Systems with Single Degree of Freedom and the Interpretation of Quantum Mechanics

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Abstract

Physical systems can store information and their informational properties are governed by the laws of information. In particular, the amount of information that a physical system can convey is limited by the number of its degrees of freedom and their distinguishable states. Here we explore the properties of the physical systems with absolutely one degree of freedom. The central point in these systems is the tight limitation on their information capacity. Discussing the implications of this limitation we demonstrate that such systems exhibit a number of features, such as randomness, no-cloning, and non-commutativity, which are peculiarities attributed to quantum mechanics (QM). After demonstrating many astonishing parallels to quantum behavior, we postulate an interpretation of quantum physics as the physics of systems with a single degree of freedom. We then show how a number of other quantum conundrum can be understood by considering the informational properties of the systems and also resolve the EPR paradox. In the present work, we assume that the formalism of the QM is correct and well-supported by experimental verification and concentrate on the interpretational aspects of the theory.

1. Introduction

A one-bit message can be stored on any physical system possessing at least two possible distinguishable states. The two states may be two distinct voltage levels in an electrical device, two directions of magnetization in a small region of a computer disk, two faces of a coin, etc. All such attributes in a physical system can be employed to represent bits of data and to convey pieces of information. The messages and pieces of information represented by those attributes can be read later using appropriate physical measurements.

Physical systems can be used accordingly to store data and convey messages[1]. Conventional memory storages in computers use Avogadro-scale numbers of particles to register a single bit; the idea of using one quantum degree of freedom for each bit was an inspiration to design quantum computers. In any case, a physical system's capacity to store data and pieces of information is bounded [1]. Generally, the capacity of macroscopic physical systems for storing information is huge. For example, a coin is conventionally thought of as a representation of a 1-bit system since its two faces can represent a one-bit message. However, a coin has many other physical attributes, such as diameter, weight, height, temperature, that can also be used to convey messages. For instance, given only four possible options for the coin's monetary value, 1, 5, 10 & 25 cents, the coin's monetary value itself can represent a two-bits message.

[1] Hereafter we use 'a message' and 'a piece of information' in the same sense: a message, composed of bits of data, is a piece of information.

The information capacity of a physical system is limited by the number of its attributes that can be reliably distinguished and varied independently. Each of the independent variable attributes which can be assigned to specify a physical system can be thought of as a degree of freedom (DOF) of the system. A physical system with N number of DOF, each with d_n distinguishable states, possesses the total number of $d_{tot} = d_1 \times d_2 \times \ldots \times d_N = \prod_n d_n$ distinct states that can be used for storing data. Thus on this physical system, up to $\log_2 d_{tot} = \sum_n \log_2 d_n$ bits of data can be stored. Furthermore, a message with the information content of H_i bits can be loaded to any one of those DOFs if its number of states satisfies the relation $d_n \geq 2^{H_i}$.

To read the information content of a physical system one needs to perform a physical measurement on each of the system's DOF. The capacity of a physical system for conveying distinct pieces of information is thus limited by the number of its DOF; hence, a system with N number of DOF, each with d_n states has the information capacity to convey N distinct messages, each with the maximum amount of $\log_2 d_n$ bits of data. It is important to note that once we do a measurement on a DOF and read the stored message on that attribute, an additional measurement on the same DOF does not give away any independent piece of information; the new result in this case provides a measure of the mutual dependence between the two correlated measurements.

Macroscopic physical systems usually have an Avogadro-scale number of DOF that each can be used to store a piece of information. As the number of components of a system is reduced, its number of DOF also starts to decrease. Furthermore, in the microscopic realm, many classical attributes, like temperature and viscosity, cease to exist in a well-defined manner. Thus, the physical systems usually have much fewer number of DOF and therefore, a much lower information capacity compared to macroscopic physical systems. For example, for an elementary particle like an electron, attributes such as color or temperature are not well-defined, and it has only three independent DOF: energy, position, and spin.

The information capacity of a physical system can also be lowered by fixing the attributes of the system hence reducing the system's number of DOF. By preselecting the values of a number of a system's DOF, its information capacity reduces by the same number. For example, in the abovementioned coin example, if we are obliged to only use a 5-cent coin, this pre-selection of the monetary value of the coin, reduces the system's information capacity by exactly 1 compared to the prior amount.

Microscopic systems with only a few numbers of DOF can also be considered as a medium for the storage, transmission, and retrieval of information and the same abovementioned relationships apply to their informational properties. Yet, down to the smallest scales of information capacity, for the systems that can contain only one piece of information, the rules of information have implications for the physical system that can look foreign. We discuss those implications by analyzing the behavior of the physical systems reaching to the lowest limits of information storage.

