It And Bit

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Abstract

It is broadly believed that everything in the universe is found to be made from a few basic building blocks called fundamental particles, governed by four fundamental forces. However, physicists such as John Archibald Wheeler suggested that information is fundamental to the physics of the universe. According to this «*it from bit*» doctrine, all things physical are information-theoretic in origin. This doctrine is based in the old Copenhagen interpretation of quantum mechanics; an interpretation which is internally inconsistent and no applicable to the cosmos as a whole. Modern consistent interpretations of quantum mechanics eliminate the old myths about measurement processes and observers' consciousness and reintroduce the idea of a wholly physical reality, invalidating the «*it from bit*» doctrine.

Utilizing a new phase space formulation of quantum mechanics developed recently by the author, the concepts of «*bit*» and «*it*» are reconsidered. We introduce the new states D as quantum bits and the new Hamiltonians H as quantum its. The new concepts of it and bit introduced in this work have a well-defined and rigorous definition, unlike Wheeler's concepts. Moreover, the new concepts apply on situations where the traditional wavefunction theory does not work. The it H is not derivable from the bit D and, as a consequence, the old «*it from bit*» doctrine gets substituted by the new «***it and bit***».

After showing why the physical entropy used in the science of thermodynamics is not a measure of the ignorance of human observers, the final part of this Essay is devoted to emphasize the importance that the bit acquires in modern science when confronted to the delicious multiplicity of the far-from-equilibrium regimes, where the certainty of Newtonian and Schrödinger motion begin to fade in favor of a complex non-geometrical, 'living', conception of Nature: an «***it and bit***» conception.

Introduction

The theories and discoveries of thousands of physicists since the 1930s have resulted in a remarkable insight into the fundamental structure of matter: everything in the universe is found to be made from a few basic building blocks called fundamental particles, governed by four fundamental forces. Our mainstream understanding of how these particles and three of the forces are related to each other is encapsulated in the Standard Model of particle physics. Developed in the early 1970s, it has successfully explained many experimental results and precisely predicted a wide variety of phenomena. Over time and through many experiments, the Standard Model has become established as a well-tested physics theory [1].

However, some few physicists are distancing themselves from the traditional view of fundamental physics as a description of material objects and their interactions, at its deepest level, for embracing some new age conceptualization where the empirical existence of physical reality is negated.

Although information theory was founded in 1948 by Claude Elwood Shannon, and first introduced in statistical mechanics by Edwin Thompson Jaynes in 1957, it was not until 1990 when the physicist John Archibald Wheeler suggested in his work «*Information, physics, quantum: The search for links*» that information is fundamental to the physics of the universe. According to this «*it from bit*» doctrine, all things physical are information-theoretic in origin [2]:

> It from bit. Otherwise put, every "it" – every particle, every field of force, even the space-time continuum itself – derives its function, its meaning, its very existence entirely – even if in some contexts indirectly – from the apparatus-elicited answers to yes-or-no questions, binary choices, bits. "It from bit" symbolizes the idea that every item of the physical world has at bottom – a very deep bottom, in most instances – an immaterial source and explanation; that which we call reality arises in the last analysis from the posing of yes – no questions and the registering of equipment-evoked responses; in short, that all things physical are information-theoretic in origin and that this is a participatory universe.

Wheeler became deeply convinced of the importance of information on a quantum realm after analyzing what is now called the Wheeler's delayed-choice experiment. This is a modification of the two-slit experiment. According to his interpretation, when electrons are aimed at a barrier containing two slits, the electrons act like waves; they go through both slits at once and form what is called an interference pattern, created by the overlapping of the waves, when they strike a detector on the far side of the barrier. If the physicist closes off one slit at a time, however, the electrons pass through the open slit like simple particles and the interference pattern disappears. In the delayed-choice experiment, the experimenter decides whether to leave both slits open or to close one off after the electrons have already passed through the barrier with the same results. Wheeler concluded that the electrons seem to know in advance how the physicist will choose to observe them and, thus that reality is not wholly physical but generated by the act of observation and, thus, consciousness itself.

