Quantum information isomorphism: Beyond the dilemma of the Scylla of ontology and the Charybdis of instrumentalism

R. Horodecki
M. Horodecki
P. Horodecki

*In order to deal most effectively with the unanalyzable quantum whole, the Copenhagen interpretation takes as a "frame of reference" the preparation parameters and outcomes of measurements. It represents a **passive**, Ptolemaic-like instrumentalism directly related to "what we see in the sky," i.e., to the "surface" of reality. However, the notion of quantum information leads to an **active**, Copernican-like realism which involves an (intrinsic) ordering principle and the view that the quantum whole is analyzable. It is then possible to consider subsystems as localized in space, controlled individually, and communicated. This makes it natural to treat quantum information (quantum states) not merely as knowledge. Moreover, it involves complementarity between local and nonlocal information. To avoid the dilemma between the Scylla of ontology and the Charybdis of instrumentalism, we propose the concept of **quantum information isomorphism**, according to which the quantum description of nature is isomorphic to nature itself. By definition it is not just one-to-one mapping, but it preserves the full structure of nature. In particular, it allows the treatment of the wave function of isomorphic images of quantum systems in the laboratory, implying that quantum information is indeed carried by these quantum systems.*

Introduction

In science many entangled paths lead to truth about nature. On one of them, we met Charles Bennett—a co-discoverer of the quantum information phenomena that have had a decisive influence on the development of quantum information theory [1–6]. During a visit several years ago to the IBM Thomas J. Watson Research Center, we got to know him as a renaissance man and a stimulating personality. It was a great pleasure for one of us (R. H.) to participate in the May 2003 IBM symposium commemorating Charles's sixtieth birthday.

The purpose of this paper is to point out that the quantum information revolution has had a considerable influence on our thinking about quantum formalism and its relation to physical reality. Quantum information theory (QIT) is a new approach that has a significant advantage—it allows us to ask new questions that would not be thought of in the old paradigm. This new way of thinking is more fruitful not only from a pragmatic point of view: We hope it will also lead to a new *physical* view of nature, as did the Copernican scheme. Although that scheme was initially conceived as only a change of reference frame, it led to the discovery of new laws of gravitation governing planetary motion.

The phrase "interpretation of quantum mechanics" has been associated with the interpretation of quantum

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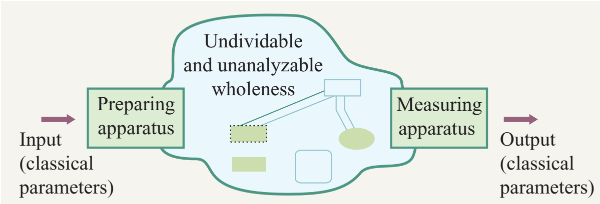

Figure 1

Ptolemaic-like passive paradigm. The paradigm takes as a "reference frame" the preparation parameters and outcomes of the measurements, i.e., the "surface" of reality.

measurements, commonly referred to as "the measurement problem." After decades, the discussions of this problem have become less and less fruitful and more and more tiresome—mainly because of a lack of connection with experimental results. The Copenhagen interpretation prevailed primarily because it was minimal. Now we ask, "Is it of use to undertake any new interpretational effort?" We believe it is still an important task. The goal of such an effort would be not to solve the measurement problem, but to provide a fresh view of quantum mechanics based on the new questions that are being asked within QIT. And on the other hand, one would hope to find an interpretation that would aid in the search for a deeper ordering principle of quantum mechanics. QIT provides a powerful notion of quantum information, which can be regarded as a new guiding principle in the current interpretive chaos, and thus as an alternative to the current principle of minimality of the Copenhagen interpretation.

Ptolemaic-like instrumentalism and Copernican-like realism in the description of quantum phenomena

There are historical reasons why an instrumental (Copenhagen) interpretation does not explicitly involve quantum entanglement at the root of the quantum formalism. However, we know that entanglement is a physical property of a compound quantum-mechanical system, and it cannot be ignored in the building of any consistent interpretation.

The other, even deeper, reason why the Copenhagen interpretation is now inefficient is that there previously existed no notion of quantum information. Information was treated only in classical terms, as knowledge rather than as a property of a physical system. In fact, the heart of this interpretation is a passive, Ptolemaic paradigm (**Figure 1**), taking as its reference frame the preparation parameters and outcomes of measurements, that is, the "surface" of reality.