2. Physical systems with a single degree of freedom, the 1-bit systems

An elementary particle, such as a photon, is a physical system that has few numbers of DOF and therefore its information capacity is very limited. A photon's position, frequency or spin can be used as information carriers to convey messages. These three attributes are utilized for example in the *'polarized 3D systems'* to convey the shape, color and depth perception in many 3D movie theatres. Also, in using electrons as information carriers, at most three pieces of information can be loaded on either of its similarly limited attributes.

In his famous lectures, Richard Feynman used the double-slit experiment to explain the "mystery" of quantum mechanics (QM), an experiment that "has in it, the heart of quantum mechanics" [2]. In the basic version of this experiment, a light beam illuminates a plate pierced by two parallel slits, and the light passing through the slits is observed on a screen behind the plate. The wave nature of light particles can cause the photons passing through the two slits to interfere, producing bright and dark bands on the screen. The experiment can include detectors at the slits to find the slit that each detected photon passes through. A prominent feature in the double-slit experiment is the fundamental limitations on what properties of the photons can be measured: either extracting the which-way information (particle property) of the photons by detecting which slit they pass through, or observing the interference (wave property) of the photons, but not both. The photons do not form the interference pattern if one detects which slit they pass through. Any effort to force the observation of both effects introduces an element of randomness that makes the results non-conclusive [3].

In practice, setting up a double-slit experiment to observe the "mysterious" quantum effects is not an easy task and requires certain prerequisites. For example, an ordinary light source cannot be used to form the interference patterns. To see the quantum interference, all the incoming photons should be highly directional, originate from the same location, and also be coherent so their energies are the same. Using a laser source provides these conditions and has made demonstrating such experiments more readily possible.

Similar to other physical systems, the available DOF of the microscopic systems can be reduced by pre-selection and screening. For example, in a setup that uses a stream of photons in which all come from the same source and have equal energy, the position and energy of the incoming photons are already fixed and the incoming photons are left with only one DOF, the spin. This is the setup of the double-slit experiment, i.e. the setup leaves the interacting photons with only one DOF. Physical systems with a single DOF can convey only one piece of information. This is the case for the photons in the double-slit experiment and why they cannot contain both the which-way information and wave information. We thus just explained the "mysterious" nature of the wave-particle duality of the photons in the double-slit experiment.

In this paper, we study such distinctive properties of the physical systems that are left with only one DOF and therefore have only one 'bit' of information capacity. Hereafter we use the term 'bit' in the sense of 'one piece' and not in the sense of 'a binary digit'. For our purpose, a *1-bit system* is a physical system with the information capacity of only one piece of information, a single message. Such 1-bit systems may physically be realized in elementary particles like photons, in big chunks of helium atoms in the Bose-Einstein condensate, or in macromolecules[2]. For the sake of consistency, we exemplify the 1-bit system by an electron spin.

It is important to remember that the 1-bit systems as defined above should not be mistaken with what are classically considered one bit systems, like a coin, which possess many more than one DOF. While in such cases the other DOF of the system are usually ignored as redundancies, the 1-bit systems have no more than a single DOF for storing messages. Having only one DOF puts a tight limit on the information capacity of the system. This limit for conveying pieces of information, gives rise to behavior for the 1-bit system that is very different from the familiar behavior of ordinary physical systems.

The goal of this paper is to determine the limits that the laws of information theory place on the physical properties of the 1-bit systems. We show that many peculiarities of quantum physics can be understood in regard to the ultimate lowest informational limits of the physical systems; thus we present a new interpretation of QM as the physics of the physical systems with only one DOF. Apart from its inherent interest, this interpretation can be used to untangle a number of quantum conundrum. One of those is the EPR paradox that we shall resolve after presenting the evidences of the interpretation.

2.1 Randomness

When performing a measurement on a 1-bit system, e.g. measuring the spin state of an electron, the information content of the system gets fully extracted and it goes into zero information state. A further measurement on the same attribute results in a piece of information that is correlated with what is already known about the system. What happens however if one performs a measurement to extract information on an independent attribute of the system, for example the spin of the electron perpendicular to that of the previous direction?

It is important to note that measurements always result in readings; and, even a ‘zero’ reading is still a result. Thus, getting no result after performing a measurement is not the answer. One may answer the abovementioned question by considering the laws of information theory. Mathematically the information content of the measured 1-bit system is fully extracted and the system is left with no further information; meaning, unless we perform a correlated measurement to collect the mutual information, we should only gain zero amount of information. In the mathematical language of the information theory, the data we collect should represent zero

[2] There is no physical reason, in principle, to prevent having macroscopic systems with just one DOF; if the substantial number of DOF of a system gets fixed, then its information capacity is reduced accordingly without having to resort to the microscopic world. It has been shown in several experiments that by careful screenings on a homogeneous beam of macromolecules, the informationally isolated macromolecules can also exhibit interference effects [4, 5].

information, meaning, we should end up collecting random readings, since as we show below, randomness is an expression of zero information.

