-678,39	969,01

Measurement at time point 1: 'Verum'

Group Statistics

	Condition	N	Mean	Std. Deviation	Std. Error Mean
measured photon emission (counts per minute)	V(I)	370,00	33569,63	1333,93	69,35
	V(D)	401,00	33254,54	1871,90	93,48

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
measured photon emission (counts per minute)	Equal variances assumed for t-test	3,08	0,08	2,67	769,00	0,01	315,09	117,93	83,59	546,60
	Equal variances not assumed for t-test			2,71	723,79	0,01	315,09	116,39	86,59	543,60

Measurement at time point 2: 'Placebo'

Group Statistics

	Condition	N	Mean	Std. Deviation	Std. Error Mean
measured photon emission (counts per minute)	P(D)	282,00	26161,84	3407,78	202,93
	P(I)	246,00	25408,82	3241,94	206,70

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
measured photon emission (counts per minute)	Equal variances assumed for t-test	0,57	0,45	2,59	526,00	0,01	753,02	290,65	182,04	1324,00
	Equal variances not assumed for t-test			2,60	522,04	0,01	753,02	289,66	183,97	1322,07

Measurement at time point 2: 'Verum'

Group Statistics

	Condition	N	Mean	Std. Deviation	Std. Error Mean
measured photon emission (counts per minute)	V(I)	250,00	18291,68	1065,78	67,41
	V(D)	281,00	18630,57	1627,05	97,06

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
measured photon emission (counts per minute)	Equal variances assumed for t-test	0,32	0,57	-2,80	529,00	0,01	-338,89	120,97	-576,53	-101,26
	Equal variances not assumed for t-test			-2,87	487,66	0,00	-338,89	118,17	-571,08	-106,70

Measurement at time point 3: 'Placebo'

Group Statistics

	Condition	N	Mean	Std. Deviation	Std. Error Mean
measured photon emission (counts per minute)	P(D)	282,00	6475,32	1067,01	63,54
	P(I)	198,00	6060,16	869,79	61,81

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
measured photon emission (counts per minute)	Equal variances assumed for t-test	0,01	0,91	4,52	478,00	0,00	415,16	91,84	234,71	595,62
	Equal variances not assumed for t-test			4,68	467,41	0,00	415,16	88,65	240,97	589,36

Measurement at time point 3: 'Verum'

Group Statistics

	Condition	N	Mean	Std. Deviation	Std. Error Mean
measured photon emission (counts per minute)	V(I)	202,00	1282,49	398,86	28,06
	V(D)	281,00	1429,59	566,64	33,80

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
measured photon emission (counts per minute)	Equal variances assumed for t-test	4,12	0,04	-3,17	481,00	0,00	-147,11	46,43	-238,34	-55,87
	Equal variances not assumed for t-test			-3,35	480,81	0,00	-147,11	43,93	-233,43	-60,78

7.3.2. Post hoc statistical exploration

7.3.2.1 Analysis of minimal complete dataset:

Measurement at time point 1: 'Placebo'

Group Statistics

	Condition	N	Mean	Std. Deviation	Std. Error Mean
Measured photon emission (counts per minute)	P(D)	282,00	82141,63	4604,52	274,19
	P(I)	198,00	81620,87	5420,04	385,19

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means				
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference
Measured photon emission (counts per minute)	Equal variances assumed for t-test	0,36	0,55	1,133	478,00	0,26	520,76	459,59
	Equal variances not assumed for t-test			1,101	379,01	0,27	520,76	472,81

Measurement at time point 1: 'Verum'

Group Statistics

	Condition	N	Mean	Std. Deviation	Std. Error Mean
Measured photon emission (counts per minute)	V(I)	202,00	33601,30	1118,98	78,73
	V(D)	281,00	33617,10	1809,97	107,97

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means				
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference
Measured photon emission (counts per minute)	Equal variances assumed for t-test	2,23	0,14		481,00	0,91	-15,81	143,80
	Equal variances not assumed for t-test				471,30	0,91	-15,81	133,63

Measurement at time point 2: 'Placebo'

Group Statistics

	Condition	N	Mean	Std. Deviation	Std. Error Mean
Measured photon emission (counts per minute)	P(D)	282,00	26161,84	3407,78	202,93
	P(I)	198,00	25837,76	2125,67	151,06

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means				
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference
Measured photon emission (counts per minute)	Equal variances assumed for t-test	4,09	0,04	-,110	478,00	0,24	324,08	273,31
	Equal variances not assumed for t-test			-,118	471,98	0,20	324,08	252,99

Measurement at time point 2: 'Verum'

Group Statistics

	Condition	N	Mean	Std. Deviation	Std. Error Mean
Measured photon emission (counts per minute)	V(I)	202,00	18366,83	767,69	54,01
	V(D)	281,00	18630,57	1627,05	97,06

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means				
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference
Measured photon emission (counts per minute)	Equal variances assumed for t-test	4,71	0,03	-2,139	481,00	0,03	-263,74	123,32
	Equal variances not assumed for t-test			-2,374	423,68	0,02	-263,74	111,08

Measurement at time point 3: 'Placebo'

Group Statistics

	Condition	N	Mean	Std. Deviation	Std. Error Mean
Measured photon emission (counts per minute)	P(D)	282,00	6475,32	1067,01	63,54
	P(I)	198,00	6060,16	869,79	61,81

