Bit is It

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Abstract

Relationship between *"Bit"* and *"It"* is based on a nature of *"It"*, a nature of quantum systems. We explore it, suggesting that quantum systems are effective systems made of fundamental particle events, described in Standard Model. Such unusual view of quantum systems, *"It"*, puts it onto the same level as observed *"Bits"*, which leads to conclusion that *"Bit"* is *"It"*.

1 Definitions of *"Bit"*, of *"It"*, and of a *Quantum Problem*

"Bits" and a quantative approach to information is a domain of information theory, which really started in late 1940's, mostly with Claude Shannon's work [1] about communications. Shannon introduces a relation between amount of information that can be sent through a communication channel and a number of states of the channel. For our purposes, particular mathematical form of that relation is not very important. Most important is that now we have a direct quantified relation between information, *"Bit"*, and features of existing physical systems, or *"It"*.

Naturally, Shannon's work [1] assumes classical physical systems, not quantum ones. Does it matter? Well, information is defined as a function of states of some system. At any given moment a classical system is always in one of its own states. But it is not exactly so for quantum systems. A quantum system may seem not to be in any of its own states (we'll talk about it below in details), yet, on observation the same system gives information about its state. Therefore, in coarse terms, Shannon's relationship can be seen not as *"It"* defining *"Bits"*, but the other way around, as *"Bits"* defining a state of *"It"* (see [2], where Wheeler introduces *bit versus it* theme). So, nature of physical quantum systems, i.e. *"It"*, is key here. Let's then look at it closer.

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2 Notion of System

Quantum Mechanics was born in the beginning of the 20-th century, with a purpose to describe little tiny physical systems like electrons, atoms. Right then it has been noticed that microscopic systems behave very differently from big, macroscopic entities. Observed bizarre behaviour has been codified in a *mathematical* form, which we know today as Quantum Mechanics (QM).

In 1935, Einstein, Podolsky and Rosen wrote a paper [3], which described a thought experiment with microscopic particles, showing a meaningful difference between codified in QM behaviour and cherished ideas about physical systems. To fix this conceptual discrepancy (referred everywhere as EPR paradox), it was argued that QM is not a complete mathematical framework, and that there should be some so-far hidden variables producing quantum behaviour. Hidden variables themselves should behave as those in Classical Mechanics.

In 1964, Bell wrote [4], where he introduced a way to quantify presence of hidden variables (if there were any) behind quantum systems. Such general quantification, without having any specific theory of hidden variables, was possible due to classical nature of hidden variables. Bell's suggested theorem allows to see experimentally, whether hidden variables govern quantum systems behaviour, or not.

An experimental setup is similar to that in EPR paradox. Two quantum systems (two particles), $|\psi\rangle$ and $|\phi\rangle$ are maid to interact with each other, so that there are two possible outcomes. Usually it is an interaction involving particles' spins, which produces discrete outcomes.

$$|\psi\rangle\,|\phi\rangle \to |\psi_1\rangle\,|\phi_1\rangle + |\psi_2\rangle\,|\phi_2\rangle \tag{1}$$

We can think about systems $|\psi\rangle$ and $|\phi\rangle$ as one composite system $|\Omega\rangle = |\psi\rangle\,|\phi\rangle$, turning equation (1) into

$$|\Omega\rangle \to |\Omega_1\rangle + |\Omega_2\rangle \tag{2}$$

After an interaction some measurements are done on each sub-system separately, and preferably so that a measurement of $|\psi\rangle$ is causally separated from a measurement of $|\phi\rangle$, as per theory of Special Relativity. Experiments are repeated over and over again to collect statistics, needed for Bell's theorem. In a case, when subsystems $|\psi\rangle$ and $|\phi\rangle$ have a classical soul in a form of hidden variables, a certain statistics is produced, which is different than that in a case, when $|\psi\rangle$ and $|\phi\rangle$ behave as inseparable parts of $|\Omega\rangle$, in strict agreement with QM formalism.

Actual runs (see [5], [6], [7]) show that nature prefers to turn $|\psi\rangle$ and $|\phi\rangle$ into inseparable parts of $|\Omega\rangle$. Somehow interaction makes boundaries of objects $|\psi\rangle$ and $|\phi\rangle$ blur into one thing $|\Omega\rangle$. These days we say that interaction entangles $|\psi\rangle$ and $|\phi\rangle$, and actual inseparability of entangled states is a feature exploited by secure quantum communication protocols.