This is similar to the Ptolemaic description that pertains directly to what we can see in the sky. However, while looking at the sky it is hard to perceive the order of planetary orbits that Copernicus proposed. The Ptolemaic description was artificial, as was known even in the time of Copernicus. At the Cracovian Academy, where Copernicus learned the Ptolemaic description, the lecturers giving the course on astronomy criticized the Ptolemaic approach.

The main point is that Ptolemy's description was a geometrical trick constructed to produce a picture that agreed with observations. Both the Ptolemaic and Copernican descriptions were compatible with observations. But while the Ptolemaic approach was passive, Copernicus proposed that there is an ordering principle connected with the Sun. This allowed Kepler and then Newton to find the deeper principle governing planetary motions. We can conclude that Copernicus's approach, was more faithful to nature than Ptolemy's; therefore, the former carried more content.

In quantum mechanics, Schroedinger's equation describes "intrinsically" the dynamics of a quantum system. In the Copenhagen approach, however, Schroedinger's description is used merely to predict the results of outcomes resulting from a given preparation of such a system. This is like using Copernicus's approach to determine the positions of the planets more and more accurately, while failing to make the step forward that Newton was able to make. Nevertheless, one of the reasons why the Copenhagen interpretation has been widely accepted is that the opposite view (that of De Broglie, Bohm, and Einstein [7]) was too classical, and hence not suitable for reflecting the curious features of quantum mechanics. Thus, the Copenhagen interpretation was the safest way to deal with the "great smoky dragon" [8]—that is, the entity between preparation and measurement.[1] QIT shows that one can avoid these two extremes. Its results are independent of interpretation, yet it is, in effect, Copernican, or post-Copernican—in most cases, the outcomes of measurement are not considered—corresponding to *analyzing* the Copernican picture rather than "looking at the sky." QIT gives us the hope that some new organizing principle will be found, based on notions such as quantum systems, the states of those systems, functions of the states (such as entanglement), and the quantum processing of the states. These notions cannot be used within the Copenhagen approach, in which the experiment, not the quantum system, is described.

In Figure 1, an experiment involves the use of a tunable preparation apparatus and a measuring apparatus that produces outcomes (classical output). That is, in the

[1] Some elements of Copernican realism can be found in the views of Bohr and Einstein; A. Plotnitsky, Purdue University, West Lafayette, IN, private communication. Our criticism is related to the "constellation of ideas" about quantum formalism called the Copenhagen interpretation.

Copenhagen interpretation one does not make reference to the quantum systems that are processed. Rather, the experiment includes everything, and this is the unanalyzable quantum whole. In QIT, we think about the whole as analyzable.

In **Figure 2,** three stages are distinguished: preparation, control, and measurement. The new feature here is the introduction of the control stage as an autonomous part. The stage contains a quantum system, which may be a compound of subsystems. The subsystems can be localized in space. They can be controlled individually, and they can be *communicated* (moved from place to place for the purpose of communication). This communication of quantum systems (or states) is especially at variance with the Copenhagen approach, allowing us to think about quantum information, which is by no means knowledge! We elaborate on this later in the context of cryptography and quantum computation. For the sake of the present discussion, let us note that in the new framework offered by the QIT approach, we have the conceptual tools that allow us to push forward new ways of understanding nature by asking new questions. One such question is, for example, "What is the capacity of a quantum channel to transmit quantum information?" A simpler question would be "Can one transform one state into another one by means of a given class of control operations?" This is the simplest, and one of the most fundamental, questions of QIT.