Mathematically the expected information gain in a process is defined as the change in the Shannon entropy [6]

$$I = H_2(X) - H_1(X), \tag{1}$$

in which the Shannon entropy is defined as

$$H_t(X) = -\sum P_t(x_i) \log_2 P_t(x_i), \tag{2}$$

where

$$X = \{x_1, x_2, x_3, \ldots\ldots\}, \tag{3}$$

is the set of probable outcomes with $P_t(x_i)$ being their probabilities.

We can examine the two cases where the information gain is zero: the case of no new data, and the case of randomness. In the first case, when one keeps getting the same result r, we have $P_t(r) = 1$ and hence $H_t(X) = 0$ and $I = 0$. The other case is randomness which is collecting conflicting data. Randomness is when the outcomes do not follow a deterministic pattern and the probability distribution of the outcomes remains the same regardless of the previous outcomes, that is $P_1(x_i) = P_2(x_i)$. In this case, the Shannon entropy stays constant, $H_1(X) = H_2(X)$, therefore $I = 0$ and the information gain is zero. In layman terms, zero information means either no new data, or receiving random data; basically, either no news or conflicting news.

In this description, the random unpredictable results in e.g. measuring the spin of an electron in independent directions are a true manifestation of dealing with a system with zero information content. Because it is impossible to extract more than one piece of information from a system that can only contain one, mathematics dictates zero information gain that gets physically manifested through the random results of the uncorrelated measurements. Meaning, the observed randomness in the results of the uncorrelated measurements on the 1-bit systems is ontological and not removable.

This behavior is very similar to quantum physics and in contrast with what we encounter in classical physics. In classical physics, the 'randomness' stems from ignorance of physical information in the initial conditions as perfect knowledge of the initial conditions render outcomes perfectly predictable. In quantum physics, however, there are many indications that randomness does not stem from any such situations [7, 8]. In the physics of 1-bit systems as we saw, randomness is an inherent consequence of performing independent measurements on the system.

2.2 Non-commutativity

A consequence of having only a single DOF in a physical system is that the system has a tight limit on its information capacity because it can only convey one piece of information. Therefore, the first measurement of the system extracts the information content and, as we just explained, a second independent measurement will result in a random reading. This means for these systems, in contrast to classical physics, the order of operations is important.

This behavior is recognized as the non-commutativity of the operators. In QM the pair of operators that do not commute represents mutually complementary variables, meaning they cannot be simultaneously measured. In the picture we presented, this limitation is explained by the impossibility of gaining two pieces of independent information from a system that contains only a single piece of information.

2.3 The singularity of the zero information state, the superposition state

Consider a 1-bit system where its information content is already extracted, i.e. a system in the zero-information state. For example, a spin state that is already measured. What can we tell about the spin state of the system in a perpendicular direction? Because this is an unfamiliar case in our classical worldview, the answer is not obvious, but some examples can help with understanding the situation.

Imagine having to install a clock on a city tower with only the hour hand on the face. Furthermore, during the installation, the clock should not be loaded with any piece of information regarding the time so bystanders won't be misled. There are different ways to accomplish this: for example, temporarily detaching the hand off the clock face so no piece of time information gets conveyed to the onlookers or, during installation, placing twelve hands on the clock pointing to all of the 12 positions so no time can be inferred. The aforementioned aren't the only options, any number of hands can be placed on the clock, provided they don't point to a certain direction. In short, the clock can be in all these states and carry no piece of information about the time.

In the physical systems, however, the constituents of a system do not change when they reach the zero-information state. For example, electrons always have spin[3] so we cannot have an electron with no spin (cf. the exampled clock with no hand) or a different total spin (cf. the exampled clock with more than one hand). But how would it be possible for a system in the zero-information state to have attributes with no values? Again imagine the clock now in utterly empty space, with no numbers on its face. In such informational isolation, the unspecified position of the hand indicates and implies no piece of information about the time. This mirrors the case of a 1-bit system's state in the zero-information state.

