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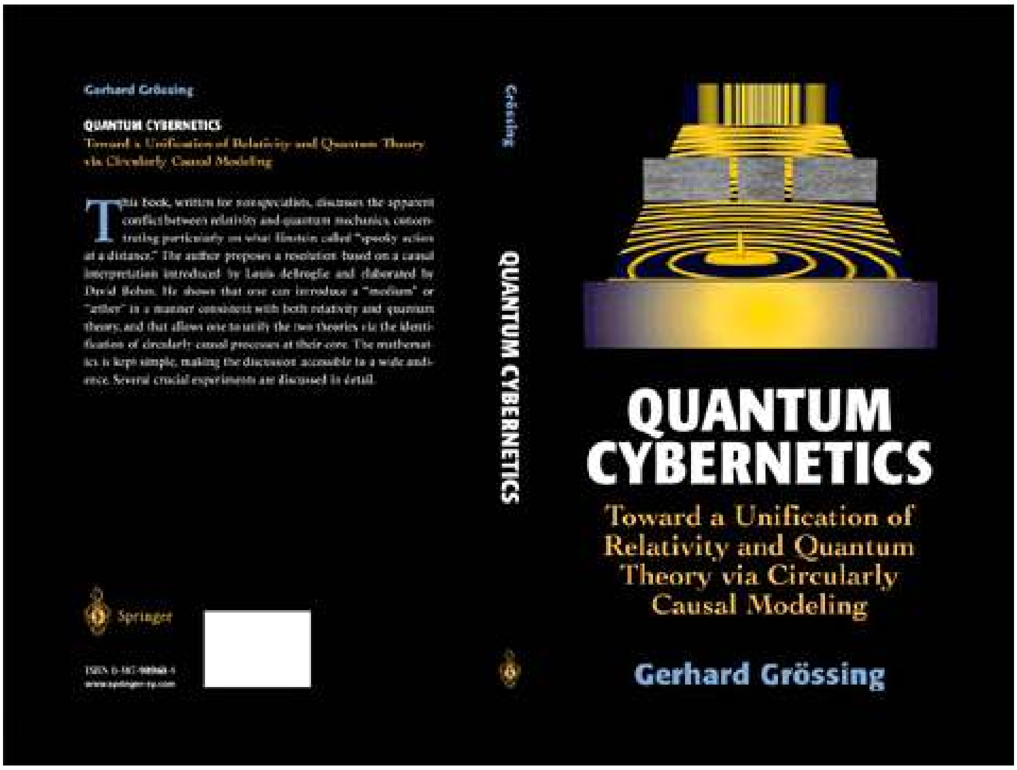
QUANTUM CYBERNETICS
TOWARD A UNIFICATION OF RELATIVITY AND QUANTUM THEORY VIA CIRCULARLY CAUSAL MODELING



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Preface

Some 350 years ago, in his *Discorsi e Dimostrationi Matematici* [Galilei], Galileo Galilei discussed whether or not light propagated with a finite though very high velocity, or with infinite speed, instantaneously. The question was an open one then, with prominent proponents for either position. For example, René Descartes argued on philosophical grounds that light dispersed itself into all of space instantaneously, whereas Galileo was more inclined toward the idea of a finite velocity. In fact, he even reported about an early experiment, which, however, would have to be refined and performed again to reach a definite conclusion.

> *"Sagredo:* ... However, of which kind, and how high might we estimate the velocity of light? Is the appearance instantaneous, momentaneous, or, like other movements, temporal? Could one decide this experimentally?
>
> *Simplicio*: Daily experience teaches us, that the spreading of light be instantaneous; if in a large distance the artillery performs shooting exercises, we see the glare of the flame without time delay, while the ear perceives the sound only after some considerable time.
>
> *Sagredo:* Oh, Mister Simplicio, from this well known attempt one can conclude nothing but that the sound takes more time than the light; in no way can one conclude that the light be momentaneous, and not temporal, if only very fast. Also another observation does not teach

more: immediately when the sun appears on the horizon, we see its rays; but who tells me, that the rays do not arise earlier at the horizon than in my eyes?

