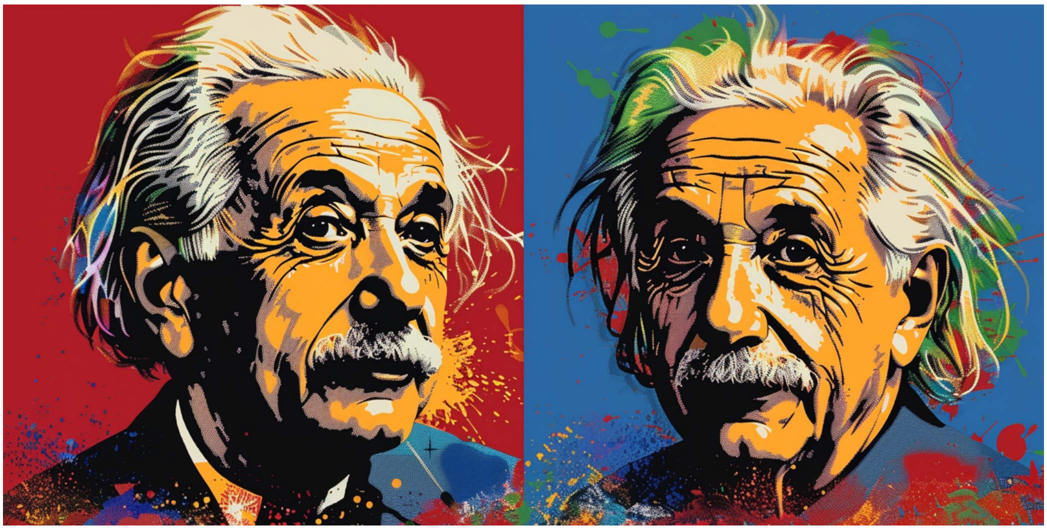

On Purported Physical Realizations of So-called Quantum Information Technologies

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Abstract

Considered by Einstein as “the fundamental dice-game”, the quantum-mechanical description of quantum objects in the real world is controversial. According to Einstein’s understanding of the physical world, the quantum-mechanical description is incomplete, but rendering quantum mechanics complete might be possible. Derived by resorting to a hidden-variable theory, Bell inequalities attempted to render quantum mechanics complete somehow. Unfortunately, the attempts all failed. More unfortunately, the failure and the widely accepted but erroneous interpretation of the failure resulted in giving up either or both of locality and realism, the two fundamental hypotheses for scientific research, and hence opened the door to so-called quantum information technologies. Consequently, quantum information technologies all stem from “the fundamental dice-game”. Based on an important mathematical fact irrelevant to any issue about measurement instruments or accuracies of measurement outcomes, namely, precise space and time coordinates are practically unattainable by measurements, which reflects a general principle regarding the nature of measurements (henceforth principle of measurements), this paper reports the following findings: (a) Einstein’s understanding of the physical world is correct. (b) Without resorting to any hidden-variable theory, rendering quantum mechanics complete is possible while keeping the mathematical setting for quantum mechanics (i.e., Hilbert space) essentially unchanged; therefore, eligible applications of quantum mechanics, which are all irrelevant to “the fundamental dice-game", will also remain unchanged. (c) As fictitious results in "the fundamental dice-game" based on the problematic postulate of quantum superposition in current quantum theory, quantum information technologies are all physically unrealizable. A very regrettable conclusion then follows inevitably from the above findings: An extremely huge amount of time, effort, funding, and investment in realizing physically unrealizable quantum information technologies has been wasted because of "the fundamental dice-game", which has seriously damaged science!

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1. Introduction

Since the inception of quantum mechanics, its conceptual foundations have been controversial[1][2][3], and are still debatable even today. Einstein considered the quantum-mechanical description of quantum objects in the physical world as "the fundamental dice-game" [4]. The quantum-mechanical description denies the objective existence of certain definite properties of some quantum objects if one does not measure or observe the objects, which contradicts Einstein's understanding of the physical world. According to Einstein's understanding, prior to observing or measuring the properties of a quantum object, the properties must exist independently of human consciousness; in the sense above, the quantum-mechanical description is incomplete, but rendering quantum mechanics complete might be possible [1].