Such questions can, of course, be formulated in terms of the language of preparation and measurement, but then they become completely artificial. Similarly, in the context of the Ptolemaic paradigm, it makes no sense to ask what forces the planets to orbit the sun. Thus, any question motivated by QIT could be rephrased in measurement-preparation terminology, yet it would never arise within the latter picture. Thus, QIT constitutes a revolution in thinking about quantum mechanics. Of course, even before the QIT era, people thought in non-Copenhagen terms, but the goals of research in quantum mechanics were somewhat dominated by the instrumental mentality enforced by the minimal Copenhagen approach. One must stress here that even in QIT we cannot fully abandon preparation-measurement terminology, because this terminology binds the Platonic world of the wave function to experimental observations. More precisely, the preparation part can be almost completely absorbed into the control part. For example, in quantum computation [9] it is only necessary to prepare the standard input state $|00\ldots0\rangle$. A quantum experiment can be thought of (on the conceptual level) as being mostly control followed by measurement (Figure 2). For example, a quantum computer, if it is to be useful, must produce some desired classical output. Thus, the main effort of the constructors of quantum algorithms is the desirable connection between processing quantum states (the Copernican part) and the "surface of reality" (what we "see in the sky"). Indeed, an important branch of QIT concerns itself with quantum input and/or quantum output algorithms—involving quantum oracles and (sometimes sophisticated) schemes of quantum state preparation that are designed to produce special quantum outputs [10]. This subdomain of QIT is perhaps most at variance with the spirit of the Copenhagen approach.

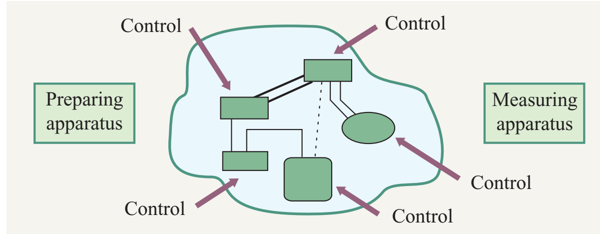

Figure 2

Copernican-like active paradigm. This paradigm takes as a "reference frame" what is actually processed in the laboratory.

Informational isomorphism

There have been numerous discussions on the status of the quantum-mechanical wave function. According to the Copenhagen approach, although the wave function is not an immanent state of the quantum system, it provides a mathematical representation of our knowledge about the experimental setup. In realistic interpretations (in their extreme version), it refers to a real wave physically present in space. The latter approach represents a naive form of realism. On the other hand, the former approach seems to be too passive. A more suitable approach should lie between these extremes; that is, any description of nature can be thought as a sort of isomorphism between the laws of nature and their mathematical representation. If we insist that the role of the wave function is simply to describe probabilities, we must give up the possibility of treating the wave function as an isomorphic image of what is actually processed in the laboratory. Using this "isomorphism" approach, we can further claim that quantum information is indeed carried by a quantum system and that the wave function is the image of this information. The former cannot be described on paper, or by means of a sequence of classical symbols on the tape of a Turing machine, but the wave function can be. Thus, we would say that quantum information does exist; yet it is not just the wave function, but it is represented by it. There are two main examples that support this view against the narrow Copenhagen treatment of the wave function or quantum state.

Before discussing these examples, let us stress that we are far away from naive realism. It is obvious that we can never say, for example, that the wave function exists, yet we can argue that the wave function is not merely an object on paper, but rather it is an image, a good mapping, of something that exists. Of course, we will never be able to prove that quantum information in this sense exists.

Fast quantum algorithms

Shor's factoring algorithm [11] is likely to be exponentially faster than any classical factoring algorithm.[2] If this is indeed the case, it should not be possible, using a classical device, to efficiently compute the wave function in a quantum computer at some stage of computation. Thus, it will never be possible to write this wave function on a piece of paper. If we insist on interpreting the quantum state as knowledge, we must say that from an operational point of view, the quantum computer is not in any state, since it is not possible to characterize it in a reasonable time. Yet something is happening during the performance of the algorithm, since after it is completed, the classical outcomes give the solution of the required task. However, what we process is definitely not knowledge known to any person, but instead of saying that the quantum computer is a "great smoky dragon," we prefer to say that we process just the quantum information that is objectively carried by the system. The wave function is an image of this information, and sometimes we will not be able to compute the wave function, even though the information is there.

It is tempting to say here that we process statistics. However, the statistics must be encoded into quantum systems, and only this form of processing gives powerful results such as fast factoring. Thus, quantum information can also be referred to as a form of encoded statistics. A notion is introduced in [13] and [14] that is especially suitable for describing the paradigm we advocate here—*information determinism*. The quantum information carried by quantum states is processed deterministically because the state into which the statistics are encoded evolves deterministically. The final stage of computation is then to extract the statistics from the quantum information by measurement. To summarize, exponentially fast quantum algorithms raise doubts about whether treating the wave function as a representation of knowledge about an experiment is fully justified. Or, more precisely, in this case it is inadequate to say that quantum evolution (i.e., the execution of a quantum algorithm) is an "evolution of our knowledge." Rather, it is a representation of quantum information—the isomorphic image of the fundamental objective property of the system—that evolves during quantum computing.