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means				
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference
Measured photon emission (counts per minute)	Equal variances assumed for t-test	0,01	0,91	4,521	478,00	0,00	415,16	91,84
	Equal variances not assumed for t-test			4,683	467,41	0,00	415,16	88,65

Measurement at time point 3: 'Verum'

Group Statistics

	Condition	N	Mean	Std. Deviation	Std. Error Mean
Measured photon emission (counts per minute)	V(I)	202,00	1282,49	398,86	28,06
	V(D)	281,00	1429,59	566,64	33,80

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means				
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference
Measured photon emission (counts per minute)	Equal variances assumed for t-test	4,12	0,04	-3,168	481,00	0,00	-147,11	46,43
	Equal variances not assumed for t-test			-3,348	480,81	0,00	-147,11	43,93

7.3.2.2 Tests for equality of means using tests which are robust against differing sample sizes

MEASUREMENT TIME POINT1 'placebo'

	Statistic(a)	df1	df2	Significance
Welch	1,213	1	379,009	0,271
Brown-Forsythe	1,213	1	379,009	0,271

MEASUREMENT TIME POINT1 'verum'

	Statistic(a)	df1	df2	Significance
Welch	0,014	1	471,301	0,906
Brown-Forsythe	0,014	1	471,301	0,906

MEASUREMENT TIME POINT2 'placebo'

	Statistic(a)	df1	df2	Significance
Welch	1,641	1	471,984	0,201
Brown-Forsythe	1,641	1	471,984	0,201

MEASUREMENT TIME POINT2 'verum'

	Statistic(a)	df1	df2	Significance
Welch	5,637	1	423,676	0,018
Brown-Forsythe	5,637	1	423,676	0,018

MEASUREMENT TIME POINT3 'placebo'

	Statistic(a)	df1	df2	Significance
Welch	21,934	1	467,408	0,000
Brown-Forsythe	21,934	1	467,408	0,000

MEASUREMENT TIME POINT3 'verum'

	Statistic(a)	df1	df2	Significance
Welch	11,211	1	480,808	0,001
Brown-Forsythe	11,211	1	480,808	0,001

(a)= asymptotically F-distributed.

7.4 Appendix 4 (Data for indistinguishability experiment: main study)

<u>Statistical analysis of 'indistinguishability' main study:</u>
(Since the two measurement time-points did yield qualitatively different results, only the data from the second measurement is shown here.)

7.4.1 Experiment 1

7.4.1.1 Experiment 1, Analysis 'Placebo'

Group Statistics

	condition	N	Mean	Std. Deviation	Std. Error Mean
counts per minute	P(D)	768	742504.57	66539.78	2401.05
	P(I)	768	744849.31	67667.83	2441.75

Independent Samples Test

		Levene's Test for Equality of Variances		T-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
									Lower	Upper
counts per minute	Equal variances assumed for t-test	0.71	0.40	-0.69	1534.00	0.49	-2344.75	3424.50	-9061.94	4372.45
	Equal variances not assumed for t-test			-0.69	1533.57	0.49	-2344.75	3424.50	-9061.94	4372.45

7.4.1.2 Experiment 1, Analysis 'Verum'

Group Statistics

	condition	N	Mean	Std. Deviation	Std. Error Mean
counts per minute	V(D)	768.00	212412.25	8915.96	321.73
	V(I)	768.00	211940.42	8860.75	319.73

Independent Samples Test

		Levene's Test for Equality of Variances		T-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
									Lower	Upper
counts per minute	Equal variances assumed for t-test	768.00	212412.25	8915.96	321.73	768.00	212412.25	8915.96	321.73	768.00
	Equal variances not assumed for t-test	768.00	211940.42	8860.75	319.73	768.00	211940.42	8860.75	319.73	768.00

7.4.2 Running Control 1

7.4.2.1 Running Control 1, Analysis 'Placebo'

Group Statistics

	condition	N	Mean	Std. Deviation	Std. Error Mean
COUNTS PER MINUTE	P(D)	768.00	701601.40	96654.30	3487.71
	P(I)	768.00	702708.69	97028.51	3501.21

Independent Samples Test

		Levene's Test for Equality of Variances		T-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
									Lower	Upper
COUNTS PER MINUTES	Equal variances assumed for t-test	0.00	0.98	-0.22	1534.00	0.82	-1107.29	4941.93	-10800.94	8586.36
	Equal variances not assumed for t-test			-0.22	1533.98	0.82	-1107.29	4941.93	-10800.94	8586.36

7.4.2.2 Running Control 1, Analysis 'Verum'

Group Statistics

	condition	N	Mean	Std. Deviation	Std. Error Mean
COUNTS PER MINUTES	V(I)	768.00	181541.37	7526.35	271.58
	V(D)	768.00	181565.36	7408.69	267.34

Independent Samples Test

		Levene's Test for Equality of Variances		T-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
									Lower	Upper
COUNTS PER MINUTES	Equal variances assumed for t-test	0.37	0.55	-0.06	1534.00	0.95	-23.99	381.09	-771.49	723.52
	Equal variances not assumed for t-test			-0.06	1533.62	0.95	-23.99	381.09	-771.49	723.52

7.4.3 Experiment 2

Due to technical problems of the pipetting robot, the last plate (plate 8) was not handled correctly and was thus excluded from the following analysis. Accordingly, plate 8 was also omitted from the running control for experiment 2. Including plate 8 in both cases does not change the statistical outcome (data not shown).