So, here we have that physical systems, *"It"*, have problems with keeping boundaries straight between each other. A notion of system becomes fuzzy. And fuzzy is not good in serving as a foundation of existence.

When we scale up to macroscopic systems, one may suggest that abovementioned problem disappears. But there are two counterarguments. The first is that all macroscopic systems are maid of microscopic ones, and, therefore, there might be a leak of uncertanty into a notion of macroscopic systems. The second has been proposed by Schrodinger in 1935. It is a clever mixing of a cat (macroscopic system) to equation (1), leaving no doubt that a notion of system is broken on both micro and macro levels.

To rescue a notion of system and to simultaneously have QM formalism in existing form, interpretations of QM sprang up. One of them, a many-worlds interpretation (MWI), illustrates this conceptual rescue most vividly. In MWI proper systems fundamentally exist, but they split into many copies, each existing in its own world, or reality. Observed QM behaviour is, thus, a result of seeing continuous splitting of reality, an additional trick on top of proper physical systems. Unfortunately, such reasoning does not always produce new experimentally verifiable predictions. And many, therefore, cast whole QM interpretation business as merely a many-words endeavour.

Such account of affairs may seem depressing, especially when we hear about experiments at LHC that successfully confirm predictions of the Standard Model in particle physics. Let's then look at what Standard Model may tell us about a notion of physical system.

3 Standard Model

Standard Model (SM) is a set of Quantum Field Theories (QFTs). The characteristic feature of QFTs is that Feynman diagrams are used to describe processes and to calculate quantative predictions (figure 1). Lines represent particles (e^- - electron, e^+ - positron, γ - photon, q - quark, g - gluon). Vertices, where lines meet, represent events of annihilation of incoming particles and creation of outgoing ones. These are particle events, and they happen at points of spacetime. Lines on diagrams may remind trajectories of classical mechanics, but they have no computational connection to spacetime points, only vertices do! In other words, every fundamental particle *touches* spacetime only at two points, at creation event and at annihilation event.

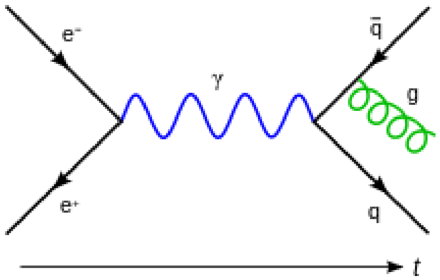

Figure 1: Feynman diagram

Notice that we start to say fundamental particle. Look at figure 2. In QFT, when particle goes from point A to point B, it might be creation at A and annihilation at B, or it might be annihilation at C with consequent event at D before there is ahhinilation at B, etc. Sum over all possible in-between fundamental particle events gives an effective particle that goes from A to B.

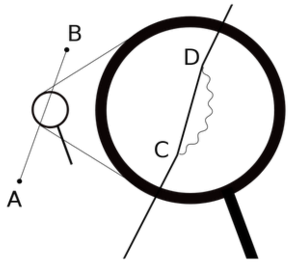

Figure 2: Effective particle

As another example, every electron in a Stern-Gerlach experiment is an effective particle assembled of many events involving fundamental electrons. Events with fundamental photons produce observed effective charge. Events with fundamental higgs produce observed effective mass.

This is similar to phonons in condensed matter physics. There is no fundamental phonon particle, yet, events in a lattice of atoms assemble into a disturbance that has wave and particle-like properties. Multitude of simpler events produces a new agreggate phenomenon. As Anderson argued in [8], “more is different”.

Given that QFTs of Standard Model produce spectacularly correct predictions, given that QFTs have no notion of systems, dealing only with particle event, where every fundamental particle *touches* spacetime only at two points, and given that all things around us are made off Standard Model's stuff, given all this, should we look at possibility that quantum systems, *“It”*, are not fundamental, and are effective entities.

4 Can *“It”* be effective, as in not fundamental?

If viewing quantum systems as effective entities is a good idea, then we should be able to construct a theory on this premise and hopefully to produce non-trivial predictions.

First, let's make existence postulates.

> **Postulate I:** There exist particles that are annihilated and created at interaction events. What sort of interaction events may or may not happen, what states of particles are required for interaction, and in what states particles are created, all of these aspects are dictated by a type of particles.
>
> **Postulate II:** Particle events are probabilistic. It is impossible to answer with certainty all following questions simultaneously: *a)* which event will occur, *b)* when and where relative to other events the said event will occur, and *c)* what will be the state of incoming and outgoing particles.