Before a measurement, that is before a 1-bit system gets in touch with a reference point, it is informationally isolated from the outside world. With no reference to discern the states of the 1-

[3] This does not imply that the spin necessarily "has" a value, the measured property, before the measurement.

bit system, they are not distinguishable, meaning, the states of the 1-bit state is indefinite before measurement. Mathematically speaking, in such a situation, all x_i's in equation (3) lose their distinction and, with no distinguishability among the possible states, the zero-information state can be regarded as being in all possible states, or in the *superposition* of all the states. Simultaneously, this state can be interpreted as being in none. A perceptible example of such a singular state is the longitude of the North Pole: it can be simultaneously viewed as all degree values and none.

This means that down to the smallest scale of physical reality, for a physical system that can contain only one piece of information, before it gets in touch with another system with a reference, the system is informationally isolated. The state of the system is indefinite and will only possess a value after interacting with a system containing a fixed point as a reference.

2.4 Measurement and the collapse of superposition

In informational isolation, no distinction exists among the possible states of a DOF; this explains how a 1-bit system in the zero-information can have attributes void of values and exist in superposition. The value of an attribute gets defined in comparison and hence a reference point is always needed to quantify the state of a 1-bit system. A *measuring apparatus*, a physical system containing a fixed state, the "zero" point, so that its "pointers" can be evaluated in comparison, after interacting with the measured system, provides such a reference, besides measuring the state of the system.

In performing a measurement on a 1-bit system, the measuring apparatus physically interacts with the system and breaks its informational isolation. The measurement, and accordingly extracting information, is essentially a physical event, entailing the establishment of a correlation between the measuring device and the system. It is, therefore, the physical act of measurement which breaks the informational isolation of the 1-bit system and creates value for the physical system. Hence, making any statement about the informational content of a 1-bit system is ultimately subject to performing a measurement.

In sum, a 1-bit system is not in a defined state before being in contact with another system with a reference. The singularity of the state is removed and it acquires value after the system gets in contact with a measuring apparatus having a fixed point. This process corresponds to what in quantum physics is described as the measurement and the collapse of the state function. We'll discuss the state function and the collapse in more detail later.

2.5 Indeterminism and gaining information

One should note that extracting information always involves a factor of unpredictability and probability. The mathematical formulation of information can be interpreted as a measure of the surprise in the outcome; the less probable an outcome it contains the more surprise and more informational value. In fact, fully predictable outcomes have zero informational worth. This is the case of deterministic formalism in classical physics, when no new piece of information, in the pure mathematical sense, is gained by solving its equations[4].

The situation is different in cases where results are in principle unpredictable. As mentioned in the previous section, before measurement the 1-bit system is in a zero information state with no definite value; measurement leads to value and results in a piece of information. The piece of information is new and unpredictable, subject to the type of measurement being performed; thus rendering the act of measuring a 1-bit system a unique event in the physical world in which, in the exact mathematical sense, a new piece of information is gained. In classical physics, with all the information already present, the reality is a primary concept prior to and independent of the measurement. In contrast, in the physics of the 1-bit systems, any statement about reality is ultimately subject to the type of the measurement being performed and the information being extracted. The concepts of reality and information are now on an equal footing and reality independent of measurement in this realm of physics cannot exist.

2.6 No counterfactual definiteness

Counterfactual definiteness is the ability to assume the definiteness of the results of measurements that have not been performed. The familiar counterfactual definiteness of classical physics such as ‘the moon is there even if no one looks’ [9] is not applicable to the 1-bit systems. The reason is simple: in systems that can only contain one piece of information, there can be no more than one piece of “definiteness” at a time and thus "counterfactual definiteness” cannot be presumed.

The rejection of the counterfactual definiteness for the 1-bit systems is a neat consequence to our picture equating the physics of the 1-bit systems with quantum physics. This feature has been debated in many discussions that contrast quantum physics with classical physics and in which many paradoxes are rooted [10-12]. As discussed, given that a corresponding measurement for an attribute is not already performed, the 1-bit systems possess no value for that attribute, and hereupon ‘the unperformed experiments have no results’ [13]. For these systems, values result after the measurement is performed, but should not be considered the disclosure of pre-existing values.

2.7 Qubit

We saw in section 2.4 that a 1-bit system whose information content is not yet measured (informationally isolated, in an indefinite state, with no distinction among the possible states) can be thought of as being anywhere in the state-space of the DOF. This is the description of a qubit [14]. A qubit, compared to a classical bit (which is always in either 0 or 1 state), can be in any mixture of those states before being observed. This means the qubit is the description of any two-state 1-bit system before measurement.

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[4] One may wonder then what is the point of doing physics; the point is that having the results in advance gives us the predictive power. This is how for example one can design on paper a piece of heavy machinery –an airplane over 500 tons – which when manufactured can “miraculously” lift itself to the sky.