7.4.3.1 Experiment 2, Analysis 'Placebo'

Group Statistics

	condition	N	Mean	Std. Deviation	Std. Error Mean
counts per minute	P(D)	672.00	894724.11	91085.51	3513.70
	P(I)	672.00	894447.22	96965.88	3740.54

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
counts per minute	Equal variances assumed for t-test	2.05	0.15	0.05	1342.00	0.96	276.89	5132.03	-9790.78	10344.56
	Equal variances not assumed for t-test			0.05	1336.78	0.96	276.89	5132.03	-9790.82	10344.60

7.4.3.2 Experiment 2, Analysis 'Verum'

Group Statistics

	condition	N	Mean	Std. Deviation	Std. Error Mean
counts per minute	V(I)	672.00	231620.80	14278.32	550.80
	V(D)	672.00	231270.98	14587.46	562.72

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
counts per minute	Equal variances assumed for t-test	0.08	0.77	0.44	1342.00	0.66	349.82	787.42	-1194.89	1894.54
	Equal variances not assumed for t-test			0.44	1341.39	0.66	349.82	787.42	-1194.89	1894.54

7.1.4 Running Control 2

7.1.4.1 Running Control 2, Analysis 'Placebo'

Group Statistics

	condition	N	Mean	Std. Deviation	Std. Error Mean
counts per minute	P(D)	672.00	390809.72	36735.02	1417.08
	P(I)	672.00	389780.17	36818.65	1420.31

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
counts per minute	Equal variances assumed for t-test	0.02	0.88	0.51	1342.00	0.61	1029.55	2006.34	-2906.36	4965.46
	Equal variances not assumed for t-test			0.51	1341.99	0.61	1029.55	2006.34	-2906.36	4965.46

7.4.4.2 Running Control 2, Analysis 'Verum'

Group Statistics

	condition	N	Mean	Std. Deviation	Std. Error Mean
counts per minute	V(I)	672.00	108178.89	7460.16	287.78
	V(D)	672.00	108302.29	7769.59	299.72

Independent Samples Test

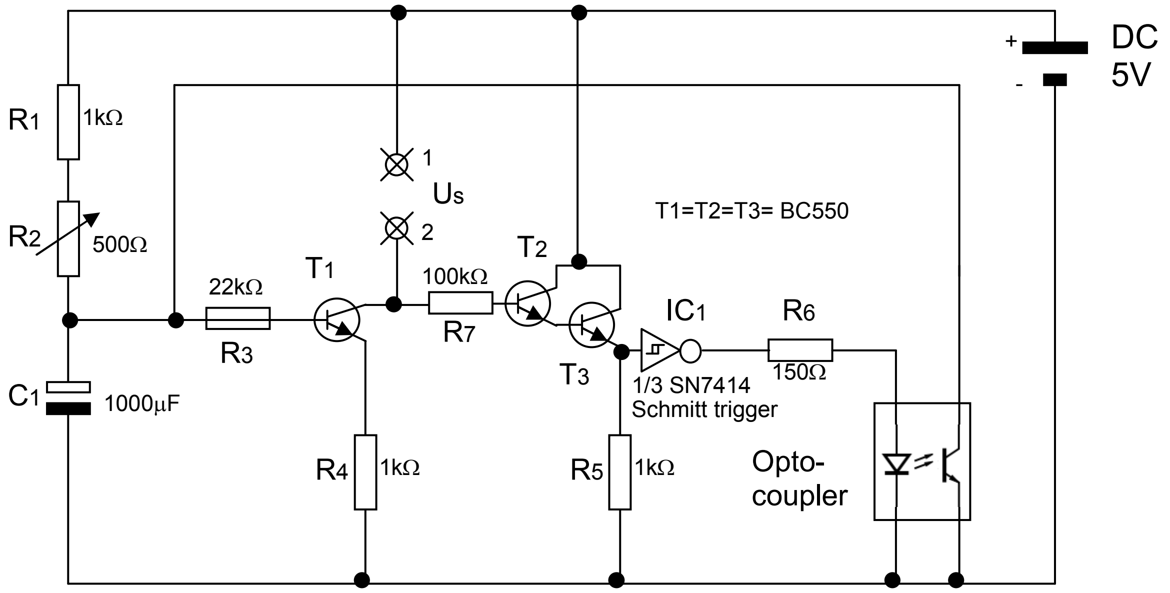
		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
counts per minute	Equal variances assumed for t-test	0.87	0.35	-0.30	1342.00	0.77	-123.40	415.51	-938.52	691.72
	Equal variances not assumed for t-test			-0.30	1339.79	0.77	-123.40	415.51	-938.52	691.73

7.5 Appendix 5 (Hardware details)

The most central piece of hardware apart from the REG was a device which allowed an organism to produce quasi-unpredictable sampling-pulses, which could be recorded by a computer program and then compared to the signals from the REG.

It was developed in a collaboration with Prof. Johannes Hagel and is joint intellectual property of the University of Freiburg and the Institute for Psychophysics (IPP) Cologne.

The following is a schematic construction plan of the device:



Description of function:

The capacitator C_1 is charged via resistor R_1 and potentiometer R_2. Thus at the entry of T_1 an increasing voltage builds up which is amplified and applied to contacts 1 and 2 ($0V < U_S < +5V$).