Salviati: The low power of decision of those and other similar processes evoked the thought in me, if one could not in some way decide with certainty, whether the illumination, i.e. the spreading of light, be really instantaneous: for, already the rather quick propagation of sound leaves one to suppose that the one of light can only be very fast. And the experiment, which I considered, was the following: Of two persons each one holds some light in a lantern or something similar to it, namely so, that each one can cover or uncover the light with the hand; then they place themselves opposite to each other within a short distance, and they practice to cover or uncover their lights for the other: namely so, that, if the one sees the other light, he immediately uncovers his; such correspondence is being mutually repeated several times, so that soon without error upon uncovering of the one follows the uncovering of the other, and, if the one uncovers his light, he will also soon see the one of the other. Having practiced within a short distance, the two persons separate with their lanterns up to 2 or 3 miles; and by performing their experiment at night, they observe carefully, whether the answering of their signal occurred in the same tempo as before, wherefrom one could conclude whether the light was propagating instantaneously; for if this were not the case, then in a distance of 3 miles, that is, on a path of 6 miles to and fro, the delay would have to be fairly well recognizable. (...)

Sagredo: A beautiful, sensible experiment; but, tell us, what has resulted from the performance of it ?

Salviati: I have done the experiment only within a short distance, within less than one mile, from which no conclusion yet can be made about the instantaneity of light; but if it is not momentaneous, it is at least very fast, even almost momentaneous..." [Galilei, pp. 39f]

The well-known measurements of Olaf Römer in 1675 eventually established that light propagates with a finite speed. However, the distances involved in the calculations were not a few miles, but literally cosmic ones, making use of the fact that the eclipses of the Galileian moons of Jupiter are time delayed once by a considerable amount if measured twice in a year: once, when the earth is on the same side as Jupiter, and half a year later. Thus, in the latter case, the light from Jupiter has to travel an additional 2 Astronomical Units (distances sun-earth) before reaching the earth. Olaf Römer in this way determined the velocity of light as about 220,000 km/sec, not too far off today's 299,792,458 m/sec [Simonyi]. Elements of Galileo's experiments on the speed of light are echoed in two main theories of the twentieth century, i.e., the theory of relativity, and quantum mechanics. First, Galileo's experiment was concerned with the simultaneity of light flashes perceived by two independent observers, and with the possible (though not achieved) obstruction of that simultaneity. And Albert Einstein began his arguments for a theory of relativity with a discussion of simultaneity as established via emission and reception of light by two independent observers. Second, the phenomenon of quantum mechanical nonlocality today puts us in a similar situation as Galileo's facing a "practically instantaneous" speed of light: the well-known "EPR type"-experiments (based on the seminal paper by [Einstein et al.]), and an increasing number of similar ones, all seem to indicate that in the presence of two independent observers' apparatuses, the effects of operations on one observer's apparatus are detectable "practically simultaneously" on the other observer's apparatus. What a Salviati and a Sagredo may have done with light lanterns 350 years ago may be very similar to what Alice and Bob could do today with quantum communication devices: (at least in retrospect) observing a "practically instantaneous" change in a state of light upon predefined manipulations over distances of miles, whereas with a much finer resolution in time one could eventually show that the effects of state manipulations really propagate with a very high, but finite speed.

If you snap your fingers in a small room with the appropriate acoustics, you will hear an echo of the "snap" almost immediately. If one considers this from a perceptual point of view, this experience may even be somehow surprising: it is, for a moment, as if your body were extended in a "medium" that reacts on your snapping with an echo so immediately afterward that it seems to still belong to your bodily action, as if you had hit the wall with a long stick in your hand. Somehow you are - via the "medium" of the air - connected to the wall, and in a simple experiment like when snapping your finger you become aware of this "connection." In other words, we are often not aware of the media that surround us, because they are always there and therefore filtered away by our perpetual routines. Only when in unusual circumstances, like in the mountains, for example, where echoes can take seconds to return, do we become aware of these echoes, and, therefore, of the finite velocity of sound. Rather different considerations hold for the velocity of light. Bodily no more, but only under very particular experimental situations, with very high resolutions in time, can we experience that it is not infinite. What, then, about the manipulation of quantum states? Could not they also occur in a "medium" that connects all participants' apparatuses, and that upon the appropriate manipulations becomes modified such that the effects of this modification spread "practically instantaneously," but nevertheless with some finite speed?

Such an option is actually being considered here in this book. It will be shown that, rather surprisingly, with the re-introduction of the concept of a quantum "medium" (or "aether"), which contradicts neither the theory of relativity nor quantum theory, in effect a unification of both theories can be envisaged. The blind Galileo, when snapping his finger, could have roughly told the size of a room he was brought into by making use of the principle of echo orientation as we know it also from bats or certain fish. In abstract terms, this principle tells us that some localizable entity may permanently emit and receive waves in a medium, where the incoming ones provide information about the surroundings of said entity, which are then used to guide its further movement. Here is where cybernetics comes in: the circular causality between a "perceptual entity" and its "environment." With the quantum cybernetics aimed at in this book I try to elaborate a corresponding "perceptual" model of quantum systems.