2.8 No-cloning

In section 2.4 we showed that the state of a 1-bit system before measurement is indefinite. An indefinite state cannot be duplicated in principle. Part of the peculiarity of the 1-bit system lies in the system's information capacity of just one; the system jumps from being in a completely unspecific state when it is in the zero-information state, to a fully known state after being measured. A 1-bit system moves between the two ultimate informational configurations for a physical system by a single act of measurement.

In general, there is no constraint on copying a state, but in the case of the 1-bit system, before measurement the system is in no defined state, and hence cannot be duplicated. Such a peculiarity has been known in quantum physics as the no-cloning theorem [15, 16] which states that it is impossible to create a copy of an arbitrary unknown quantum state.

3. Entanglement

We found that the physics of the 1-bit systems involves many peculiarities rooted upon the tight limit on their information capacity. The situation changes radically, however, as the system gains more information capacity. In a 2-bits system (a system with two DOFs) for example, since in principle each subsystem may be evaluated with respect to the other, its state cannot be described as being in all possible configurations of the state-space. Nevertheless, as we will demonstrate below, it is not impossible to have composite systems made up of two or more 1-bit subsystems that display all the peculiarities of the 1-bit systems.

The *entanglement* among the subsystems can make it possible to get a composite 1-bit system made up of more than one 1-bit subsystem. In a simple case, two electron spins with the total information capacity of two bits can be coupled to each other so that the resulting entangled system will be a 1-bit system. In this entanglement, one bit of information is already registered in the correlation they share (the subsystems have complete covariance, for example, the electrons have opposite spins) leaving only one bit of information capacity for the system. The entangled electrons therefore jointly contain just one bit of information capacity and this composite two-electron system encompasses all the same peculiarities described in the 1-bit systems.

This construct can be generalized for making a 1-bit system out of n number of 1-bit systems, as in Greenberger–Horne–Zeilinger (GHZ) states [17], in which all the n components jointly contain the one bit of information capacity (see Appendix). At first glance, such composite systems look different than the 1-bit systems, as they seem to have many more than one DOF, but the entanglement among the subsystems makes it feasible to have the composite 1-bit system.

4. Information theory based interpretation of QM

We started our scrutiny on the effects of the limited information capacity of a physical system on its behavior with a mention of the double-slit experiment, which contains, quoting Feynman, the heart of QM. Feynman also warned about attempts to understand the inner workings of quantum systems at a fundamental level stating "No one can explain…No one will give you any deeper representation of the situation" [2]. We showed that the photons in the double-slit experiment setup are 1-bit information systems and thus their limited information capacity forbids performing independent measurements and extracting more than one piece of information from them. This explains why it is impossible to observe the complimentary aspects of the photon's behavior in the double-slit experiment. We further established several fundamental results about the unique behaviors of 1-bit information systems which are in parallel with the behaviors attributed to quantum systems. With these strong similarities found between behaviors of the 1-bit information systems and quantum systems, we thus postulate an interpretation of QM as the physics of the 1-bit information systems.

The correspondence between quantum systems and 1-bit systems may not generally be as evident as in the double-slit experiment. We mentioned the entanglement phenomenon that can be considered in explaining how a composite system can have an information capacity of no more than 1-bit. In some other cases, while the system can have more than just one DOF, the other DOF of the system could be irrelevant to the problem. For example, in the Bell states, the spin DOF of the electrons can be considered unlinked to the other DOF of the system as no physical interplay is assumed between the spin state and the other DOF of the electron. In another example, in the hydrogen atom, with regard to the electric force between the electron and the proton, the electron's position and energy DOF are correlated through Coulomb's law and therefore jointly make a 1-bit system, and the spin DOF is irrelevant in the context. Therefore, the equivalence of the quantum systems and the 1-bit system is not an unjustified assumption.

Next, in the light of this interpretation, we attempt to use our picture for a better understanding of some quantum riddles and peculiar concepts.

5. Resolving the EPR paradox and explaining the 'spooky action at a distance'

In a thought experiment proposed by Albert Einstein, Boris Podolsky and Nathan Rosen (EPR) [11] two entangled particles, S_1& S_2, are spatially separated. When the particles are so far apart that any classical interaction between the two would be impossible, a measurement on one particle nonetheless determines the corresponding result of the measurement of the other. How is it possible for the particles to coordinate the outcomes of the measurements?

This experiment also poses another challenge to quantum physics: In this setup, it seems possible to measure non-commuting variables (for example S_x and S_y) on each particle: the values of S_{1x} and S_{2y}, can be measured directly on the corresponding particle without the classical disturbance from the other and at the same time the values of S_{1y} and S_{2x} can be determined due to the particle's correlation. Einstein and colleagues argued that "every element of the physical reality must have a counterpart in the physical theory", and pointed out that in terms of QM formalism "when the operators corresponding to the two physical quantities do not commute, the two quantities cannot have simultaneous reality" [11].