When an organism (in the experiments described in this study plant and/or human) is connected to contacts 1 and 2 and an increasing current I_S now flows through it ($0 < I_S < 5/(R_2+1000)$).

This very small current is amplified by the combination T_2-T_3 (Doorlington) and flows into the Schmitt trigger IC_1. As soon as its threshold current is reached, the Schmitt trigger switches to 'ON' and the capacitator C_1 is rapidly discharged via the transistor of the optocoupler. Then the cycle starts again by charging of the capacitator C_1.
The discharge was used as the sampling-pulse. It was recorded via the parallel port of the PC where it was compared to the REG output (which was recorded via the serial port) by the software described in Appendix 6. The exact time at which this signal is produced is

sensitive to the electrical resistance of the tissue of the organism which connects contacts 1 and 2. The higher its resistance the longer it will take for the current to reach the threshold of the Schmitt trigger. Since the electrical resistance of living tissue (both in humans and in plants) shows rapid small scale fluctuations in a quasi-unpredictable way as well as more large scale changes over longer time periods (Boucsein, 1992; Volkov and Brown, 2006), the intervals between signals varied accordingly. In this way it was possible to record signals which on the one hand occur reliably and often enough to allow for solid statistical analysis and on the other hand are to some extend unpredictable and genuinely dependent on the properties of the organism.

7.6 Appendix 6 (Software details)

The essential part of the experimental software was a program called ‘corr’ which was written in C-programming language. What follows is the source code corr.c. Executable files are available upon request. The relevant functions of ‘corr’ are detailed in chapter 4.2.2.4.

