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On Feasibility of Quantum Computation and Quantum Communication

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Abstract

Bell tests and Bell's theorem used to interpret the test results opened the door to quantum information processing, such as quantum computation and quantum communication. Based on the erroneous interpretation of the test results, quantum information processing contradicts a well-established mathematical fact in point-set topology. In this study, the feasibility of quantum computation and quantum communication is investigated. The findings are as follows. (a) Experimentally confirmed statistical predictions of quantum mechanics are not evidence of experimentally realized quantum information processing systems. (b) Physical carriers of quantum information coded by quantum bits (qubits) do not exist in the real world. (c) Einstein's ensemble interpretation of wave-function not only will eliminate inexplicable weirdness in quantum physics but also can help us see clearly none of quantum objects in the real world carry quantum information. The findings lead to an inevitable conclusion: Without carriers representing quantum information, physical implementations of quantum information processing systems are merely an unrealizable myth. Examples are given for illustrating the reported results. For readers who are unfamiliar with point-set topology, the examples may alleviate difficulty in understanding the results.

Keywords: Bell tests; Bell's theorem; Einstein-Bohr debate; quantum information processing; quantum information; quantum bits (qubits)

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1. Introduction

Bell tests, namely, the experimental tests of Bell inequalities [1–4], are intended to resolve the Einstein-Bohr debate on the conceptual foundations of quantum mechanics [5,6]. According to the opinion of most physicists, Bell's theorem is the standard interpretation of the test results [1,7,8]. According to Bell's theorem, the Einstein-Bohr debate seems to have been resolved "in the way which Einstein would have liked least" [9]. But some researchers consider Bell's theorem questionable [10,11]. Although the Einstein-Bohr debate has not been resolved yet as we shall expound shortly, the Bell tests and Bell's theorem opened the door to quantum computation and quantum communication [12]. In this study, we investigate the feasibility of quantum computation and quantum communication. The results are formulated as two propositions.

Proposition 1. *Experimentally confirmed statistical predictions of quantum mechanics are not evidence of experimentally realized quantum information processing systems.*

Proposition 2. *Physical carriers of quantum information coded by quantum bits (qubits) do not exist in the real world.*

Based on a well-established mathematical fact in point-set topology, we can justify the propositions and show that Einstein's ensemble interpretation of ψ-function not only will eliminate inexplicable weirdness in quantum physics but also can help us see clearly none of quantum objects in the real world carry quantum information. By justifying the propositions, we can also clarify confusion caused by a widespread opinion in a popular text [13]. According to this opinion, quantum information processing cannot be precluded unless quantum mechanics fails to be correct. As we shall see, it is not appropriate to connect quantum information processing with quantum mechanics. An inevitable conclusion then follows: Without carriers representing quantum information, physical implementations of quantum information processing systems, such as quantum computers, quantum communication networks, quantum cryptography, and quantum teleportation, are merely an unrealizable myth.

In the rest of this paper, we first expound why the Einstein-Bohr debate remains unsettled and why the unresolved debate suggests that Bell's theorem is problematic (Section 2). Then we justify the propositions (Section 3). Next, we examine the Bell tests and revisit Einstein's ensemble interpretation of ψ-function (Section 4). After illustrating the reported results with examples (Section 5), we discuss briefly the generalization of the results (Section 6) and conclude the paper (Section 7).

2. Unresolved Debate and Bell's Theorem

As we can see from [14] and from Ref./23/ in [15], Bell and his followers regarded Einstein as a proponent of hidden variables and tried to reinterpret quantum mechanics while keeping its current form intact by resorting to hidden-variables theories [7,9,16]; thus, the Bell tests presume the legitimacy of quantum superposition. However, Einstein never endorsed any hidden-variables theory ([17], p.254) and argued against the legitimacy of quantum superposition in his debate with Bohr. As indicated by the above historical fact, the Einstein-Bohr debate is actually irrelevant to the Bell tests. Therefore, the debate still remains unsettled.