Quantum cryptography

Quantum cryptographic key distribution schemes [1] (see also the pioneering work in [15]) also suggest that there is an attribute, quantum information, that can naturally be ascribed to quantum systems. It is clear that there must be quantum communication between Alice and Bob in order to obtain a secret key. Alice cannot simply throw a wave function written on paper to Bob, because Eve could read it without disturbing it; such knowledge is something classical, which can be copied. Yet, by sending quantum systems Alice and Bob can achieve something that would be impossible within the classical world. The object of the protocol is to obtain a joint distribution of outcomes of Alice, Bob, and Eve, having the feature that Alice and Bob are correlated, but that Eve is not correlated with Alice or Bob. These properties must be discussed in terms of the preparation and measurement of quantum systems. However, in the "Copernican" approach, the heart of the phenomenon can be explained in one sentence: Quantum information cannot be cloned. Thus, it is reasonable to postulate that Alice sends Bob systems that carry quantum information. Again, the wave function represents this information, rather than being merely the tool for calculating the fact that, in the end, Alice's and Bob's outcomes will be correlated, but they will not be correlated with Eve's outcomes.

Directly computing functions of a quantum state

Another interesting quantum scenario is one in which both the natural character of quantum information and its isomorphism to reality in nature are clear. This is the direct calculation of a function of a quantum state [16, 17]. As depicted in **Figure 3**, consider a stationary quantum source that produces copies of a d-level system in an unknown quantum state ρ. Suppose the goal is to find a given function of quantum state $f(\rho)$. There are two basic approaches that can be used: In the first, one performs tomography estimating $d^2 - 1$ parameters and reconstructing the *density matrix* ρ_{mn} in some basis. Then the function of the state is calculated as a function of those parameters. The second approach [16, 17] is quite different. Instead of performing estimation of many states, we create a specially designed quantum evolution that involves interaction between different copies of the system and, possibly, interaction of our system with some controlling ancilla (a portion of the system). This is *a kind of quantum computing on purely quantum input*. Finally, we subject the ancilla to an elementary binary measurement on its quantum output, which reproduces just $f(\rho)$. This approach has two advantages: 1) It is more natural if ρ is viewed as representing a real quantity to be processed

[2] There are some doubts, however, about the full completeness of the proof of nonexistence of fundamental obstacles against efficient quantum computing (see [12]).

rather than a state of knowledge (the latter approach comes from the orthodox Copenhagen interpretation). Indeed, a more realistic interpretation of ρ makes it more natural to devise such quantum computing schemes. 2) It is much more "ecological," involving much less production of entropy in the devices and records. We are not left with informational by-products; that is, we do not need to collect and process classical information that will be, in the end, almost entirely discarded because it is not of interest to the observer.

A nice example has been proposed [16] with the function

$$f(\rho) \equiv \mathrm{Tr}(\rho^k). \quad (1)$$

Instead of tomography and classical matrix multiplication, one can perform a controlled shift operation on k copies. A final binary measurement of the polarization of a controlling qubit completely reproduces the above function.

Information and entanglement

Quantum entanglement has been one of the most important aspects of QIT, and it continues to be the subject of intensive investigations [18]. Inspired by connections between information and thermodynamics, and also by entanglement-manipulation theory, in collaboration with J. Oppenheim we have applied the Bennett–Landauer paradigm [19–22] to distributed quantum systems. We considered work (in the thermodynamic sense) which can be extracted locally from heat baths by the use of a bipartite state that can be processed by means of local operations and classical communication (LOCC[3]) [23]; see also [24]. Since from this point of view work is equivalent to information, one can consider localizing information by LOCC. It turns out that analyzing what is local (or what can be localized), we also determine what is nonlocal. Part of the information content of the state is, from the beginning, local. The other part, mutual information, represents correlation and can be partially localized. The part of the correlation that cannot be localized must be in some sense quantum-mechanical. For pure states, we have shown that the nonlocalizable part of information corresponds exactly to entanglement. Thus, by analyzing what is local, we have arrived at entanglement. This connects the thermodynamic approach, for which the information losses are counted, with entanglement theory. It is interesting that for these two features of pure quantum states, localizable information and entanglement, we have unique measures.