Derived by resorting to a hidden-variable theory, Bell inequalities attempted to render quantum mechanics complete somehow [5][6]. Unfortunately, the attempts all failed when tested by experiments against quantum mechanics [7][8][9][10][11][12]. More unfortunately, the failure of Bell inequalities and the widely accepted but erroneous interpretation of the failure [13][14] resulted in giving up either or both of locality and realism, the two fundamental hypotheses for scientific research. Renouncing either or both of the hypotheses then opened the door to so-called quantum information technologies [15][16][17][18][19][20][21][22]. Consequently, such technologies all stem from what Einstein called "the fundamental dice-game" in quantum mechanics [4]. Nevertheless, all eligible applications of quantum mechanics have nothing to do with "the fundamental dice-game".

Nowadays, most physicists consider Einstein wrong. However, the disagreements with Einstein's point of view actually result from the erroneous explanations of the measurement outcomes observed in the experiments with quantum objects described by *quantum superpositions*. Needless to say, laboratories in the real world are the only places where experimental physicists can perform experiments to measure quantum-mechanically described quantum objects for observing quantum phenomena. On the other hand, as the mathematical setting devised to describe a quantum object studied in quantum physics, the Hilbert space is the model used by physicists to explain quantum phenomena observed in the laboratories. Only in this mathematical sense, we may say “the quantum object lives in the Hilbert space”.

However, the physical world consists of physical objects, not their mathematical descriptions. Physically, any quantum object can only exist in the real world rather than in the Hilbert space. In the real world, the model of space is the three-dimensional Euclidean space, and the model of time is the set of nonnegative real numbers. As a mathematical fact irrelevant to anything about instruments used for measurements in practice or accuracies of measurement outcomes, precise space and time coordinates are unattainable by measurements [23][24][25]. This fact reflects a general principle regarding the nature of measurements (henceforth, *principle of measurements*). This principle will remain unchanged although we can always improve the measurement accuracy. Consequently, we may have to live with it forever.

For macroscopic objects studied in classical physics, the impact of the principle of measurements is hardly noticeable and hence ignorable. However, for quantum objects studied in quantum physics, the impact is no longer ignorable. Unfortunately, the Hilbert space for describing quantum objects is founded on the postulates in current quantum theory formulated without considering this important principle. Misguided by the problematic postulates, physicists may take precise space and time coordinates for granted and hence violate this principle when explaining quantum phenomena observed in the real world. It is the problematic postulates that lead to “the fundamental dice-game” in quantum mechanics.

Among the erroneous explanations of the outcomes obtained by measuring quantum objects, as described by quantum superpositions, the widely accepted interpretation of the experimental invalidation of Bell inequalities eventually resulted in a disaster for science by renouncing either or both of two fundamental hypotheses for scientific research, namely, locality and realism, and hence opened the door to quantum information technologies. In fact, Einstein’s understanding of the physical world is correct; the quantum-mechanical description of quantum objects in the physical world is indeed incomplete, and it is possible to render quantum mechanics complete without resorting to any hidden-variable theory while keeping the mathematical setting of quantum mechanics (i.e., Hilbert space) essentially unchanged.

Stemming from “the fundamental dice-game”, quantum information technologies are questionable. The aim of this paper is to show that such technologies are all physically unrealizable. Because the notion of “quantum bits” lies at the core of all such technologies, if quantum bits are physically unrealizable, neither are any of such technologies. Therefore, to show that quantum information technologies are all physically unrealizable, it is sufficient to show that quantum bits are not physically realizable *in principle*. As we shall see, the purported physical realizations of quantum bits are fictitious results in “the fundamental dice-game” based on the postulate of quantum superposition in current quantum theory; they do not really exist in the physical world.

In the rest of this paper, Section 2 shows the falsity of a bold, fundamental assumption adopted by quantum information theorists. Section 3 reveals the connection between the false assumption and the problematic postulate of quantum superposition. Section 4 suggests a possible way to render quantum mechanics complete without resorting to any hidden-variable theory or changing the mathematical setting for quantum mechanics essentially. Section 5 further elucidates, with examples, why quantum bits and hence quantum information technologies are not physically realizable. After a brief discussion on the relation between quantum information technologies and our understanding of the physical world, the paper concludes in Section 6 with a summary of the reported findings.