Bell and his followers intended to reproduce statistical predictions of quantum mechanics in the Bell tests but failed. The failure of the Bell tests is an irrefutable experimental fact. Nowadays nobody doubts the correctness of experimentally confirmed quantum-mechanical predictions. However, Bell's theorem erroneously links Einstein's argument to the failure of the Bell tests. Misguided by such nonexistent linkage, most physicists consider Einstein's argument wrong. Also misguided by the nonexistent linkage, experimental physicists and quantum-information theorists have been attempting to realize physically unrealizable quantum information processing systems. As we shall see in the next section, quantum mechanics is a powerful tool for making statistical predictions on empirical results and has nothing to do with quantum information processing. Because Einstein's argument is irrelevant to the failure of the Bell tests, the unresolved debate suggests that Bell's theorem is problematic.

For the purpose of this study, we need only consider ideal experiments, focus on identical observables of individual quantum-mechanical systems taken from a pure ensemble, and adhere to the following terminology for ease of exposition.

- The term "repetitions" means "repeating a fixed experiment multiple times under the same experimental conditions".
- Quantum objects that are described by the same pure state and will be measured in different repetitions of a given experiment are called "identically prepared quantum-mechanical systems".
- An ensemble consisting of identically prepared quantum-mechanical systems is called "a pure ensemble".
- An experiment with quantum objects taken from a pure ensemble is called "an ideal experiment".

It is worth emphasizing that any single measurement performed in only one repetition of a fixed experiment can only produce a deterministic result and makes no sense statistically. This is why we need to explain the meaning of "repetitions" explicitly in the terminology.

3. Quantum Mechanics and Quantum Information

In quantum physics, physicists somehow treat continuous observables and continuous parameters differently. The continuous parameters are involved in specifying experimental conditions. As everybody knows, precise values of all continuous quantities cannot be obtained by measurements;

their values are unattainable. However, physicists consider precise values of continuous parameters attainable. To see this, let us quote the late A. Peres ([18], p.39): "*Quantum tests may depend on classical parameters which can be varied* ***continuously****, and nevertheless these tests have fixed,* ***discrete****, outcomes.*" Peres also gave two examples of continuous parameters used to specify experimental conditions. One example is the angle of orientation of a calcite crystal used to test the linear polarization of a photon; the other is the angle of orientation of a Stern-Gerlach magnet. The precise values of the angles are elements of $\mathbb{R}$, the set of all real numbers. We shall examine these two examples in Section 5. While experimental conditions specified by precise values of continuous parameters allow us to obtain meaningful results in classical physics, specifying experimental conditions using precise values of continuous parameters is misleading in quantum physics as we shall see below based on a concise point-set topological analysis. As a prelude to justifying the propositions formulated in Section 1, let us first recall a few definitions in point-set topology.

Denote by $\mathbb{R}^3$ the three-dimensional Euclidean space, which is the mathematical model of the space in which we live. The range of a quantity is the set of all values the quantity can have. To avoid overusing mathematical notations, we use the same symbol G to denote both the range of a continuous parameter and the range of a continuous observable. Let X be a topological space. A metric is defined on X. The metric is identical to the usual distance function. If X is the three-dimensional Euclidean space, the distance function is defined on $\mathbb{R}^3$. If X is the real line, the distance function is defined on $\mathbb{R}$. Suppose a one-to-one correspondence exists between elements of G and elements of an uncountable set $S \subset X$. Let s_0 be an element of S.

Definition 1. *If there is a number $r > 0$ such that the distance between s_0 and any other point of S is at least r, then s_0 is an isolated point of S.*

A well-established mathematical fact in point-set topology follows immediately from Definition 1. We state this fact as a lemma.

Lemma 1. *The set S has no isolated points.*

An attainable element of G implies the existence of an isolated point of S, thus contradicting Lemma 1. Concerning experiments in quantum physics, the practical implication of Lemma 1 is self-evident; we state it as a theorem. The theorem looks trivial, but it is still worth emphasizing that continuous quantities mentioned in the theorem include both continuous observables and continuous parameters.