[3] To this end, one has to keep track of the flow of the information, and take into account the information contained in all systems that are added. In practice this can be achieved by using a class of operations called NLOCC (noisy LOCC), by means of which one is allowed to add local systems in maximally mixed states only; any other systems must be taken into account in the initial state rather than in the processing stage.

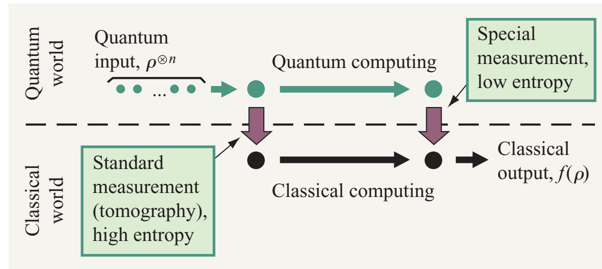

Figure 3

Obtaining the function of a quantum state via quantum computing. The quantum computing estimation of $f(\rho)$ is more natural if ρ is viewed as an autonomic quantity to be processed rather than as a state of knowledge (within the orthodox Copenhagen interpretation).

Indeed, we have two theories of information processing: the "noisy operations" (NO) model and the theory of pure state entanglement.

In general, the theory is given by a class of operations. Any function that cannot increase under the class is regarded as being a *resource*. For reversible theories, there is only one type of resource. In the NO model [23], we consider simple (i.e., not compound) quantum systems, and the class of operations known as "noisy operations," including unitary operations, partial trace, and adding an ancilla in a maximally mixed state. It turns out that under the following conditions, the theory is asymptotically reversible, and the only resource is what we can call information. It is quantified by n–S, where n is the number of qubits and S is the von Neumann entropy. In the theory of pure state entanglement [5], the class is LOCC, and under the same conditions there is only one resource, quantified by subsystem entropy—entanglement.

Local–nonlocal complementarity

Bohr's complementarity [25, 26] applies to the properties of the system that are observable. Indeed, Bohr thought about complementary classical setups of experiments. Two observables that cannot be measured jointly correspond to two setups of a device. In QIT there are complementarities between quantities that are not directly related to outcomes of measurements. Moreover, in Bohr complementarity there is no place for the notion of locality. In [27] we propose a complementarity that involves the notion of locality. It describes the mutual exclusivity of two processes performed on a multi-part quantum system by means of classical communication between its separated subsystems. One process involves gaining the maximum number I_1 of local qubits in a pure state. The second involves communicating the maximum amount of quantum information Q. We observe that instead of performing one of the above two tasks optimally, one can consider a protocol P which produces some (possibly nonoptimal) number $I_1(P)$ of pairs in a local pure quantum state and also leads to the transfer of some number of qubits with the rate $Q(P)$. The protocol P performs two tasks, but in general performs neither of them optimally. It can be shown [27] that the following basic inequality holds:

$$Q(P) + I_1(P) \leq I_1 . \quad (2)$$

One might think that information complementarity is trivial in the sense of the well-known saying that one cannot have one's cake and eat it too. Indeed, it seems natural to interpret our complementarity as follows: Suppose that one has two qubits in a singlet state. One cannot retain a pair of qubits in that state for teleportation and simultaneously use it to obtain local information. Of course, this is not complementarity, and moreover it is completely trivial. However, our phenomenon is not trivial, for the following reasons. First, we do not consider a tradeoff between singlets and local information. Rather, we consider the tradeoff between the number of qubits teleported through the singlets and the number of pure local qubits obtainable using the singlets.

In fact, it could happen that using one singlet one could teleport one qubit and also use the remaining state to obtain one bit of local information, or at least some nonzero amount of local information. That would apply if the teleportation process did not produce two bits of entropy. However, as was shown in the original paper on quantum teleportation [3], one must send two bits in the teleportation process. This follows from causality; it is not obvious, but is an implication of quantum mechanics.