Later Einstein restated this as "the real factual situation of system S_1 is independent of what is done with system S_2, which is spatially separated from the former" [18]. In QM, if you measure S_1's spin, the state gets "set" by the measurement, but somehow S_2 also instantly, in a *spooky way*, "feels" what spin it is supposed to take on. To Einstein, this was a clear violation of the principle of locality and he argued against the notion that the theory provided "a complete description of a real factual situation" [18]. Hence, questioning the completeness of quantum theory.

Here we discuss the situation according to the interpretation presented in the current paper. The two entangled electrons in the EPR pair already share one bit of information, namely, their sum of spins is zero. The remaining one bit of information capacity is jointly shared by the two subsystems. The pair is thus in the zero-information state; *a priori* this joint 1-bit system has the same properties as any other isolated 1-bit system. That means its state is not defined, so no assumption can be made regarding its value as it only will possess value after a measurement. Bell inequalities also indicate clearly that the presumption of value on the pair leads to contradictions [7]. In short, the EPR pair is two spatially separated entangled electrons that jointly have the information capacity of one; it is a physically expanded 1-bit system. We argue that the solution to the EPR paradox is to bear in mind that I) mathematical correlations are non local, and II) a system in the zero-information state holds no element of reality.

Informational correlations are mathematical and while mathematical correlations can be shared between two physical systems, this does not make them local. For example, if my brother and I jointly have $10,000.00 in an account, it does not matter whether we reside in the same location or not. Assuming I withdraw nothing, as soon as I look up the account balance, I know instantaneously the amount he has taken regardless of his physical distance. Physical systems can jointly share correlations between themselves, but one does not force the other to be correlated. (cf. temperature does not prompt the molecules to go fast). A distinction should be made between nonlocal enforcement of correlations –as in the EPR case– and nonlocal communication, which, although sometimes confused with the former, is a far stronger condition. It has been made clear that EPR's nonlocality of correlations cannot be exploited for nonlocal observer-to-observer communication [19-21].

In the EPR pair, we should note that any separated measurements of the properties of an extended 1-bit system should be treated as parts of the same informational state, regardless of the degree of separation of the measurements in time and/or space. Considering the nonlocal nature of the informational correlations, the relative time ordering of the observations on the two systems, as well as their relative spatial arrangement, are irrelevant to the result. It has to be also noted that before the measurement, no value pre-exists on the system and there is no physical reality to be changed.

With these considerations there is no magical interaction between the EPR pair: the informational correlation that is shared between the pair secures the combined value of information on the system. When compared, the results on the subsystems match if the measurement decisions were consistent; otherwise, there is randomness. In any case, no message can be transmitted between the two. The problem of completeness postured in the EPR paper is also quashed as there exists no value (physical quantity) in the zero-information states to be concerned about.

6. Null-information state; where God plays dice with the universe

In dealing with situations involving the zero-information state, confusions can arise because reaching that state is not part of our natural familiar world and grasping its peculiarities needs contemplation. We mentioned that the 1-bit information systems should not be mistaken with the classical one bit systems since the latter still can be loaded with many other pieces of information in its other DOFs. A similar distinction exists between the zero-information state and the more familiar classical zero information state. In a classical zero information state, regardless of its nomenclature, the system is in a certain, yet unknown state, for the observer. The classical systems possess many more than one DOF which are not informationally isolated and their states are definable. Thus, in classical systems, a measurement reveals the value of the state of the system, unlike the 1-bit system in which the measurement creates value for the state of the system by collapsing the singularity. Meaning, classical systems in the zero information contain pieces of information on their states, albeit inaccessible to the observer; but, the 1-bit systems in the zero-information state contain no value before getting measured, they are in the *null-information state*.

This is the crucial difference between the classical zero information state and the null-information state. In the classical zero information case, the system is in a certain state, and one's ignorance is due to the lack of knowledge that the omniscient God has access. In the null-information case, there is no definite state, even for the omnipotent, omniscient God. This distinction was not evident to Einstein when he rejected the probabilistic nature of QM by saying that "God does not play dice with the universe" [22]. Zero information is about the unknown, while null-information is about the indefinite.

7. What state function represents

Following the aforementioned points, a question arises about whether a 1-bit system in the null-information state can even be studied. To be exact, nothing definite can be said about the state of a 1-bit system before a measurement; but one may still be able to make a few probabilistic remarks about that system, using the boundary conditions and "peripheral" facts that confine the system[5].