Theorem 1. *Precise values of all continuous quantities are unattainable.*

In the quoted examples ([18], p.39), the observables are not continuous quantities. In Heisenberg's position–momentum uncertainty relation, the position and momentum of a particle are continuous observables. Neither the position nor the momentum can be measured perfectly accurately. It is Theorem 1 that prohibits us from obtaining precise values of the position or momentum. Theorem 1 also prohibits us from obtaining precise values of continuous parameters. Ironically, as shown in the quoted examples, physicists and quantum-information theorists only consider precise values of continuous observables unattainable while considering precise values of continuous parameters attainable and capable of specifying experimental conditions in the Bell tests.

As a common practice in quantum physics, physicists use a fictitious quantum-mechanical system to represent all the members of a pure ensemble, because they believe experimental conditions specified by precise values of continuous parameters are exactly the same in different repetitions of a given experiment [18,19]. The following corollary forbids such practice; the corollary is an immediate consequence of Theorem 1.

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Corollary 1. *Neither experimental conditions specified by precise values of continuous parameters nor fictitious quantum-mechanical systems exist in the real world.*

Surely, a prerequisite of using a fictitious quantum object is to keep the experimental conditions unchanged in different repetitions of the corresponding experiment. If the prerequisite does not hold, then it is not legitimate to use the fictitious object. The use of fictitious quantum objects is largely responsible for Bell's erroneous interpretation of the test results. The above analysis paves the way for us to justify the propositions formulated in Section 1.

In any given experiment with quantum objects taken from a pure ensemble, experimental conditions specified by precise values of any continuous parameter do not exist in the real world, and outcomes of measuring identical observables of the quantum objects correspond to mutually exclusive properties represented by orthogonal vectors spanning a Hilbert space. The Hilbert space is the mathematical setting for quantum mechanics, and the outcomes are obtained in different repetitions of the experiment. Attaching the outcomes measured in different repetitions to a fictitious quantum object, physicists unable to understand the exhibited random phenomena. Thus Bell and many other physicists interpreted the random phenomena exhibited in the Bell tests as inherent randomness. Einstein disliked such interpretation; this is why Einstein questioned current quantum theory by calling it "the fundamental dice-game" ([20], p.149).

In fact, the random phenomena are due to lack of knowledge about precise values of the continuous parameters used to specify the experimental conditions. Therefore, the existence of purported inherent randomness can be excluded. In current quantum theory, the logical relation between the orthonormal vectors is conjunction ("and"). Experimentally confirmed statistical predictions of quantum mechanics are correct, because we can replace conjunction ("and") with disjunction ("or"). Using disjunction ("or") to replace conjunction ("and") can keep quantum-mechanically calculated probabilities unchanged while not modifying the mathematical setting essentially. As a powerful tool for predicting empirical results, quantum mechanics is irrelevant to quantum information processing. In quantum information theory, fictitious quantum objects are supposed to carry quantum information coded by qubits, but none of such objects exist in the real world; it is misleading to use a fictitious quantum object to represent all the members taken from a pure ensemble. Therefore, there is no evidence to support experimentally realized quantum information processing systems. By examining one of the Bell tests in the next section, we shall address the issues further in more detail and show that Einstein's ensemble interpretation of ψ-function can remove inexplicable weirdness in quantum physics. As we shall see in Section 5, Einstein's ensemble interpretation can also exclude the existence of physical carriers of quantum information.

4. Bell Tests and Einstein's Ensemble Interpretation of ψ-Function

Consider the experimental test of the CHSH inequality [2]. Because this inequality is well-known, we need not give its expression or repeat its derivation here. Like other Bell inequalities, the CHSH inequality is not a result about quantum mechanics, but it can be tested by real experiments using technologies of modern optics. In experiments with single pairs (ν_1, ν_2) of correlated photons, experimental physicists have intensively tested this inequality against quantum mechanics [3,4]. In the test, each pair can be detected once in only one repetition. The photons are analyzed by two linear polarizers. For simplicity, the polarizers are assumed to be perfectly efficient.