So far we have shown that our phenomenon is nontrivial, but it can still be referred to as a tradeoff; the concept of complementarity is still not needed. However, there is another feature of the phenomenon that makes it necessary to refer to it as complementarity. That is, if one decides to perform one task—teleportation of a qubit—one irreversibly loses the possibility of obtaining local information. And vice versa—if one chooses to obtain one bit of local information, one irreversibly loses the possibility of teleportation of one qubit. As a matter of fact, one might think that after the local information had been obtained, one could reverse the process (using the information that had been obtained) to restore the possibility of performing teleportation. However, this is not possible because obtaining local information destroys entanglement, which is an irreversible process in the LOCC paradigm.

Local–nonlocal complementarity from basic principles

How fundamental is the complementarity we have discussed above? More precisely, is our complementarity a consequence of the properties of space–time and of fundamental quantum theory, or is it based on some additional, less fundamental assumptions? At first glance it seems to be based on some specific additional, less fundamental assumptions. It could be argued, for example, that we have arbitrarily allowed for only classical communication between distant observers. Such an assumption is not of a fundamental nature: The privileged role of classical communication comes from de-coherence. The latter is the consequence of the specific form of physical Hamiltonians. Therefore, this privileged role for classical communication cannot be regarded as a consequence of basic properties of space–time and of quantum mechanics.[4]

However, we now argue that our complementarity is indeed a more fundamental phenomenon. To this end, we cannot use LOCC as the basis of the analysis. To begin with, note that the notion of entanglement of pure states can be regarded as a consequence of locality and the quantum description of compound systems. Indeed, since quantum interactions are local (in the sense that they decrease as distance increases), for spatially separated systems, local operations are natural. Since, in quantum mechanics, pure quantum states play a fundamental role, it is enough to define entanglement for pure states. We do so by assuming that the pure state is entangled if it cannot be produced by local operations. Then the concept can be naturally extended to mixed states, still without introducing any *a priori* notion of classical communication, but simply by taking into account the probabilistic nature of mixed states. A suitable definition of entanglement of mixed states is of course the one by Werner (the state is entangled if and only if it is not a mixture of product states) [29].

The notion of entanglement itself induces a class of operations: We can single out those operations that do not create entanglement out of separable states (such a class was considered in [28]). The operations do not have an *a priori* definition, but are defined by the notion of entanglement, which in turn is a consequence of locality and the quantum description of compound systems. We designate the operations as being separability-preserving (SP).

Let us now consider another notion: *information*. We then assume that the only states that do not contain information are maximally mixed ones. This gives rise to a class of operators that do not create information. This is the class of operations that preserve maximally mixed states (designated as "PMM" operations); cf. [30].

[4] A formulation of LOCC in more basic terms is possible if we define classical communication as communication by clonable means. This feature of classical communication was used in [28] to derive the equivalence between the no-cloning principle and the principle of non-increase of entanglement by use of local operations and one-way classical communication. This was noted in a discussion of one of us with Aditi Sen(De) and Ujjwal Sen of the University of Gdańsk.

Having the two notions of information and entanglement and an associated pair of classes of operations, those not creating entanglement and those not creating information, we consider a class that is the intersection of the two: the class that does not create information and also does not create entanglement (denoted as the PMMSP class). Let us repeat here that this class is not an independent notion, assumed *a priori*: We have derived it from entanglement and information. This class is a tool with which we can trace the flow of information while using the SP class. We can now ask, "How much information can be localized by SP operations?" Note again that the key word "locality" is invoked. Also note that to answer this question we must of course consider the joint class PMMSP. In this way we arrive at the notion of localizable information without involving LOCC as a basic notion. The complementarity between quantum communication via PMM and localization of information via SP can be now be viewed as a fundamental one.

Note that since the PMMSP class is larger than the NLOCC one, the localizable information obtained here may be greater than that defined by means of NLOCC. Thus, in this paper, we have modified somewhat the quantity we used in the derivation of complementarity, yet the modification does not change the main idea of the interplay between local information and entanglement.