I would like to thank those scholars who have massively influenced my thinking and who, throughout the years, and in numerous discussions, helped to shape my understanding of quantum theory, and of science generally: Heinz von Foerster, Daniel Greenberger, Franco Selleri, Jean-Pierre Vigier, and Anton Zeilinger. Although I've had the opportunity only once in each case, I also gratefully remember stimulating discussions on the idea of quantum cybernetics with David Bohm and John Bell. I am also most thankful for reading and providing comments on the first draft of this book to Helmut Erber, Siegfried Fussy, Richard Gordon, Peter Holland, Helmut Rauch, Herbert Schwabl, and Johannes Werner. Fritz Bergler, Peter Ferschin, Joseph Hartmann, Elisabeth Kopf, and Werner Korn have been of invaluable help in preparing the illustrations. Furthermore, I thank Tom von Foerster for the very fine collaboration with Springer-Verlag. And finally, I am most grateful to Angelika, my other half of the sky, for sharing with me the elating experience of this month's total solar eclipse, and much more.

GG

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[1] By the time he wrote the *Discorsi,* Galileo was placed under house arrest; he was already blind and had only a few more years to live, but it is obvious from the following that in principle he considered an experimental decision possible.

Introduction: The Return of the Aether

> Nicht *wie* die Welt ist, ist das Mystische, sondern *dass* sie ist.
>
> (It is not *how* the world is that is mystical, but *that* it is.)

Ludwig Wittgenstein

Tractatus Logico-Philosophicus

Most of theoretical physics in the twentieth century can be characterized by a reductionist attitude that has revealed a hierarchical structure of the physical world. However, instead of being "radically" reducible to one "basic" level only, each layer of the hierarchy has turned out as largely autonomous. The great success of this approach consists in a huge amount of often very precise knowledge about each of these layers, unified in the "fundamental" descriptions via "universal" laws. The successful strategy of reduction and unification is due to a quite remarkable level independence, such that, for instance, the effective Lagrangian on the level of molecular interactions is for all practical purposes decoupled from the one on the level of quarks constituting the molecules' individual nuclei.

However, level independence is not only a "fact of nature" that we observe; it is also to some degree a consequence of the reductionist strategy per se [Primas 1983], which actively closes its eyes upon other, level connecting phenomena, like self-organization, emergence, etc. According to Sam Schweber, "it is not enough to know the 'fundamental' laws at a given level. It is the solutions to equations, not the equations themselves, that provide a mathematical description of the physical phenomena. 'Emergence' refers to properties of the solutions - in particular, the properties that are not readily apparent from the equations" [Schweber]. Thus, one can say that toward the end of the twentieth century, physicists, and scientists in general, although (necessarily) still remaining "reductionists" in a weaker sense, increasingly tend to direct their attention from level independence toward "holistic" phenomena. This is done in very diverse areas such as, e.g., quantum theory (where holism has - "philosophically" - always been an issue, but in recent years has also become of operational importance), or the transdisciplinary study of *self-organized* criticality [Bak et al.].

In general, holistic phenomena cannot be described by linear, monocausal reasoning. Rather, whichever element on some particular level is chosen for investigation, it must be considered in its context involving other levels, with circularly causal relations between them. Contextuality and circularly causal (or feedback-based) reasoning nowadays can be found in practically all fields of knowledge. Although not always explicitly stated as such, in practice they are a matter of course in the humanities, as in sociology or psychology. In evolutionary biology, one speaks of "evolutionary landscapes" (e.g., in "fitness space"): if classical Darwinism today resembles the study of the flow of a river's water by tracing the trajectories of individual droplets back to their origins, the new systemic approach to evolution has to consider also the river bed and the constant interactions between the "water" and its surroundings. In other words, there exists a circularly causal relationship between the trajectories of individual evolutionary units (such as species) and their surrounding ecologies. A very similar systemic relationship can be found on the level of the genes: Formerly having been considered as constituting the "atoms of heredity," genes now are rendered to assume new roles within "autocatalytic networks" [Kauffman].

Even in the physical sciences of "inanimate matter," contextuality and circular causality abound. For example, in General Relativity, a massive body influences the spacetime curvature of its surroundings, and vice versa: the curvature of spacetime determines the trajectories of the massive bodies. Moreover, in the Maxwell-Lorentz theory of the electron, particles and field mutually influence each other. Furthermore, in energetically open systems, processes of self-organization are characterized by a mutual relationship between the dynamics of individual entities and the boundary conditions of the whole system.