The polarization part of the state vector consists of $\frac{1}{\sqrt{2}}|x,x\rangle$ and $\frac{1}{\sqrt{2}}|y,y\rangle$, which are the superposed components, where $|x\rangle$ and $|y\rangle$ are linear polarizations states. With conjunction ("and") being the logical relation between the superposed components, a quantum superposition expresses an entangled state, see Figure 1 in [12].

$$|\Psi(\nu_1,\nu_2)\rangle = \frac{1}{\sqrt{2}}\{|x,x\rangle + |y,y\rangle\}.$$

The entangled state $|\Psi(\nu_1, \nu_2)\rangle$ describes each pair. Physicists also use $|\Psi(\nu_1, \nu_2)\rangle$ given above to calculate quantum-mechanical probabilities of obtaining the corresponding outcomes by measuring the polarizations of the photons. In the experiment designed to test the CHSH inequality, the parameters specifying the experimental conditions can be varied continuously. The values of the parameters are coordinates of points on a unit sphere $E \subset \mathbb{R}^3$. This unit sphere is not the "Bloch sphere" in quantum information theory [13]. The "Bloch sphere" is not contained in $\mathbb{R}^3$ and should not be confused with E. The coordinates of some points on E specify the polarizations and propagating directions of different photons detected in different repetitions of the experiment; the coordinates of some other points specify the orientations of the polarizers used to analyze the polarizations of the photons. When interpreting the experimental results, the experimental physicists take precise coordinates for granted and believe they can keep the experimental conditions specified by the coordinates exactly the same in different repetitions of the experiment. Thus, the random phenomenon observed in this Bell test is interpreted as inherent randomness.

However, by Theorem 1, the precise coordinates of points on E are unattainable. The observed random phenomenon is actually due to lack of knowledge about the coordinates used to specify the experimental conditions. For a pair of correlated photons described by $|\Psi(\nu_1, \nu_2)\rangle$ with conjunction ("and") being the logical relation between $\frac{1}{\sqrt{2}}|x, x\rangle$ and $\frac{1}{\sqrt{2}}|y, y\rangle$, physicists claim that no well-defined state can be ascribed to each photon, because they do not know how to assign any polarization to either photon [4]. This claim is based on the legitimacy of quantum superposition. As a historical fact, Einstein argued against the legitimacy of quantum superposition in his debate with Bohr. When calculating the quantum-mechanical probabilities, physicists rely on the reduction postulate in current quantum theory and assert that any polarization measurement performed on a photon in a pair will trigger an abrupt collapse of $|\Psi(\nu_1, \nu_2)\rangle$ [4]. The collapse of $|\Psi(\nu_1, \nu_2)\rangle$ in such a telepathic way is a typical situation unspeakable in current quantum theory. So long as the logical relation between the superposed components is conjunction ("and"), the entangled state $|\Psi(\nu_1, \nu_2)\rangle$ cannot describe anything physically meaningful in the real world.

In contrast, according to Einstein's argument based on his separability principle [21], the correlation between the photons in each pair is determined by the common source that emits the photons, and either of the correlated photons in each pair possesses its autonomous polarization state independent of whatever happened non-locally, and measuring the polarization of either photon cannot affect the other photon in any way. Consequently, corresponding to the autonomous polarization states simultaneously possessed by both correlated photons in each pair to be detected jointly in the real world, the outcome (+, +) or (-, -) is obtained in one repetition of the experiment, even though the precise coordinates used to detect the pair are unattainable by measurements and unknown. However, we can never detect (+, +) and (-, -) for the same pair in the same repetition; thus the observed random phenomenon should not be characterized as inherent randomness. The above deliberation is actually based on Einstein's ensemble interpretation of ψ-function.

In Einstein's ensemble interpretation, different pairs of correlated photons constitute an ensemble. The autonomous polarization states of the correlated photons in each pair are detected in different repetitions of the experiment. For each detected pair taken from the ensemble, the logical relation between $\frac{1}{\sqrt{2}}|x, x\rangle$ and $\frac{1}{\sqrt{2}}|y, y\rangle$ is disjunction ("or"), which will remove inexplicable telepathic collapse of $|\Psi(\nu_1, \nu_2)\rangle$ triggered by measurements. Such collapse is what Einstein called "spooky actions at a distance" in his debate with Bohr ([20], p.158). We still need probabilities to describe the observed random phenomenon, and the probabilities in Einstein's ensemble interpretation are exactly the same as those quantum-mechanically calculated probabilities in current quantum theory.