Concluding remarks

To conclude, quantum information isomorphism allows us to domesticate the "great smoky dragon"—the reality that lies between preparation and measurement. In particular, it implies informational determinism, according to which quantum information carried by quantum states is processed deterministically. It is consistent with the fact that in quantum field theory the fundamental symmetry constraints are imposed on the quantum state rather than on probabilities. It is also compatible with the generic information paradigm [13, 14], according to which the notion of information is a fundamental category in the description of physical reality and can be defined independently of probability itself. On this basis, the existence of a unitary information field was postulated as a necessary condition for any communication (or correlation). In particular, the double, hylemorphic nature of the unitary information field involves two mutually coupled levels of physical reality: logical (or informational), due to the potential field of alternatives, and energetic, due to the fields of activities (or events).[5] The logical level naturally requires the use of sets of axioms to extract facts that hold within quantum formalism and are essential for quantum information processing (cf. [28] and [30]).

Finally, note that quantum informational isomorphism opens many interesting questions: "Is there an intimate connection between symmetries in nature and robustness of quantum states against quantum noise?" "Is there a one-to-one connection between fundamental interactions and the spectrum of physical states?" (For instance, why do the spectra of quark states not contain GHZ states [31]?) "Is gravitation somehow distinguished in nature from the other physical interactions?" "If so, does this have an influence on quantum information processing?"

Our hope is that quantum information isomorphism will allow for an improved understanding of the fundamental processes of nature. Indeed, it may be possible to treat the processes in the context of information processing; see for example [13, 14, 32, 33]. Finally, we would like to emphasize that although quantum information isomorphism does not solve the longstanding measurement problem, it can nevertheless serve as a guide for new interpretations of quantum mechanics, which would go beyond either of the two extremes—the Scylla of ontology and the Charybdis of instrumentalism.

[5] In fact, the coupling of these two levels was first explicitly recognized by Landauer [19] and Bennett [20].

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Ryszard Horodecki *Institute of Theoretical Physics and Astrophysics, University of Gdańsk, 80-952 Gdańsk, Poland (fizrh@univ.gda.pl).* Professor Ryszard Horodecki graduated from the Technical University of Gdańsk in 1967; he received a Ph.D. degree in 1976 from the University of Gdańsk, where he was appointed Professor in 2000. His main research interests are in quantum information theory and the foundations of quantum mechanics, including its interpretation and philosophical aspects. Since 1999, he has led the research efforts of the Gdańsk node of European Commission projects on quantum information. Professor Horodecki is a member of the Council of the Polish Laboratory of Physics of Information Processing, and a coauthor of *Quantum Information*, published by Springer-Verlag in 2001. His main achievements include the analysis of interpretational problems of quantum formalism and pioneering research on the entanglement of mixed states, in particular, *bound entanglement*.

Michał Horodecki *Institute of Theoretical Physics and Astrophysics, University of Gdańsk, 80-952 Gdańsk, Poland (fizmh@univ.gda.pl).* Dr. Michał Horodecki graduated from the University of Gdańsk in 1997 and received a Ph.D. degree from that university in 2000. His research interests are in quantum information theory and the foundations of quantum physics. He received a Foundation for Polish Science Fellowship in 1998, the Grzegorz Białkowski Award in 2001 for the best Ph.D. thesis in physics in Poland (for the period 1997–2000), and an award from Department III of the Polish Academy of Sciences in 2001. Dr. Horodecki is a coauthor of *Quantum Information*, Springer-Verlag, 2001, and his main achievements include pioneering research on the entanglement of mixed states, in particular, *bound entanglement*.

Paweł Horodecki *Faculty of Applied Physics and Mathematics, Gdańsk University of Technology, 80-952 Gdańsk, Poland (pawel@mifgate.mif.pg.gda.pl).* Dr. Paweł Horodecki graduated from the University of Gdańsk in 1995; he received a Ph.D. degree from the Technical University of Gdańsk in 1999. His research interests are in quantum information theory and the foundations of quantum physics. He received a Foundation for Polish Science Fellowship in 1998 and a DAAD Research Fellowship (Hannover) in 1999, and was Fujitsu Visiting Professor of DAMTP at Cambridge University in 2003. Dr. Horodecki is a coauthor of *Quantum Information*, Springer-Verlag, 2001. His main achievements include pioneering research on the entanglement of mixed states, in particular, *bound entanglement*.