(This program was developed in a collaboration with Prof. Johannes Hagel and is joint intellectual property of the University of Freiburg and the Institute for Psychophysics (IPP) Cologne)

```
/* corr -- Korrelationsmessung zwischen digitalen Signalen und  */
/*         Zufallsgeneratoren  J.H. 30.12.2004                  */

#include <stdio.h>
#include <stdlib.h>
#include <math.h>
#include <conio.h>
#include <time.h>
#include <pc.h>
#include <values.h>
#include <dos.h>

/* ------------------------------ */
/* Erklaerung der Funktionen      */
/* ------------------------------ */
double scrin(char* ident , char* c);
double zufall();
double erf();
int eingabe();
int hauptschleife();
uclock_t uclock();
/* ------------------------------ */


/* ------------------------- */
/* Globale Variablen */
/* ------------------------- */
double tm_delay;
long int perioden,freq_rng,seed,durchgaenge;
int mode_zufall,i0,ireact,iba;
double xx,xr,xo,xox,sigmax,p_corr,q_corr,num_erw_corr,sig_corr_unit;
char *fname;
FILE *ofile;
/* ------------------------- */

/* --------------- */
/* Hauptprogramm   */
/* --------------- */
int main( void )
{
```

```
init();
eingabe();
hauptschleife();
gotoxy(1,23);
}

/* --------------- */
/* Initialisierung */
/* --------------- */
int init()
{
double t_last;
ScreenClear();
gotoxy(1,1);
/* */
/* Titel schreiben */
/* ----------------*/
printf("%s","ZUFALLSKONDITIONIERTER IMPULSGENERATOR - jh 30.12.2004\n");
/* */
/* Anfangszahl fuer random() setzen */
/* ---------------------------------*/
seed = time(0);
srandom(seed);
iba=1016;
system("mode com1:9600,n,8,1");
outp(iba+4,2);
delay(300);
/* */
/* Anfangszahl xx fuer logistische Abbildung setzen */
/* ------------------------------------------------ */
xx = fabs(sin((double)(seed)));
/* */
/* Anfangszahl xr fuer Rechteckschwingung setzen */
/* --------------------------------------------- */
xr = 0.;
/* */
/* Korrelationsanzeiger auf Null setzen */
/* ------------------------------------ */
outp(0x378,0x0);
/* */
/* Outputfiles oeffnen und definieren */
/* ---------------------------------- */
fname="impulse.out";
ofile=fopen(fname,"wt");
/* */
/* Null-Status des Inputports festlegen */
/* ------------------------------------ */
i0=inp(0x379);
/* printf("i0 = %3d",i0); */
/* */
/* Initialisierung des Timers UCLOCK */
/* --------------------------------- */
t_last=(double)(uclock())/(double)(UCLOCKS_PER_SEC);
}

/* ------- */
/* Eingabe */
```

```
/* --------*/
int eingabe()
{
struct date d;
struct time zeit;

getdate(&d);
gettime(&zeit);

gotoxy(1,3);
printf("Festlegung der Korrelationsdaten:\n");
printf("---------------------------------\n");
perioden    = scrin("ld","Perioden fuer Korrelationstest: ");
durchgaenge = scrin("ld","Anzahl der Durchgaenge        : ");
sigmax      = scrin("lf","Korrelationsstaerke [sig]     : ");
ireact      = scrin("d","1=Corr -> Sign.  0=NoCorr -> Sign.: ");
gotoxy(1,10);
printf("Art des Zufallsgenerators:\n");
printf("--------------------------\n");
gotoxy(1,12);
printf("RANDOM() aus libC ................ (1)\n");
gotoxy(1,13);
printf("Logistische Abb. (mu=4) .......... (2)\n");
gotoxy(1,14);
printf("Rechteckschwingung ............... (3)\n");
gotoxy(1,15);
printf("Orion-Biermann .. (4) / mit XOR .. (5)\n");
gotoxy(33,10);
mode_zufall = scrin("d","==> ");
p_corr = 1.-erf(0.5*sigmax*sqrt(2.));
q_corr = 1.-p_corr;
num_erw_corr = durchgaenge*p_corr;
sig_corr_unit=sqrt(durchgaenge*p_corr*q_corr);

gotoxy(40,11);
printf("p(Korr)           = %5.4lf\n",p_corr);
gotoxy(40,12);
printf("Erwartete Korr.:  = %6.0lf\n",num_erw_corr);
gotoxy(40,13);
printf("z = 1 entsprechen   %6.0lf Korr.\n",sig_corr_unit);
gotoxy(1,16);
freq_rng = scrin("d","Frequenz des RNG [Hz] = ");
gotoxy(1,18);
printf("Timersetting:\n");
printf("-------------\n");
tm_delay=scrin("lf","Aktionszeit [s] = ");
gotoxy(40,18);
printf("Run:\n");
gotoxy(40,19);
printf("----\n");

fprintf(ofile,"#Datum:
%d:%d:%d\n",(int)(d.da_day),(int)(d.da_mon),d.da_year);
fprintf(ofile,"#\n");
fprintf(ofile,"#Zeit :
%d:%d:%d\n",(int)(zeit.ti_hour),(int)(zeit.ti_min),(int)(zeit.ti_sec));
fprintf(ofile,"#\n");
```

```
fprintf(ofile,"#Perioden           : %ld\n",perioden);
fprintf(ofile,"#Durchgaenge        : %ld\n",durchgaenge);
fprintf(ofile,"#Notwendige Sigmas  : %lf\n",sigmax);
fprintf(ofile,"#\n");
fprintf(ofile,"#Art des Zufalls: ");
if (mode_zufall == 1)
{
    fprintf(ofile,"RANDOM() aus libC mit            seed=%ld\n",seed);
}
if (mode_zufall == 2)
{
    fprintf(ofile,"Logistische Abbildung mit mu=4 und x0=%16.14lf\n",xx);
}
if (mode_zufall == 3)
{
    fprintf(ofile,"Rechteckschwingung    mit          xr=%16.14lf\n",0.);
}
if (mode_zufall == 4)
{
    fprintf(ofile,"Orion (Biermann)      mit          ohne SEED  \n");
}
if (mode_zufall == 5)
{
    fprintf(ofile,"Orion (Biermann)      mit   XOR    ohne SEED  \n");
}
fprintf(ofile,"#\n");
fprintf(ofile,"#p(Korr.)          = %5.4lf\n",p_corr);
fprintf(ofile,"#Erwartete Korr.:  = %6.0lf\n",num_erw_corr);
fprintf(ofile,"#z = 1 entsprechen   %6.0lf Korr.\n",sig_corr_unit);
fprintf(ofile,"#\n");
fprintf(ofile,"#-------------------------------------------------\n");
fprintf(ofile,"#|       N    |     n   |  n_RNG  |  t[s]  |  z  |\n");