So, if the context of a research topic is not chosen too narrowly, circular causality is state-of-the-art, even in the (classical) physics of matter. But what about quantum theory? Apparently, this seems to be the only field of physics where causality is seriously questioned, and with respect to local monocausal explanations this is certainly justified. However, it is also justified to enquire whether the behavior of quantum systems really differs so much from all the other systems studied in the sciences. On the contrary, I shall try here to indicate the use of systemic thinking in quantum theory as well: the key issue will be contextuality and a circularly causal, i.e., a cybernetic viewpoint.

There may be several reasons why such an approach has not been considered extensively so far.[2] One of them is certainly given by the many successful applications of quantum theory without any serious need for refined viewpoints. Moreover, the implications of the quantum phenomena may also be seen as being so radical for our whole understanding of the material world we live in, that it may well take at least decades to fully realize them. In fact, the development of quantum mechanics in the twentieth century does show a steady increase in awareness of its central feature, i.e., of nonlocality.[3]

While Albert Einstein referred to the corresponding phenomena only as a "spooky action at a distance," John Bell was able to show that no local hidden variable model whatsoever can reproduce the predictions of quantum mechanics. Rather, quantum mechanics violates his famous inequalities which are today named after him[4] [Bell]. Later, Alain Aspect's group [Aspect et al. 1982a, Aspect et al. 1982b] was the first to experimentally verify the violations of Bell's inequalities (although with a small caveat, later to be overcome, as mentioned by [Zeilinger]), and nowadays a whole series of experiments makes direct use of the nonlocal nature of quantum theory [Aspect].

In other words, during the last decades of the twentieth century we have become witnesses of what I call "the end of the twentieth century atomism," i.e., the end of "the belief (put into practice with the atom bomb, nuclear reactors, or particle accelerators) that the world, in its deepest essence, is composed of tiniest entities - these 'atoms' today being some kind of 'elementary particles' - such that any object can be considered, at least in principle, as a spatially limited collection of a finite number of such entities" [Grössing 1993a]. In contrast, it has become feasible to speak about dynamical "holistic" networks where "particles" are embedded in a relevant (i.e., irreducible) environment or "context." In this regard, I have already mentioned the demise of the concept of genes as the "atoms of heredity" above, giving way to the framework of autocatalytic networks. Similarly, atoms, electrons, neutrons, etc., which have once been considered as "fundamental particles," now have to be described in modern quantum theory within the framework of nonlocal holism, viz., the phenomenon of entanglement [Schrödinger 1935], for example.

This amounts to nothing less than a "Copernican revolution" on the level of "objects." Instead of being separate entities "centered in themselves," - like some massive object with its gravitational field - with the rest of the world somewhere around them, quantum "objects" are not necessarily "centered" anywhere, but rather connected to different and distant parts of the world that are simultaneously parts of the quanta themselves. So, if we speak about quantum "objects" at all, we must be aware that thereby we already introduce a "de-finition" (or delimitation) that excludes parts of the correlations of the quantum system with the rest of the world: as Hans Primas has repeatedly pointed out, quantal "objects" do not exist in an absolute sense, but only in a contextual one, i.e., in the framework of our chosen delimitations. In this sense, "observable phenomena are created by abstracting from some EPR correlations" [Primas 1983, p. 253]. From ontological and epistemic points of view, this has an interesting corollary:

> According to quantum mechanics the electrons of the moon are entangled with their radiation field. If we are not willing to abstract from the quantum mechanical structure of this radiation field on the grounds that it is irrelevant for the problem under discussion, then the moon becomes entangled with the sun, etc. and cannot be said to possess an individuality. So without abstracting from the quantum structure of the radiation field, the moon cannot be an object [Primas 1983, p. 292].