2. False Assumption in Quantum Information

In the Hilbert space for describing quantum objects, unit vectors represent “pure quantum states”. All vectors with unit norm and different only by a phase factor in the Hilbert space are the same pure state; their collection is a “ray”. Thus, a ray represents a pure state. To show that quantum bits are not physically realizable in principle, it is sufficient to show that their candidates, given by quantum superpositions of two-level systems, do not exist in the physical world. The superposed states in such superpositions are pure states, namely, orthonormal vectors in the Hilbert space. By focusing on pure states, we can avoid distractions such as “mixed states” (or “statistical mixtures”), which do not exist in the physical world either.

According to current quantum theory, as a theoretical notion, a quantum system does not really exist in the physical world [26]. By definition, a quantum system is an equivalence class of “preparations”, namely, a set of instructions. Experimental physicists follow the instructions when they perform “tests” in their experiments for observing quantum phenomena by making measurements. The terms “preparations” and “tests” are primitive notions of quantum theory in its current form. The intuitive meanings of the terms are as follows.

A “preparation” is a completely specified experimental procedure, and a “test” includes a preparation and a final step of the experiment. The final step produces the outcome of the test. One test yields one outcome. To obtain sufficiently many outcomes, a large number of repetitions of the experiment is necessary. The outcomes produced by identically prepared, different tests may not necessarily be identical; they are unpredictable or random, but statistically predictable with definite probabilities. Because the Hilbert space is a vector space, the superposition principle allows physicists to obtain a pure state from other pure states: if two pure states do not belong to the same ray, their properly normalized superposition is also a pure state. The following is a bold, fundamental assumption adopted by quantum information theorists [26].

Assumption in Quantum Information Theory: Every vector (except the null vector) in the Hilbert space represents a physically realizable pure state, and hence quantum bits are physically realizable.

However, this assumption is false and misleading. The assumption is false, not only because it is impossible to design equipment in the real world for preparing a pure state represented by a quantum superposition, but also because the assumption takes precise but practically unattainable space and time coordinates for granted and hence violates the principle of measurements [23][24][25]. The assumption is misleading because it is based on a misleading analogy between the ordinary three-dimensional Euclidean space and the Hilbert space; the former is the model for describing macroscopic objects studied in classical physics, but the latter is the model for describing the quantum objects studied in quantum physics.

According to the analogy, the orthonormal vectors in the Hilbert space are analogous to the unit vectors along a set of orthogonal axes in Euclidean space [26]. Such an analogy is misleading because the orthonormal vectors in the Hilbert space correspond to the superposed states, and according to the postulate of quantum superposition in current quantum theory, the orthonormal vectors represent mutually exclusive properties of the same quantum object at the same time before measurements or observations; in contrast, the orthogonal vectors in Euclidean space do not represent mutually exclusive properties of any macroscopic object [23][24][25].

Supplying no instructions for actually setting up any laboratory procedure to prepare the*pure state* represented by a given quantum superposition, current quantum theory merely provides a way to compute probabilities for the outcomes obtained by measurements in the experiment with purportedly identically prepared quantum objects. Misguided by the false and misleading assumption, quantum information theorists are content with the conceived laboratory procedures, which only exist in their *imagination*, and use whatever is available in current quantum theory to*analyze, a posteriori*, their claimed physical realizations of quantum bits. Various advantages of quantum information technologies over the corresponding classical counterparts then follow from such analysis based on the false assumption. In the next section, we shall reveal the connection between the false assumption and the postulate of quantum superposition in current quantum theory.

3. Problematic Quantum Superposition

Consider a quantum object described by a pure state represented by a quantum superposition in the Hilbert space. In current quantum theory, the formulation of the postulate of quantum superposition is based on the measurement outcomes observed in *different* repetitions of the corresponding experiment. All available experiments have already confirmed the correctness of the probabilistic predictions given by quantum mechanics. Nevertheless, why are the measurement outcomes unpredictable or random rather than definite or deterministic? According to the widely accepted answer to this question, the measurement outcomes are intrinsically unpredictable, and hence quantum mechanics is intrinsically probabilistic. However, this answer is wrong.