fprintf(ofile,"#-------------------------------------------------\n");
return(0);
}

/* -------------------------------------- */
/* Zufallsabarbeitung und Impulserzeugung */
/* --------------------------------------*/
int hauptschleife()
{
int bin,k,ndurch;
long int count,n,ntrue,nfalse,cd,ncorr;
double sig,asig,t_last,t_aktuell,delta_t,r,t_a,dt,tm_start,t_test;

dt=1./freq_rng;

ndurch=0;
ncorr=0;
tm_start=0.;

/*-*/
LOOP:
/*-*/
ndurch=ndurch+1;

if(ndurch==durchgaenge+1)
```

```
{
while((double)(uclock())/(double)(UCLOCKS_PER_SEC)-tm_start < tm_delay)
{
}
outp(0x378,0x0);
return(0);
}

ntrue=0;
nfalse=0;

n=0;
t_last=(double)(uclock())/(double)(UCLOCKS_PER_SEC);

while (n < perioden)
{
      n=n+1;
      count=0;
      for(;;)
      {
      t_test = (double)(uclock())/(double)(UCLOCKS_PER_SEC);
      if(t_test-tm_start > tm_delay)
      {
         outp(0x378,0x0);
      }
         t_a = (double)(uclock())/(double)(UCLOCKS_PER_SEC);
         while((double)(uclock())/(double)(UCLOCKS_PER_SEC)-t_a < dt);
         /* */
         r = zufall();
         count=count+1;
         /* */
         /* Abfrage auf Aenderung des Registers 0x379 */
         /* ---------------------------------------- */
         if ( inp(0x379) != i0) break;
      }
      /* */
      /* Zeitmessung */
      /* ------------*/
      t_aktuell = (double)(uclock())/(double)(UCLOCKS_PER_SEC);
      t_last = t_aktuell;
      /* */
      /* Berechnung der CD und des sigma-Wertes
      /* -------------------------------------- */
      RNGEVAL:
      if (r > 0.5)
      {
          bin=1;
          ntrue  = ntrue  + 1;
      }
      if (r < 0.5)
      {
          bin=0;
          nfalse = nfalse + 1;
      }
      if (r == 0.5)
      {
          r=zufall();
```

```
            goto RNGEVAL;
        }
        cd =nfalse - ntrue;
        sig=(double)(cd) / sqrt((double)(n));
        asig=fabs(sig);
        fprintf(ofile,"%10ld %10ld %10ld %8.5lf
%8.5lf\n",ncorr,n,count,t_aktuell,sig);
        while(inp(0x379) != i0);
}
gotoxy(40,20);
printf("Durchgaenge: %5ld von %5ld\n",ndurch,durchgaenge);

if(ireact==1)
{
    if(asig > sigmax)
    {
        /* */
        /* Ausgabe des Korrelationssignales bei sig > sigmax */
        /* ------------------------------------------------- */

        outp(0x378,0x1);
        tm_start = (double)(uclock())/(double)(UCLOCKS_PER_SEC);
        /* */
        /* Zaehler fuer Korrelationen */
        /* -------------------------- */
        ncorr=ncorr+1;
        gotoxy(40,21);
        printf("Korrelationen: %5ld\n",ncorr);
    }
}
if(ireact==0)
{
    if(asig < sigmax)
    {
        /* */
        /* Ausgabe des Korrelationssignales bei sig < sigmax */
        /* ------------------------------------------------- */

        outp(0x378,0x1);
        tm_start = (double)(uclock())/(double)(UCLOCKS_PER_SEC);
        /* */
        /* Zaehler fuer Nicht-Korrelationen */
        /* -------------------------------- */
        ncorr=ncorr+1;
        gotoxy(40,21);
        printf("Nicht-Korrelationen: %5ld\n",ncorr);
    }
}
        goto LOOP;
return(0);
}



double zufall()
/* */
/* Erzeugung der Zufallszahlenreihe */
```

```
/* ----------------------------------*/
/* */
/* Methode mode_zufall = 1: RANDOM() aus libC */
/* Methode mode_zufall = 2: Logist. Abbildung x(n+1)=4*x(n)*(1-x(n)) */
/* Methode mode_zufall = 3: Rechteckschwingung mit Tastverhaeltn. 1:1 */
/* Methode mode_zufall = 4: Orion (Biermann) an COM1 */
{

double r,xox;

if (mode_zufall==1)
{
    r=random()/((double)(MAXINT));
    return(r);
}
if (mode_zufall==2)
{
    xx=4.*xx*(1.-xx);
    return(xx);
}
if (mode_zufall==3)
{
    xr=1.-xr;
    return(xr);
}
if (mode_zufall==4)
{
    xo=(double)(inp(iba)/255.);
    return(xo);
}
if (mode_zufall==5)
{
    xo=(double)(inp(iba)/255.);
    r=random()/((double)(MAXINT));
    if((xo-0.5)*(r-0.5) > 0.)
    {
        xox=0.25;
        return(xox);
    }
    else
    {
        xox=0.75;
        return(xox);
    }
}

}


double scrin(char* ident , char* c)
/* */
/* Hilfsroutine fuer Bildschirmeingabe */
/* ----------------------------------- */
/* */
/* Verwendung: variable = ("typ","text") */
/* */
/* Beispiel:   x0 = ("lf","x0 = "); */
```

```
/* */
/* schreibt    x0 =   auf den Bildschirm und wartet auf Eingabe des */
/*             Zahlenwertes von x0 ueber die Tastatur */
/* */
{
long int varld;
double varlf;
int vard;
char* form;

printf("%s",c);
if (ident == "lf")
   {form="%lf";
    scanf("%lf",&varlf);
    return(varlf);
   }
if (ident == "ld")
   {form="%ld";
    scanf("%ld",&varld);
    return(varld);
   }
if (ident == "d")
   {form="%d";
    scanf("%d",&vard);
    return(vard);
   }
}


double erf(double x)
/* */
/* Mathematische Funktion erf(x) mit rationaler Approximation */
/* ---------------------------------------------------------- */
/* */
/* (Quelle: Abramowitz - Stegun Table of Mathematical Functions) */
/* */
{
double p,a1,a2,a3,a4,a5,t,pol,er;
p=0.3275911;
a1=0.254829592;
a2=-0.284496736;
a3=1.421413741;
a4=-1.453152027;
a5=1.061405429;
t=1./(1.+p*x);
pol=(a1*t+a2*pow(t,2)+a3*pow(t,3)+a4*pow(t,4)+a5*pow(t,5))*exp(-pow(x,2));
er=1.-pol;
return(er);
}


/* end of file */
```