... Nor can a single tree, or a single electron, for example. Of course, in our lives of daily routine, this does not change much - just as for us the sun still "rises" in the east and "sets" in the west, despite the heliocentric revolution of Copernicus and others. But if we are really interested in how the world is, we have to face the "Copernican revolution" of quantum theory in its full extent: that in its "deepest essence" (and as far as we can talk about it today), there are no "atoms" of the physical world separable from the rest; rather, the world has to be considered as a whole, with "parts" constituting only (more or less viable) simplifications of the actual ongoing dynamics, or of what David Bohm has called the "holomovement" [Bohm 1980]. The fascinating perspective of this new world view is, however, that under particular circumstances the "wholeness" of the physical world can be used to show nonlocal correlations that under our old atomistic perspective could only be qualified as "magic." It is clear that such a sweeping revolution literally affecting our fundamental concepts of the whole universe cannot be fully grasped within short periods of time, or be accepted by a scientific community with firm roots in an "atomistic" world view to be overcome. This situation today is, in fact, very similar to the cosmological "Copernican revolution" during the times of the Renaissance, of which Alexandre Koyré has pointed out, that it, too, did not succeed in one great step, but took decades, or even centuries to become settled into the minds of individuals [Koyré].

I believe that the "quantum revolution" still has not yet reached the full extent of its meanings. For many physicists, for example, the spectacular nonlocal correlations represent nothing more than the bizarre outcome of calculations with quantum mechanical wave functions, which themselves many consider as just symbolizing our knowledge of a quantum state. Of course, any symbolization is a mental construct that only refers to a physical (or other) state, just as a map is not a landscape itself. The crucial point about the nonlocal correlations of quantum mechanics is, however, that here one talks about physical processes with conspicuous simultaneous interdependences, although they are miles (or further) apart. So, in between Alice and Bob, who perform an EPR-type experiment and who may be some 10 miles apart, there exists nothing but the vacuum. Entanglement, EPR correlations, and the like, all refer to quantum systems, aspects of which are measurable at some distant points A and B, with only the vacuum in between. Perhaps one should skip the word "only" in the last sentence? Perhaps the vacuum, rather than being "nothing," is a "something" that does transmit information between A and B?

In fact, it has long been known that the vacuum is actually a "plenum", rather than mere emptiness. In a very definite sense, then, it constitutes what has in earlier centuries been called the "aether." This is also how Edmund T. Whittaker argues in the preface of his *History of the Theories of Aether and Electricity*:

> As everyone knows, the aether played a great part in the physics of the nineteenth century; but in the first decade of the twentieth, chiefly as a result of the failure of attempts to observe the earth's motion relative to the aether, and the acceptance of the principle that such attempts must always fail, the word "aether" fell out of favour, and it became customary to refer to the interplanetary spaces as "vacuous"; the vacuum being conceived as mere emptiness, having no properties except that of propagating electromagnetic waves. But with the development of quantum electrodynamics, the vacuum has come to be regarded as the seat of the "zero-point" oscillations of the electromagnetic field, of the "zero-point" fluctuations of electric charge and current, and of a "polarisation" corresponding to a dielectric constant different from unity. It seems absurd to retain the name "vacuum" for an entity so rich in physical properties, and the historical word "aether" may fitly be retained [Whittaker, p. v].

When Whittaker wrote this, neither the "Casimir effect" (to be discussed briefly in Section 4.4) was well known, nor were the whole physical implications of EPR-type correlations. So, the existence of an "aether" today is well established, and I shall use the word further on, even though for said historical reasons many physicists are not willing to do so. However, to do more justice to history, the concept of the aether actually has had some proponents even among twentieth century physicists, and it is their work that major portions of the present elaborations are based on. I am referring to the de Broglie-Bohm interpretation of the quantum-mechanical formalism. It has its roots in first attempts by de Broglie in the 1920s [de Broglie 1927], experienced a major boost in the form of two papers by David Bohm in 1952 [Bohm 1952a, Bohm 1952b], and since the late 196os is being worked on by an increasing number of physicists. Its main feature is that it represents a "realistic" (as opposed to "idealistic" or "Platonistic") interpretation of quantum mechanics, in the sense that it can give an ontological meaning to quantum systems, and quantum systems themselves are considered as consisting of localizable particles whose dynamics are governed by a holistic nonlocal wavelike field, sometimes called the "guiding (or pilot) waves," and sometimes the "quantum potential."