Represented by mathematical objects with unusual properties in quantum mechanics, the physical quantities are properties belonging to *physical objects* studied in quantum physics. The unusual properties of the mathematical objects do not belong to the physical objects. All physical objects can only exist in the space and time of the real world. To measure physical quantities, we need mathematical models of space and time, respectively, in the real world. No Hilbert space for describing a quantum object is the right model because the mathematical model of space in which we live and measure physical quantities is the three-dimensional Euclidean space endowed with a metric, which is the usual distance function, and the mathematical model of time elapsed in the real world is the set of nonnegative real numbers, but it is sufficient for us to focus only on its subset consisting of all positive real numbers equipped with a metric, which is the usual distance function on this subset [23][24].

As shown in [23], as a consequence of the principle of measurements, unpredictability is not intrinsic, and quantum mechanics is not intrinsically probabilistic. Unfortunately, although the principle of measurements is annoying and unwelcome, we may have to live with it forever. The formulation of the postulate of quantum superposition in current quantum theory fails to consider this important principle. Violating this principle is responsible for the false assumption revealed in the preceding section. Misguided by precise but practically unattainable space and time coordinates, quantum information theorists might be allured to characterize a given kind of purportedly identically prepared individual quantum objects by using a single quantum object.

For example, consider a sequence of purportedly identically prepared individual photons described by a pure state, namely, a quantum superposition. The photons have purportedly the same (desired) polarization direction and encounter the same polarizer astride their purportedly the same (desired) propagating direction. The desired orientation of the polarizer is neither parallel nor perpendicular to the desired propagating direction. As a consequence of the principle of measurements, the unpredictability exhibited in the outcomes of measuring the polarizations of the photons is not intrinsic. The erroneous explanation of the unpredictability is due to taking precise space coordinates for granted and hence violates the principle [23][24][25]. The coordinates specify directions and orientations, including

- the *desired* same propagating direction and the *desired* same polarization direction, purportedly specified for each photon,
- the *actual* propagating direction and polarization direction of each photon,
- the *desired* same orientation of the polarizer, purportedly specified for measuring each photon, and
- the *actual* orientation for measuring each photon.

The coordinates are all unattainable by measurements and hence are unknown for actually performed experiments and tests. The corresponding small volumes contain the coordinates in question and serve as the approximations to the precise space coordinates. As a banal fact, no physicist can measure the *same* photon more than once. In general, no physicist can measure the same single quantum object more than once. Because the *actual* propagating directions and polarization directions of different photons are almost surely different, and because the *actual* orientations for measuring different photons are also almost surely different, taking precise space coordinates for granted will result in using a single photon to characterize different, purportedly identically prepared individual photons, leading to the erroneous interpretation of the unpredictability given by current quantum theory.

Similarly, precise time coordinates are also unattainable by measurements[23][24][25]. Some quantum objects, described by pure states in the form of quantum superpositions, can be measured repeatedly. For a quantum object of this kind, taking precise time coordinates for granted, a quantum information theorist might confuse the outcomes of measuring the object at almost surely *different* instants in *different* repetitions of the experiment in question with the outcomes measured at the same instant, again, leading to the erroneous interpretation of the unpredictability implied by current quantum theory. As an approximation to the specified coordinate of the *desired* instant, a small time interval contains the coordinate of the *desired* instant and the *actual* coordinates of almost surely *different* instants for measuring the quantum object in *different* repetitions.

By introducing a hidden variable for interpreting the unpredictability, Bell inequalities attempted to render quantum mechanics complete somehow. The attempts all failed because Bell experiments devised for testing Bell inequalities already presume the erroneous interpretation of the unpredictability given in current quantum theory, and because the derivations of Bell inequalities involve improper counter-factual reasoning [23]. Nevertheless, without resorting to any hidden-variable theory, rendering quantum mechanics complete is possible, and meanwhile, the mathematical setting for quantum mechanics can remain essentially unchanged, as shown in the next section.

4. Rendering Quantum Mechanics Complete

As we all know, according to the postulate of quantum superposition, before measurement or observation, a quantum object described by a quantum superposition is *simultaneously* in each orthonormal state, and hence possesses mutually exclusive properties at the *same time*, which implies that, in the Hilbert space for describing the quantum object, the logical relation between the superposed orthogonal vectors is conjunction. It is this postulate that leads to “the fundamental dice-game” in quantum mechanics [23][24][25].