7.7 Appendix 7 (overview of results of REG experiments)

List of conducted experimental 'runs' in reverse chronological order. (More detailed data and analysis available upon request.)

Name of data file	**Type of experiment (source of sampling-pulse)**	**Direction of hypothesis (1=more correlations; 0=less correlations)**	**Number of periods (n)**	**Number of trials (ndurch)**	**Cutoff value for correlation significance in standard deviations (sigmax)**	**Number of statistically expected correlations (n(corr))**	**Number of observed correlations (N(corr))**	**Significance of observed deviation from expectancy (one tailed p-value)**
tqm09	plant 4	0	300	100	1.934123	5.66	4	0.33
auh52	plant 4	0	1000	100	1.976424	4.63	10	0.99
pnl11	Human	1	101	100	1.940323	4.60	8	0.09
khw83	Human	1	101	100	1.940323	4.60	11	0.01
mar43	Human	1	101	100	1.940323	4.60	2	0.95
pbg57	Human	1	101	1	1.940323	0.05	0	0.95
ubw00	Human	1	101	1	1.940323	0.05	0	0.95
epv17	Human	1	101	100	0.646774	55.07	53	0.70
nrh70	Human	1	101	100	0.646774	55.07	53	0.70
bxj31	Human	1	101	100	0.646774	55.07	61	0.14
rdn41	Human	1	101	100	0.646774	55.07	46	0.97
vnr94	Human + plant	0	1000	1	1.976424	0.05	0	0.95
ucp31	Human + plant	0	401	60	1.55	6.60	5	0.34
shz95	oscillator	1	200	10000	2	400.37	371	0.95
shz95b	oscillator	0	200	10000	2	400.37	371	0.95
ejl71	oscillator	1	10000	1000	2	43.38	40	0.72
ejl71b	oscillator	0	10000	1000	2	43.38	40	0.33
lac89	oscillator	1	50	1000	2	32.84	35	0.37
lac89b	oscillator	0	50	1000	2	32.84	35	0.69
hgx00	oscillator	1	50	1000	2	32.84	28	0.83
hgx00b	oscillator	0	50	1000	2	32.84	28	0.22
xkp21	oscillator	1	50	1000	2	32.84	32	0.58
xkp21b	oscillator	0	50	1000	2	32.84	32	0.49
vfh92	oscillator	1	50	1000	2	32.84	39	0.16
vfh92b	oscillator	0	50	1000	2	32.84	39	0.88
kwg07	resistor	1	50	1000	2	32.84	27	0.87
kwg07b	resistor	0	50	1000	2	32.84	27	0.17
fml62	resistor	1	50	1000	2	32.84	32	0.58
fml62b	resistor	0	50	1000	2	32.84	32	0.49
fnd09	resistor	1	50	1000	2	32.84	37	0.25
fnd09b	resistor	0	50	1000	2	32.84	37	0.80
xbn03	plant 3 control	0	50	1000	2	32.84	31	0.42
zjx74	plant 2b control	0	50	1000	2	32.84	29	0.28
mes60	plant 2b control	0	50	1000	2	32.84	32	0.49

Name of data file	Type of experiment (source of sampling-pulse)	Direction of hypothesis (1=more correlations; 0=less correlations)	Number of periods (n)	Number of trials (ndurch)	Cutoff value for correlation significance in standard deviations (sigmax)	Number of statistically expected correlations (n(corr))	Number of observed correlations (N(corr))	Significance of observed deviation from expectancy (one tailed p-value)
bzq81	plant 2b control	0	50	1000	2	32.84	33	0.56
jis37	plant 2b control	0	50	1000	2	32.84	42	0.95
ava06	plant 2b control	0	50	1000	2	32.84	29	0.28
ujv35	plant 2b control	0	50	1000	2	32.84	32	0.49
twg37	plant 2b control	0	50	1000	2	32.84	30	0.35
dck20	plant 2b control	0	50	1000	2	32.84	33	0.56
yol99	plant 2b control	0	50	1000	2	32.84	28	0.22
mpg49	plant 2b control	0	50	1000	2	32.84	44	0.98
feb66	plant 2b control	0	50	1000	2	32.84	29	0.28
jiz85	plant 2b control	0	50	1000	2	32.84	30	0.35
kzs36	plant 2b control	0	50	1000	2	32.84	43	0.97
mdb05	plant 2b	0	50	1000	2	32.84	26	0.13
dnx44	plant 2b	0	50	1000	2	32.84	36	0.75
dew70	plant 2b	0	50	1000	2	32.84	42	0.95
zrg91	plant 2b	0	50	1000	2	32.84	28	0.22
zgl26	plant 2b	0	50	1000	2	32.84	25	0.09
smv23	plant 2b	0	50	1000	2	32.84	30	0.35
hcv51	plant 2b	0	50	100	2	3.28	5	0.89
juf20	plant 2b	0	50	100	2	3.28	2	0.36
mmq32	plant 2b	0	50	100	2	3.28	5	0.89
mck32	plant 2b	0	50	100	2	3.28	7	0.98
egf08	plant 2b	0	50	100	2	3.28	1	0.16
rid92	plant 2b	0	50	100	2	3.28	2	0.36
ejk81	plant 2b	0	50	100	2	3.28	2	0.36
dcp22	plant 2b	0	50	100	2	3.28	3	0.58
ctw85	plant 2b	0	50	100	2	3.28	4	0.77
jfl92	plant 2a	0	50	100	2	3.28	0	0.04
jeu46	plant 2a	0	200	100	2	4.00	2	0.23
ytz84	plant 2a	0	200	100	2	4.00	2	0.23
zgp54	plant 2a	0	200	100	2	4.00	3	0.43
slc01	plant 2a	0	200	100	2	4.00	3	0.43
tds12	plant 2a	0	200	100	2	4.00	1	0.09
kjj26	plant 2a	0	1000	100	2	4.63	10	0.99
mpl63	plant 2a	0	3200	100	2	4.39	6	0.85
iwa73	plant 2a	0	2400	100	2	4.55	4	0.52
eqz93	plant 2a	0	2400	100	2	4.55	9	0.98
wxw27	resistor	1	126000	16	1	5.05	8	0.10
wxw27b	resistor	0	126000	16	1	5.05	8	0.96
xxx00	plant dark	1	180000	72	2	3.25	5	0.22
uie67	oscillator	1	101	2000	2	92.09	93	0.48