Any system is a collection of particle events. Probabilistic nature of events will lead to probabilistic events in systems. But, since we do not derive this statement rigorously, we shall call the following a postulate.

> **Postulate III:** When two systems ψ and ϕ interact with each other, they undergo a transition from some initial states $|\psi_{init}\rangle$ and $|\phi_{init}\rangle$ to final states $|\psi_j\rangle$ and $|\phi_j\rangle$, where only one of j possibilities may occur at a time with some probability:
>
> $$|\psi_{init}\rangle, |\phi_{init}\rangle \longrightarrow \bigcup_j \Big(|\psi_j\rangle, |\phi_j\rangle \quad with \quad P^{\psi}_{\psi_{init}\to\psi_j} = P^{\phi}_{\phi_{init}\to\phi_j} \Big), \tag{3}$$
>
> $$where \quad \sum_j P^{\psi}_{\psi_{init}\to\psi_j} = \sum_j P^{\phi}_{\phi_{init}\to\phi_j} = 1 \tag{4}$$
>
> We will say that states $|\psi_j\rangle$ and $|\phi_j\rangle$ in each final pair are entangled with each other as a result of interaction.

We may view systems ψ and ϕ as two subsystems of a bigger system. Then (3) will describe an internal interaction, in which some particular final states $|\psi_j\rangle$ and $|\phi_j\rangle$ are "chosen".

Let's recall that EPR paradox shows a difference between classical systems and those described by QM. In particular, if ψ and ϕ are classical sub-systems, then addition of a third system Υ, that interacts with neither sub-system ψ, nor sub-system ϕ, will look as follows

$$|\Upsilon\rangle \left(|\psi_{init}\rangle , |\phi_{init}\rangle\right) \longrightarrow \bigcup_j \left(|\Upsilon\rangle \left(|\psi_j\rangle , |\phi_j\rangle\right) \quad with \;\; P_j\right) \tag{5}$$

saying that a choice of final states is fixed for the rest of the world, even if a system of ψ and ϕ is not interacting with anything else. Or, in other words, information about internal choice of states is fixed for the rest of the world, even without interaction.

But, if information transfer occurs only via interaction, then instead of (5), we should have

$$|\Upsilon\rangle \left(|\psi_{init}\rangle , |\phi_{init}\rangle\right) \longrightarrow |\Upsilon\rangle \left(\bigcup_j \left(|\psi_j\rangle , |\phi_j\rangle \quad with \;\; P_j\right)\right) \tag{6}$$

Which one of options (5) and (6) does nature prefer? Let's look at double-slit experiment. In it, particles go through two slits and fall on the screen, that records their positions. Let's label particle as ψ and slits, or a material in which slits are cut, as ϕ. A combined system $|\psi_{init}\rangle , |\phi_{init}\rangle$ "chooses" slit, through which particle goes. If (5) is correct, and a choice of a slit is fixed for the rest of the world, then nothing should change, if we add an additional particle counting at each slit. But, in actual experiment, an additional counting of particles changes a recorded pattern on the screen, in comparison to the pattern, when there is no particle counting. Thus, (5) is not consistent with evidence, and, by implication, (6) is what happens in reality. This we formulate as

> **Postulate IV (Interaction Confinement):** When interaction occurs between subsystems of a closed system, resulting entanglements between final states and choices thereof are confined to the system.

Postulates III and IV are what is needed to have usual Quantum Mechanics. Check [9] for technical details on how usual formalism of Hilbert spaces of system states can be introduced for these postulates.

Notice that in this formulation, and let's give it a name of Waterloo Formulation of Quantum Mechanics, postulates I through IV give a physical essence, which is later expressed in some mathematical form. Firstly, this gives room in a choice of a suitable mathematical tool. Secondly, quite often there is a need to trim mathematical solutions, cause not all of them may correspond to physical reality. For example, in high-school problems about objects thrown in a gravitational field, a quadratic equation is solved, producing two results, of which only one is used, and another is dropped as a non-physical mathematical artifact. Preferred basis problem in QM is of the same sort. Constraint by the size of this essay, I leave it as an exercise to show, using postulates, why a multitude of non-preferred bases never shows on experiment.