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[5] A similar example is gaining knowledge about the future 50th president of the United States. As of now, the United States has only had 45 presidents and the 50th president is unknown; however, common knowledge and census information can give some idea, for example, about the probable gender, age, weight, and height of that person. Such analyses however, are not about a real physical matter and are not definite.

This approach can help in getting some statistical idea about the situation. While having some general idea does not provide a definite predictive power, it is still better than no information.

In this approach, a mathematical construct can be employed to represent the statistical knowledge of the behavior of the 1-bit system. The null-information state is literally in no state, however, one can theorize a function describing a pseudo-state which can be interpreted as the superposition of all possible states. This *state function* should include all the possible outcomes of the planned measurement of the system. This is similar to contemplating all possible scenarios when there is no information available. In the statistical analysis of such no information cases, it is taken into account that for the classical zero information cases the alternatives are not possible simultaneously; however, for the null-information cases, the singular state can be interpreted as the coexistence of all the possibilities at the same time. One should bear in mind, however, that there is no underlying reality in the null-information case and not to be misled by the term "state" in the 'state function'. The state function should, therefore, be understood as an epistemic state (state of knowledge) rather than an ontic state (state of reality).

The aforementioned approach can help us to understand the general framework that is followed in the mathematical formalism of QM. Unlike classical physics, where seeking deterministic results is the common practice, in QM generally, the outcome of a measurement is unpredictable and only probabilistic knowledge is possible. The mathematics that is employed no longer represents the behavior of the quantum system but rather the statistical knowledge of its behavior.

7.1 Collapse of the state function

In the presented interpretation, the state function does not represent a physical entity and is solely the mathematical expansion of the null-information state according to the possible outcomes of the planned independent measurement[6]. Therefore, the state function collapse is the collapse of that mathematical expansion of the unknowable to a piece of information. The collapse happens when the informationally isolated 1-bit system interacts with another system that contains a set point and hence the singularity of the null-information state instantaneously breaks. Such symmetry breaking is not an unfamiliar occurrence in physics and constitutes the underlying concept of a vast number of physical phenomena ranging from ferromagnetism and superconductivity in condensed matter physics to the Higgs mechanism in the standard model of elementary particles.

It is, therefore, the act of measurement that creates an "element of reality" and a value for the quantum system. This means that the collapse of the state function happens at the time of measurement by a physical act, which is in sharp contrast with some metaphysical suggestions [23-25] attempting to explain that process.

[6] Note that at this stage we solely discuss the independent measurement cases. The notion of state function for predicting the results of a dependent measurement would be an extension of the current picture and will be discussed elsewhere.

8. Concluding remarks

> *"I remember discussions with Bohr which went through many hours till very late at night and ended almost in despair; and when at the end of the discussion I went alone for a walk in the neighbouring park I repeated to myself again and again the question: Can nature possibly be so absurd as it seemed to us in these atomic experiments?"* W. Heisenberg [26]

About a century has passed since its development and, quantum physics still remains somewhat mysterious. Despite the unparalleled predictive capacity of QM, an uncontroversial interpretation of its formalism is not available to the scientific community. Basically, there is no consensus on the interpretational aspect of the theory [27-29].

In this paper we demonstrated that the physical systems with only a single degree of freedom exhibit a number of peculiarities that are very similar to those of quantum systems. Those similarities lead us to postulate an interpretation of QM as the physics of the systems with only a single DOF. Furthermore, we showed how this picture provides comprehensible explanations for concepts such as the nature of randomness, no-cloning, non-commutativity, superposition, state function, and the collapse. We also solved the EPR paradox and rejected Einstein's attacks on QM. In establishing the presented interpretation, we used two principal elements:

1. There are physical systems at the extreme that have only one unoccupied degree of freedom and accordingly the information capacity to contain no more than one piece of information.
2. Zero information means either getting no new data or conflicting data (randomness).

We also benefited from four axioms: I) Physical systems' capacity to store pieces of information is limited; II) Measurement always results in value; III) Information can be shared and held jointly by physical systems, and IV) Mathematical correlations are not necessarily local.

A novel subject that we presented in our interpretation is the concept of null-information state; a singular state with zero information content that can be viewed as being in all possible states[7]. Similar to times in history when a new concept, like the number zero, negative numbers or imaginary numbers were introduced, it is not unexpected that at first controversies in interpreting the philosophical and epistemological implications of null information arise; however, as in the other cases, soon this concept can be a part of common scientific knowledge.