Consider a quantum object described by a pure state represented by a quantum superposition in a Hilbert space. As shown in the previous section, the formulation of the postulate of quantum superposition is based on the measurement outcomes observed in different repetitions of the experiment in question. This postulate is problematic because its formulation takes precise space and time coordinates for granted and hence violates the principle of measurements.

Actually, for any quantum object in the real world, it is not legitimate to use conjunction as the logical relation between the superposed orthonormal vectors in a Hilbert space for describing the quantum object. Whether or not a measurement is performed on the object, the logical relation between the orthonormal vectors must be disjunction if such vectors represent mutually exclusive properties of the object.

In fact, the concepts for defining a Hilbert space in general are all highly abstract and have no practical meanings. For a given application, practically meaningful concepts are necessary to define a specific Hilbert space. Consequently, Hilbert space has widespread applications, not only in quantum physics but also in many other fields. The elements in a Hilbert space are vectors. Orthogonality, defined by an inner product of two vectors, is one of the most important concepts to define a Hilbert space. Because Hilbert space is a natural generalization of Euclidean space, the inner product and the orthogonality defined for the vectors in a Hilbert space may look similar to the scalar product defined for ordinary Euclidean vectors and the orthogonality defined for orthogonal vectors in ordinary Euclidean space. Compared with the similarities, the differences between Euclidean space and Hilbert space are essential, and hence we must pay more attention to the essential differences.

The vectors and orthogonality for defining Hilbert space in general are purely mathematical concepts without geometric or any other practical meaning. In particular, assigning practical meanings to orthogonality is unnecessary. Moreover, for Hilbert space in general, it is even unnecessary to specify the logical relation between orthogonal vectors. For a specific Hilbert space, the logical relation between its orthogonal vectors can be conjunction. In this case, however, orthogonal vectors must not represent mutually exclusive properties of any element in the Hilbert space.

Consider the ordinary three-dimensional Euclidean space. With the inner product defined for Euclidean vectors, Euclidean space is a Hilbert space. For this Hilbert space, the orthogonal Euclidean vectors do *not* represent mutually exclusive properties of any geometric object, and the logical relation between the orthogonal vectors is conjunction. However, for *any other* Hilbert space, the logical relation between orthogonal vectors can also be disjunction, or even neither conjunction nor disjunction.

For instance, consider the classical prototype of a Hilbert space, namely, the space of infinite sequences. Each sequence consists of complex numbers. This space was first studied by D. Hilbert with applications to the theory of integral equations. For this space, the logical relation between orthogonal vectors is neither conjunction nor disjunction. It is not necessary to specify the logical relation.

If we take into account the principle of measurements, and if we use disjunction to serve as the logical relation between orthonormal vectors in a Hilbert space for describing a quantum object, then rendering quantum mechanics complete is indeed possible without resorting to any hidden-variable theory while keeping the mathematical setting for quantum mechanics essentially unchanged. By doing so, we can end “the fundamental dice-game”, which has seriously damaged sciences, and get rid of all fictitious things in this game, in particular, physically unrealizable quantum bits and quantum information technologies. The next section will further elucidate, with examples, why quantum bits and quantum information technologies are not physically realizable.

5. Unrealizable Quantum Bits: Examples

To elucidate further why quantum bits and hence quantum information technologies are not physically realizable, we can roughly divide quantum objects described by quantum bits into two categories, according to whether physicists can measure the quantum objects at most only once or repeatedly. According to quantum information theory, quantum bits are quantum superpositions (pure states) of two-level systems.

1. Physicists can measure quantum objects in this category at most only once.
2. Physicists can measure a quantum object in this category repeatedly.

Category (1) includes single, individual quantum objects, such as photons or quantum particles. A single quantum bit for describing a quantum object in this category has a geometric representation, which is a three-dimensional unit sphere called the Bloch sphere [16]. Quantum information theorists use this geometric representation to illustrate various operations (in their *imagination*) performed on the single quantum bit. However, the Bloch sphere is not a subset of the three-dimensional Euclidean space and has nothing to do with any actual measurement of the single quantum object in the real world. As we have shown, the mathematical model of space in the real world is the three-dimensional Euclidean space.