At this point we have Waterloo Formulation of Quantum Mechanics (postulates I through IV), which produces usual QM, without having usual interpretational problems. Mostly this is due to not having fundamental proper systems in a classical meaning of this word, and instead having effective systems. Double-slit experiment's results are used to form Interaction Confinement postulate (IV), in a manner, how observed constancy of speed of light has been postulated in theory of Special Relativity (SR). And like in SR, we do not have to show why interaction confinement is true, but we can use consequences of such natural phenomenon. Thus, we have been able to complete first point of Wheeler's agenda list in [2].

Postulates I and II are existence postulates. Yet, they say nothing about spacetime. We may add additional postulates about it, or, we may try to follow Wheeler words (in [2]):

> *We will not feed time into any deep-reaching account of existence. We must derive time and time only in the continuum idealization out of it. Likewise with space.*

Let us take a route towards Wheeler's dream.

5 Time

Following Interaction Confinement postulate (IV), that is (6), a composite system (ψ, ϕ) is "not loosing" any probability, as far as external system Υ is concerned. Therefore, when described using Hilbert spaces' language, a state vector that describes closed system (ψ, ϕ) should keep the same unit length as it goes through its evolution. In other words, postulate IV, when expressed using usual Hilbert spaces' language, says that evolution of a closed system is described by unitary transformations.

From a mathematics class we know that, given a hermitian operator $\hat{H}$ and a real number t, the following $\hat{U}$ operator is unitary:

$$\hat{U} = exp\left(-\frac{i}{\hbar}\hat{H}t\right) \tag{7}$$

and, therefore, it may describe a transformation of a state vector as a function of a numeric parameter t:

$$|\psi(t)\rangle = \hat{U}\,|\psi(0)\rangle$$

Taking a t derivative will do the following:

$$\begin{aligned}\frac{\partial}{\partial t}|\psi(t)\rangle &= \frac{\partial}{\partial t}\hat{U}\,|\psi(0)\rangle = \frac{\partial}{\partial t}exp\left(-\frac{i}{\hbar}\hat{H}t\right)|\psi(0)\rangle \\ &= -\frac{i}{\hbar}\hat{H}exp\left(-\frac{i}{\hbar}\hat{H}t\right)|\psi(0)\rangle = -\frac{i}{\hbar}\hat{H}\hat{U}\,|\psi(0)\rangle = -\frac{i}{\hbar}\hat{H}\,|\psi(t)\rangle\end{aligned}$$

Which turns out to be a Schrodinger equation with a time-independent Hamiltonian $\hat{H}$:

$$\hat{H}\left|\psi(t)\right\rangle = i\hbar\frac{\partial}{\partial t}\left|\psi(t)\right\rangle \tag{8}$$

This illustrates an important point, that in QM, time is a change of states in quantum systems. To measure time, people have neen using different processes throughout the history. Particular process changes some system's state, and that is recorded as a passage of time. And since this has always worked, we can make the following statement:

Time Hypothesis: A change of states in quantum system is time.

It is a cute hypothesis. But to decide how useful it is, we should look for its consequences.

When we grant this proposition, then, in principle, any system can be used as a clock, and we should label states with a real number t, making every state to correspond to some particular value of t. To make a system as best clock as possible, labeling of states should be such that there should be as less as possible change of state, indicated as L, in any short span of Δt, for any long period t_1 to t_2. In other words, the following integral quantity

$$S = \sum_{t=t_0}^{t_1} L\Delta t \tag{9}$$

should be minimal for proper labeling of states with t. Recall from (8) that an operator of infinitesimal change in time is an energy operator, making units to be S as $energy \times time$.

Voila! This is a principle of least action. Correspondence between system's states and t is called an equation(s) of motion, and is found by minimizing quantity S in (9).

Since Time Hypothesis produces such a remarkable consequence as a direction to use a principle of least action in finding equations of motion, we have to conclude that hypothesis is valid.

6 Spacetime

Time Hypothesis talks about quantum systems, that are effective entities. Therefore, this hypothesis is applicable only at that level. How about fundamental level? Where do particle events happen?

As Giovanni Amelino-Camelia points in [10], we have never detected empty points of spacetime, only those with particle events. The points in between particle events is a useful abstract concept, but is redundant in certain cases, and is probably misleading in a study of quantum gravity. With this in mind, and given only two existence postulates, that postulate existence of fundamental particles and particle events, we can postulate the following:

Spacetime Postulate: Particle interaction events define spacetime points.