The main point, where the attempts on a quantum cybernetics presented here diverge from the modern de Broglie-Bohm versions, can be formulated by the explicit introduction of a circularly causal relationship between "particles" (which are here considered as nonlinear parts of waves) and their surrounding waves. The latter are not only "guiding" passive "particles" in quantum cybernetics, but also being actively "co-determined" by the "particles." It is clear from the present status of quantum theory that a complete picture of quantum processes must be able to give an account of what happens to an individual quantum system. As can be seen from the implications of the Greenberger-Horne-Zeilinger experiment [Greenberger et al.], for example, a merely statistical interpretation of quantum mechanics is not sufficient any more for a full account: in this experiment, a single event can disprove any local hidden variable explanation or prove the nonlocality of quantum theory, respectively. So, quantum cybernetics is also an attempt at the construction of a theory of individual quantum systems. Of course, the statistics and the many-particle properties must be derivable from the theory, too. When I speak about "circular causality," it must be clear that this refers to just a single quantum and its surroundings, with which it has this form of causal relationship. In the case that more than one particle are involved, then, of course, we are faced with several "circular causalities" that actually cannot be separated into individual circles. These, then, rather represent a "web" of interdependent, mutually causal processes, which one could also term "holistically causal." However, in the present work, I shall retain the term "circular causality," mainly to illustrate the mutual relationship between "particles" and waves, even though in many actual situations a simple circle will not suffice for a complete description of the causal web involved. Nevertheless, causal circles are considered here as the essential dynamic "units," which define the organizational properties of quantum systems of whatever complexity.

This book is structured as follows. In Chapter 1, some of the problems concerning the compatibility of quantum theory and the special theory of relativity are discussed. It is shown that a hitherto ignored consequence from the principle of relativity has a wide range of implications even for the quantum domain. Specifically, it is shown how upon the assumption of a relativistic "aether," both Born's rule for calculating probabilities of events and nonlocal correlations follow from the principle of relativity. Although not necessarily based on the idea of quantum cybernetics, but in perfect agreement with it, a calculation scheme is presented with which the results of quantum theory can be obtained without invoking complex-numbered "probability amplitudes." A brief review of the de Broglie-Bohm interpretation of quantum theory and problems concerning relativistic formulations thereof rounds up the first chapter. In Chapter 2, the approach of quantum cybernetics is presented, i.e., the idea of a circular causality between waves and "particles." A relativistic quantum cybernetics is proposed that can avoid problems of other relativistic formulations of the causal interpretation. Furthermore, it is shown how the rules to calculate probabilities in quantum theory can be understood in principle. Chapter 3 presents a discussion of experiments relevant for the approach of quantum cybernetics. In particular, it is shown how superluminal velocities and perhaps even signaling might occur. With regard to special relativity, a solution of an apparent conflict between different observers' descriptions of nonlocal effects is given within a realistic framework, as well as a discussion of "causal paradoxes" associated with eventual superluminal signaling. In Chapter 4, Einstein's equations for the gravitational field are derived from quantum cybernetics, thereby providing a close link between circular causality at the quantum level and Mach's principle. Finally, in Chapter 5, circular causality at the quantum level is discussed, both with respect to the historical context and future perspectives.

To complete this introduction, I want to point out what this book is not about. Although the term "cybernetics" may evoke associations with computing devices in the reader, I do not deal with the field of quantum computing here. Also, the recently increasing interest in controlling the performance of quantum precision experiments by using feedback processes against decoherence effects [Anderson, Dunningham et al.] is not covered. With the latter being rather of the type of a "quantum control theory," I would like to reserve the term quantum cybernetics for the proposed feedback processes constituting any quantum system. Finally, let it be said here that I have no intention whatsoever to propose an "alternative" to quantum theory. Cybernetics, as I understand it, is a way of looking at things, with a particular focus on feedback processes that are describable as circularly causal ones. This does not mean that any description via the usual linearly causal approaches must be wrong. In effect, we know that quantum systems are to be seen holistically, and any type of description, which by its very nature is "reductionist" to some degree, will be only of some limited value. Still, I hope to be able to show that some central issues of quantum mechanics can in fact be illustrated very aptly with cybernetic concepts. In particular, the establishment and changes in nonlocal correlations shall be a primary focus of my explorations. Thus, quantum cybernetics is quantum theory from a cybernetic point of view.

Actually, quantum theory is so complex and rich of curious phenomena that, to grasp it fully, no single canonical theory could highlight all its features optimally. In this sense, quantum cybernetics is an attempt to draw attention to some aspects of quantum processes, which may explain some central questions of today's theory, but simultaneously opens many new ones.

2 Exceptions discussing different aspects of a hypothesized quantum "control theory" include [Guerra and Morato, Santamato, Rosenbrock, MacGregor, Yasue].
3 In general, I refer to "nonlocality" in the sense that spacelike separate regions of spacetime are correlated or can influence each other. I will thus retain this nomenclature even in the case where superluminal propagations are made responsible for the experimental results, which one might then consider as elements of a "local" but "holistically" causal theory.
4 Naturally, the remaining proponents of locality insist that there are a few holes in the present experimental evidence [Selleri], but the latter will most likely soon be filled.