To conclude this section, let us compare Bell's interpretation of the test result with Einstein's ensemble interpretation. In Bell's interpretation, inexplicable telepathic collapse of $|\Psi(\nu_1, \nu_2)\rangle$ is claimed to be a property of the real world, and "in the way which Einstein would have liked least", the Einstein-Bohr debate seems to have been resolved [9]. In sharp contrast to Bell's interpretation, there is no inexplicable weirdness in Einstein's ensemble interpretation; everything is intuitively understandable and nothing is illusive.

5. Examples

In quantum information theory, some experiments with two-level quantum systems are claimed to be evidence for physical carriers of quantum information. With disjunction ("or") serving as the logical relation between orthonormal vectors or superposed components in question, Einstein's ensemble interpretation of ψ-function not only will remove the inexplicable weirdness in the experiments but also can help us see clearly none of quantum objects in the real world carry quantum information. All the purported physical carriers of quantum information are fictitious quantum systems based on the legitimacy of quantum superposition in current quantum theory. Such fictitious quantum systems correspond to nothing whatever in the real world; Einstein's ensemble interpretation can eliminate all of them. Thus quantum information has no physical carriers. For readers who are unfamiliar with point-set topology, concrete examples given below may alleviate difficulty in understanding the above results.

Example 1. *In quantum information theory, photons are claimed to be highly stable carriers of quantum information coded by qubits [13]. Let us consider an experiment with single photons. In this experiment, a photon is described by a quantum superposition with conjunction ("and") being the logical relation between two superposed polarization states. A polarizer (i.e., a crystal) is used to measure the linear polarization of each photon. Precise values of a continuous parameter are supposed to specify the experimental condition. The parameter is the angle of the polarizer axis relative to the polarization plane [18]. In the real world, the photons are measured in different repetitions of the experiment; each photon can at most be detected only once. Quantum-information theorists take the experimental condition specified by precise values of the angle for granted and are unaware that the experimental condition cannot be the same in different repetitions. Consequently, they use a fictitious photon to represent all the photons in the experiment. While photons are all real physical objects, there is no such fictitious photon in the real world. Therefore, photons are not physical carriers of quantum information.*

Example 2. *Consider the famous Stern–Gerlach experiment with single spin-1/2 particles. In this experiment, a spin-1/2 particle is described by a quantum superposition with conjunction ("and") being the logical relation between two eigenvectors spanning a Hilbert space. Similar to Example 1, precise values of a continuous parameter are supposed to specify the experimental condition. The parameter is the angle of orientation of a Stern-Gerlach magnet [18]. Like single photons in Example 1, the particles are measured in different repetitions of the experiment; each particle can at most be measured only once. In quantum information theory [13], the experimental condition specified by precise values of the angle is considered exactly the same in different repetitions, and quantum-information theorists use a fictitious particle to represent all the particles in the experiment. Although the particles are all real physical objects, the fictitious particle does not exist in the real world and cannot be a physical carrier of quantum information.*

Example 3. *In quantum physics, the energy of a particle is quantized to discrete energy levels. Consider a single particle confined to a rigid one-dimensional box with impenetrable walls. If only two lowest energy levels are considered, the particle is a two-level system described by a time-independent wave-function. The wave-function is a quantum superposition with the logical relation between the superposed components being conjunction ("and"). As we see in current quantum theory, physicists need perform an experiment to decide whether the particle can have different energies at the same time. Instead of considering only one particle, physicists must consider a large number of particles taken from a pure ensemble, and a precise value τ of a continuous time variable is supposed to specify the experimental condition in different repetitions of the experiment. By measuring the particles at the purported same time τ in different repetitions of the experiment, physicists assert that the particles possess different energies simultaneously. Based on this assertion, quantum-information theorists then claim that each particle taken from the ensemble is a physical carrier of quantum information coded by a qubit*

[13]. Both the assertion and the claim are wrong. The particle can indeed have different energies. But in no sense can the same particle have different energies at the same time. Different energies observed in the experiment actually belong to different particles measured in different repetitions. The particle is a real physical object, possesses different energies, but does not carry quantum information.