But spacetime is not only a collection of points. Points have a particular order. What can force order upon particle events?

Recall that every fundamental particle participates in exactly two events, a creation event, and an annihilation event. We may say that there must be a natural causal order, in which creation event should by considered earlier than annihilation. More so, collections of so ordered points have already been studied mathematically under the name of partially ordered sets. Sorkin's study under the name of causal sets shows how Minkowski-like spacetime emerges out of partially ordered sets. This gives a causal, time-like order. What can we say about spatial order?

Fundamental particles have an internal spin characteristic. While spin is internal, rotation in physical 3D space changes relative spin orientations. This we take as a clue, that a spatial order between particle events is an accomodation of spin relationships. Here some more work needs to be done to establish exact mathematical framework. It might be something like partially ordered sets, with a bit different ordering dictated by spin group.

Given an existing work on causal sets, we can say that Spacetime Postulate is good, as it provides reasonable way to get order over point events as a function of fundamental particle properties.

Based on postulates of Waterloo Formulation of Quantum Mechanics (I through IV), we have managed to articulate a nature of spacetime, the way Leibniz talked about it (see quote in [2]):

> *Time and space are not things, but orders of things.*

7 Quantum Zeno Effect and Gravity

We said that Waterloo Formulation of Quantum Mechanics has no problem with interpretation of different quantum effects. But one such effect is very different from double-slit or EPR spectacles. This is a Quantum Zeno Effect (QZE) in quantum systems, which show "inhibition of quantum evolution by measurement" (see [11], [12]). In QZE some quantum system is taken in an excited state, and, when left alone, system transitions to a ground state. Time for these transitions is known, and conceptually similar systems are even used as extremely precise clocks. But when an additional interaction is done to said system, transition time dilates. Intervening interactions are carefully timed, and they are of a "measure system state" type.

Quantum system in QZE experiments is an effective system, consisting of a multitude of fundamental particle events. Any intervening interaction is an addition of extra fundamental events. In the light of Time Hypothesis, which says that a change of states in quantum system is time, we have to say that additional events dilate quantum system's initial time!

Compare this with Higgs mechanism, now confirmed at LHC. Fundamental electron, for example, has no notion of mass. But additional events with higgs make effective electron behave as if it has mass.

According to Special Relativity (SR), the faster an effective electron goes, the more mass it has, as a result of having more of additional interactions events with higgs, due to higher energy. At the same time, according to SR, the faster system travels, the more dilated its time should be. Therefore, given Time Hypothesis, and by analogy of what we just said about time and QZE, we have to conclude that time dilation in SR is a result of additional interaction events in a Higgs mechanism.

Experiments on equivalence of inertial and gravitational masses still show that the two are same. Applying Einstein's razor forces us to say that gravitational phenomena must be a result of a Higgs mechanism as well.

For example, the closer the effective test particle to a massive body, the more it will be engaged into additional higgs events, due to extra higgs flying around given massive body, and the more dilated time of a test system will be. Experiment tells that time dilate in gravity fields, making it another fit with rough considerations presented here.

8 Summary for *"Bit"* and *"It"*

Shannon gave a quantative definition of information as a function of system(s) that carry it. EPR-like arguments show that a nature of physical system is not what people have always thought. This essay introduces Waterloo Formulation of Quantum Mechanics, in which systems are effective entities, arising from simpler particle events, putting both *"Bit"* and *"It"* onto the same "not-fundamental" list. Thus, we say that *"Bit is It"*.

Let's give final word to Wheeler, from [2]:

> *Finally: Deplore? No, celebrate the absence of a clean clear definition of the term "bit" as elementary unit in the establishment of meaning. We reject "that view of science which used to say, 'Define your terms before you proceed.' The truly creative nature of any forward step in human knowledge," we know, "is such that theory, concept, law and method of measurement forever inseparable are born into the world in union." If and when we learn how to combine bits in fantastically large numbers to obtain what we call existence, we will know better what we mean both by bit and by existence.*
>
> *A single question animates this report: Can we ever expect to understand existence? Clues we have, and work to do, to make headway on that issue. Surely someday, we can believe, we will grasp the central idea of it all as so simple, so beautiful, so compelling that we will all say to each other, "Oh, how could it have been otherwise! How could we all have been so blind so long!"*

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