Name of data file	Type of experiment (source of sampling-pulse)	Direction of hypothesis (1=more correlations; 0=less correlations)	Number of periods (n)	Number of trials (ndurch)	Cutoff value for correlation significance in standard deviations (sigmax)	Number of statistically expected correlations (n(corr))	Number of observed correlations (N(corr))	Significance of observed deviation from expectancy (one tailed p-value)
uie67b	oscillator	0	101	2000	2	92.09	93	0.57
qwj61	oscillator	1	101	2000	2	92.09	107	0.06
qwj61b	oscillator	0	101	2000	2	92.09	107	0.95
kbc64	oscillator	1	101	2000	2	92.09	81	0.89
kbc64b	oscillator	0	101	2000	2	92.09	81	0.13
jpl59	electronic noise	1	101	2000	2	92.09	86	0.76
jpl59b	electronic noise	0	101	2000	2	92.09	86	0.28
igp66	electronic noise	1	200	2000	2	80.07	96	**0.04**
igp66b	electronic noise	0	200	2000	2	80.07	96	0.97
xkg14	electronic noise	1	200	1000	2	40.04	42	0.40
xkg14b	electronic noise	0	200	1000	2	40.04	42	0.66
qqp22	electronic noise	1	1000	1000	2	46.29	47	0.48
qqp22p	electronic noise	0	1000	1000	2	46.29	47	0.58
iaz58	resistor	1	200	1000	2	40.04	25	1.00
iaz58b	resistor	0	200	1000	2	40.04	25	**0.01**
bwh19	resistor	1	200	1000	2	40.04	40	0.52
bwh19b	resistor	0	200	1000	2	40.04	40	0.54
syi25	resistor	1	1000	1000	2	46.29	39	0.88
syi25b	resistor	0	1000	1000	2	46.29	39	0.15
dop94	resistor	1	200	1000	2	40.04	40	0.52
dop94b	resistor	0	200	1000	2	40.04	40	0.54
sqx44	resistor	1	200	1000	2	40.04	40	0.52
sqx44b	resistor	0	200	1000	2	40.04	40	0.54
exf66	resistor (K2)	1	200	100	2	4.00	6	0.21
exf66b	resistor (K2)	0	200	100	2	4.00	6	0.89
lun40	resistor (K2)	1	200	100	2	4.00	2	0.91
lun40b	resistor (K2)	0	200	100	2	4.00	2	0.23
qjf93	resistor (K2)	1	200	100	2	4.00	2	0.91
qjf93b	resistor (K2)	0	200	100	2	4.00	2	0.23
xwp04	resistor (K2)	1	200	100	2	4.00	2	0.91
xwp04b	resistor (K2)	0	200	100	2	4.00	2	0.23
ugf53	resistor (K2)	1	200	100	2	4.00	6	0.21
ugf53b	resistor (K2)	0	200	100	2	4.00	6	0.89
dfy70	resistor (K2)	1	200	100	2	4.00	4	0.57
dfy70b	resistor (K2)	0	200	100	2	4.00	4	0.63
pdx88	resistor (K2)	1	200	100	2	4.00	5	0.37
pdx88b	resistor (K2)	0	200	100	2	4.00	5	0.79
iqf51	resistor (K2)	1	200	100	2	4.00	4	0.57
iqf51b	resistor (K2)	0	200	100	2	4.00	4	0.63
shw59	resistor (K2)	1	200	100	2	4.00	3	0.77
shw59b	resistor (K2)	0	200	100	2	4.00	3	0.43

Name of data file	Type of experiment (source of sampling-pulse)	Direction of hypothesis (1=more correlations; 0=less correlations)	Number of periods (n)	Number of trials (ndurch)	Cutoff value for correlation significance in standard deviations (sigmax)	Number of statistically expected correlations (n(corr))	Number of observed correlations (N(corr))	Significance of observed deviation from expectancy (one tailed p-value)
yqu34	resistor (K2)	1	200	100	2	4.00	6	0.21
yqu34b	resistor (K2)	0	200	100	2	4.00	6	0.89
hsg87	plant 1	0	200	100	2	4.00	2	0.23
fbw83	plant 1	0	200	100	2	4.00	2	0.23
prs38	plant 1	0	200	100	2	4.00	3	0.43
ngf27	plant 1	0	200	100	2	4.00	1	0.09
zea76	plant 1	0	200	100	2	4.00	5	0.79
pyz21	plant 1	0	200	100	2	4.00	5	0.79
hsf83	plant 1	0	200	100	2	4.00	3	0.43
wwf79	plant 1	0	200	100	2	4.00	7	0.95
20050302-2	plant 1	0	200	100	2	4.00	2	0.23
20050302-1	plant 1	0	200	100	2	4.00	3	0.43
20050301-2	plant 0	0	200	100	2	4.00	2	0.23
20050301	plant 0	0	200	100	2	4.00	5	0.79
20050226-2	plant 0	0	200	100	2	4.00	7	0.95
20050226	plant 0	0	200	100	2	4.00	2	0.23
20050228-6	plant 0	0	200	100	2	4.00	4	0.63
20050228-5	plant 0	0	200	100	2	4.00	4	0.63
20050228-4	plant 0	0	200	100	2	4.00	3	0.43
20050228-3	plant 0	0	200	100	2	4.00	6	0.89
20050228-2	plant 0	0	200	100	2	4.00	3	0.43
20050228	plant 0	0	200	100	2	4.00	2	0.23

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