In different repetitions of a given experiment, such as those in the above examples, outcomes are obtained by measuring single quantum objects taken from a pure ensemble. In current quantum theory, each object is described by a quantum superposition with conjunction ("and") being the logical relation between the corresponding orthonormal vectors or superposed components. The orthonormal vectors or superposed components represent mutually exclusive properties possessed by a single object. The outcomes correspond to the mutually exclusive properties. Inexplicable weirdness in quantum physics stems from attaching the outcomes measured in different repetitions of the experiment to a fictitious object. The fictitious object is supposed to carry quantum information. With disjunction ("or") serving as the logical relation, Einstein's ensemble interpretation of ψ-function can eliminate both the explicable weirdness and the fictitious object, the purported physical carrier of quantum information. The above analysis suggests a way to generalize the results illustrated by the examples, as discussed in the next section.

6. Discussion

For any quantum-mechanical system described by a quantum superposition with conjunction ("and") being the logical relation between the orthonormal vectors or superposed components in question, if physicists want to decide whether the system can possess mutually exclusive properties at the same time as illustrated in Example 3, they must perform an experiment and rely on a continuous time variable to specify the experimental conditions in different repetitions of the experiment. We distinguish two situations. At the purported same time, the exclusive properties observed in different repetitions of the experiment either belong to different microscopic systems that constitute a pure ensemble, or belong to the same macroscopic system that can be repeatedly measured in different repetitions of a time ensemble [22]. In both situations, the microscopic systems and the macroscopic system are indeed real physical objects, possess mutually exclusive properties at different times, but cannot have such properties at the same time as required by physical carriers of quantum information. While the macroscopic system can be measured repeatedly, the measurement outcomes obtained in different repetitions of the time ensemble correspond to the exclusive properties and will only be observed at different, unknown times. Of course, physicists can imagine a fictitious macroscopic system that might possess exclusive properties simultaneously; the system is analogous to Schrödinger's cat described by a quantum superposition in current quantum theory [23].

$$|\text{Schrödinger's cat}\rangle = a|\text{Schrödinger's cat is alive}\rangle + b|\text{Schrödinger's cat is dead}\rangle.$$

But by no means is such a fictitious system a real physical object; it only exists in the imagination of physicists rather than in the real world. The above argument, which is based on Einstein's ensemble interpretation, can be readily generalized to eliminate any purported physical carrier of quantum information.

As shown in the previous sections, inexplicable weirdness in quantum physics is due to the notion of quantum superposition with conjunction ("and") being the logical relation between the orthogonal vectors or superposed components. Based on a recent experiment, some experimental physicists claim that a macroscopic quantum state exists in the real world; the state is analogous to Schrödinger's cat: "a macroscopic object that defies intuition because it involves a superposition of classically distinct trajectories" [24]. Quantum-information theorists might interpret the purported macroscopic object as evidence for the physical existence of qubits. However, if we replace conjunction ("and") with disjunction ("or"), we can easily get rid of anything that defies intuition, meanwhile, everything else in quantum mechanics will remain unchanged. By doing so, we can make quantum mechanics intuitively understandable. While physicists believe quantum mechanics is counterintuitive, an intuitively understandable quantum theory is not impossible. A famous philosopher once said: "Everything that can be thought at all can be thought clearly." To conclude our discussion, let us say something similar: "Everything that can be understood at all can be understood intuitively."

7. Conclusions

Bell's theorem interpreted the results of the Bell tests erroneously, which opened door to quantum information processing, such as quantum computation and quantum communication. In this study, we investigated the feasibility of quantum computation and quantum communication. The investigation is based on a well-established mathematical fact in point-set topology, see Lemma 1 in Section 3. The findings are as follows. (a) Experimentally confirmed statistical predictions of quantum mechanics are not evidence of experimentally realized quantum information processing systems. (b) Physical carriers of quantum information coded by qubits do not exist in the real world. (c) Einstein's ensemble interpretation of ψ-function will eliminate not only inexplicable weirdness in quantum physics but also all the purported physical carriers of quantum information. A regrettable conclusion then follows inevitably: Without carriers representing quantum information, physical implementations of quantum information processing systems are merely an unrealizable myth.

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