Consider, for example, single, individual photons in category (1). As shown in Section 3, physicists cannot measure any single photon more than once. However, precise but practically unattainable space coordinates might allure quantum information theorists to use a single photon to characterize purportedly identically prepared but *different* individual photons.

As shown in Section 2, for such photons, the false assumption adopted by quantum information theorists cannot supply any instruction necessary to set up the laboratory procedure for preparation and testing. However, based on the calculated probabilities and the conceived laboratory procedure in their *imagination*, quantum information theorists might use whatever is available in current quantum theory to *analyze, a posteriori*, their claimed physical realization of a quantum bit for describing the single photon and the corresponding physical realization of optical photon quantum computers. Under the false assumption, such analysis then leads to various advantages of optical photon quantum computers over classical computers. For the same reason, based on physically unrealizable quantum bits for describing single, individual photons, various quantum communication technologies are all physically unrealizable. Individual atoms are also in category (1), used for realizing physically unrealizable quantum bits and the corresponding physically unrealizable ion trap quantum computers.

Category (2) contains composite quantum objects. Physicists can repeatedly measure such objects. For example, consider a quantum object composed of non-Abelian anyons. Such a quantum object can only be constructed theoretically in two-dimensional spaces, which are subspaces of the three-dimensional Euclidean space. The construction is guided by numerical studies. Using non-Abelian quantum phases of matter, the quantum object is purportedly capable of encoding quantum bits in a non-local manner, and quantum information theorists consider such objects as promising candidates for building topological quantum computers. However, the possibility of using some specific quantum objects of this kind (i.e., Majorana fermions in two-dimensional p + ip Fermi superfluids) for topological quantum computation has already been questioned recently [27].

In addition, as shown in Section 3, although physicists can measure the quantum object in this category repeatedly, quantum information theorists might take precise time coordinates for granted and hence violate the principle of measurements when they explain the measurement outcomes observed in different repetitions of the corresponding experiment. Consequently, they might confuse the outcomes of measuring the object at almost surely *different* instants in different repetitions with the outcomes measured at the same instant, as if the quantum bits for describing the quantum object and the so-called topological quantum computers were physically realizable. Actually, the quantum bits and the topological quantum computers are created by an illusion because precise time coordinates are unattainable by measurements.

6. Discussion and Conclusion

Einstein mentioned “the fundamental dice-game” several times in his correspondences with Born. In a letter to Born, Einstein wrote [4]:

“We have become Antipodean in our scientific expectations. You believe in the God who plays dice, and I in complete law and order in a world which objectively exists, and which I, in a wildly speculative way, am trying to capture. I firmly believe, but I hope that someone will discover a more realistic way, or rather a more tangible basis than it has been my lot to find. Even the great initial success of the quantum theory does not make me believe in the fundamental dice-game, although I am well aware that our younger colleagues interpret this as a consequence of senility. No doubt the day will come when we will see whose instinctive attitude was the correct one."

What Einstein expressed in the letter indicates clearly his understanding of the physical world and shows why the debate concerning the conceptual foundations of quantum theory is so important for sciences, not merely for quantum physics. Understanding the physical world incorrectly can cause serious consequences for scientific research in practice. Supported by arguments based on the principle of measurements, this paper has reported the following findings.

a. Einstein's understanding of the physical world is correct.
b. Without resorting to any hidden-variable theory, rendering quantum mechanics complete is indeed possible in a way such that the mathematical setting for quantum mechanics (i.e., Hilbert space) will remain essentially unchanged, and eligible applications of quantum mechanics, which are all irrelevant to "the fundamental dice-game", will also remain unchanged.
c. As fictitious results in "the fundamental dice-game" based on the problematic postulate of quantum superposition in current quantum theory, quantum information technologies are all physically unrealizable.

The findings then inevitably lead to a very regrettable conclusion: An extremely huge amount of time, effort, funding, and investment for realizing physically unrealizable quantum information technologies has been wasted because of "the fundamental dice-game", which has seriously damaged sciences!

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