This interpretation depicts quantum behavior as the result of the interplay between physics and mathematics at the ultimate informational limits of a physical system. It is the information theory that dictates the behavior of the physical systems at the lowest levels of information handling. This makes the interrelation between the laws of physics and information in nature very fascinating: at large scale, the laws of physics dictate the information processing limitations of a system [1], and at the other end, the laws of information dictate the physical systems how to behave.

[7] The view of null-information state as the superposition of all possible states is in a sense similar to regarding number zero as the superposition of all integers, $0=-1+1-2+2-3+3\ldots-\infty+\infty$.

The interpretation we presented in this paper, quantum physics as the physics of the systems with single DOF, can be the unification model for explaining QM by explaining where quantum physics comes from. By clarifying the apparent oddness and confusion of quantum physics, this interpretation can help to finally clearly grasp the physical meaning of the theory. It is suggestive that our presented picture sheds new light on the meaning and philosophical implications of concepts such as entanglement, information, reality, and quantum computation.

Appendix: GHZ and W entangled states

Greenberger–Horne–Zeilinger state is a type of entangled quantum state that involves at least three subsystems. In simple words, it is a superposition of all subsystems being in state $|\uparrow\rangle$ with all of them being in state $|\downarrow\rangle$. The 3-qubit GHZ state can be written as

$$|GHZ\rangle = \frac{|\uparrow\uparrow\uparrow\rangle + |\downarrow\downarrow\downarrow\rangle}{\sqrt{2}}, \tag{A.1}$$

and in the general form with $n \geq 3$ subsystems as

$$|GHZ\rangle = \frac{|\uparrow\rangle^{\otimes n} + |\downarrow\rangle^{\otimes n}}{\sqrt{2}}. \tag{A.2}$$

For the general n-particle $|GHZ\rangle$ entangled state the information capacity of the system can be found by these considerations: the n subsystems can hold n bits of information in total. However, $n-1$bits are already set in the correlations among the subsystems in the type of: $|S_1\rangle = |S_2\rangle, |S_2\rangle = |S_3\rangle, \ldots, |S_{n-1}\rangle = |S_n\rangle$. That leaves only 1 bit of information capacity for this n-particle system.

The W state involves another class of a multipartite entangled state. For three qubits it has the following form

$$|W\rangle = \frac{|\uparrow\downarrow\downarrow\rangle + |\downarrow\uparrow\downarrow\rangle + |\downarrow\downarrow\uparrow\rangle}{\sqrt{3}}. \tag{A.3}$$

The notion of W state can be generalized for n-particles [27] as the superposition state with equal expansion coefficients of all possible pure states in which exactly one of the particles is in an “excited state”, $|\uparrow\rangle$, while all other ones are in the “ground state”, $|\downarrow\rangle$:

$$|W\rangle = \frac{1}{\sqrt{n}}\left(|\uparrow\downarrow\downarrow\ldots\downarrow\rangle + |\downarrow\uparrow\downarrow\cdots\downarrow\rangle + \cdots + |\downarrow\downarrow\cdots\downarrow\uparrow\rangle\right). \tag{A.4}$$

For general n-particle $|W\rangle$ state also the information capacity of the system is only 1 bit; from the n bits of information that can be carried by the system$n-1$ bits are already set: 1 bit of information is embedded in $\sum\langle\uparrow|S_k\rangle = 1$ (*i.e.* exactly one of the subsystems is in the “excited state”). The $n-2$ correlations of the form $|S_i\rangle = |S_j\rangle$ among the $n-1$ subsystems (*i.e.* all these subsystems are in the same state) fix $n-2$ bits of information. Thus, only 1 bit of information remains as the information capacity of the system.

A.1 Pairwise entanglement

Note that the GHZ state can be written as

$$|\uparrow\uparrow\uparrow\rangle + |\downarrow\downarrow\downarrow\rangle = (|\uparrow\uparrow\rangle + |\downarrow\downarrow\rangle) \otimes |\rightarrow\rangle - (|\uparrow\uparrow\rangle - |\downarrow\downarrow\rangle) \otimes |\leftarrow\rangle \tag{A.5}$$

where the third particle is written as a superposition in the X basis (in contrast with the Z basis) in which $|\uparrow\rangle = |\rightarrow\rangle - |\leftarrow\rangle$ and $|\downarrow\rangle = |\rightarrow\rangle + |\leftarrow\rangle$. In this case, measurement of the GHZ state along the X basis for the third particle then results in a maximally entangled Bell state.

In writing the GHZ according to this expansion one bit of information is fixed by $|S_1\rangle = |S_2\rangle$. For the remaining two bits of information, measurement in the X basis yields one bit of information, and finally, the remaining 1 bit of information is shared between the first two particles, in a Bell state.

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