Nice if it were not for all this being incorrect. WHEELER's «*it from bit*» doctrine is based in the old COPENHAGEN interpretation of quantum mechanics; an interpretation which is internally inconsistent and no applicable to the cosmos as a whole. Modern consistent interpretations of quantum mechanics eliminate the old myths about measurement processes and consciousness [3]:

> Measurements play no fundamental role in quantum mechanics, just as they play no fundamental role in classical mechanics. In both cases, measurement apparatus and the process of measurement are described using the same basic mechanical principles which apply to all other physical objects and physical processes. Quantum measurements, when interpreted using a suitable framework, can be understood as revealing properties of a measured system before the measurement took place, in a manner which was taken for granted in classical physics.

and reintroduce the idea of a wholly physical reality:

> Both quantum mechanics and classical mechanics are consistent with the notion of an independent reality, a real world whose properties and fundamental laws do not depend upon what human beings happen to believe, desire, or think. While this real world contains human beings, among other things, it existed long before the human race appeared on the surface of the earth, and our presence is not essential for it to continue.

In particular, the so named delayed-choice experiments are perfectly compatible with the idea of an independent physical reality. Of course, quantum experiments indicate that the nature of this independent reality is in some respects quite different from what was earlier thought to be the case, but there is a continuity from the classical to the quantum world. The strong relation between both cannot be perceived with formulations of quantum mechanics based in wavefunctions and the SCHRÖDINGER equation.

Fortunately, a new formulation of quantum mechanics has been developed recently [4]. This novel approach eliminates the interpretational puzzles of the existent formulations. From a conceptual point of view, the elimination of the wavefunctions from quantum theory is in line with the procedure inaugurated by EINSTEIN with the elimination of the ether in the theory of electromagnetism. This new formulation provides the framework for a reconsideration of the concepts of «*bit*» and «*it*». This is the goal of the following section.

The quantum it and the quantum bit

For conservative N-particle systems, the new equation of motion is [4]

$$\frac{\partial D}{\partial t} = \mathcal{L} D, \tag{1}$$

with the state $D = D(\boldsymbol{p}, \boldsymbol{q}; t)$, where $\boldsymbol{p}$ is the momentum and $\boldsymbol{q}$ the position, and the Liouvillian operator given by

$$\mathcal{L} \stackrel{\text{def}}{=} -\sum_{j=1}^{N} \left(\frac{\partial H}{\partial \boldsymbol{p}_j} \frac{\partial}{\partial \boldsymbol{q}_j} - \frac{\partial H}{\partial \boldsymbol{q}_j} \frac{\partial}{\partial \boldsymbol{p}_j} \right), \tag{2}$$

where $H = H(\boldsymbol{p}, \boldsymbol{q}; t)$ denotes the phase space Hamiltonian and the ∂ partial derivatives. This Hamiltonian $H = H_{\mathrm{cl}} + H_{\mathrm{Q}}$ consists of a purely classical term plus a quantum term that depends on PLANCK constant $\hbar$. For a single particle of mass m and potential energy V

$$H(\boldsymbol{p}, \boldsymbol{q}; t) = \frac{\boldsymbol{p}^2}{2m} + V - \frac{\hbar^2 (\partial/\partial \boldsymbol{q})^2 \sqrt{\int D \, \mathrm{d}\boldsymbol{p}}}{2m \sqrt{\int D \, \mathrm{d}\boldsymbol{p}}}. \tag{3}$$

The state D is a concise representation of all the observable properties of the system, this is the quantum **bit**. At the other hand, the Hamiltonian H represents the system; this is the quantum **it**.

The new concepts of **it** and **bit** introduced in this work have a well-defined and rigorous definition, unlike WHEELER's concepts. Moreover, we are working with a generalized quantum theory. For instance, the quantum wavefunctions Ψ used by WHEELER in his analysis of the delayed-choice experiment are an approximation to the state D considered here –see [4] for a detailed derivation of wavefunctions and their limits of applicability–.

Note that H and D are mutually *irreducible*; this is another important difference between our concepts of **it** and **bit** and those introduced by WHEELER. In particular the **it** H is not derivable from the **bit** D and, as a consequence, his «*it from bit*» doctrine vanishes.

Thermodynamic entropy is not a measure of ignorance

As remarked above, the state D is a concise representation of all the observable properties of a mechanical system. One of those properties is the thermodynamic entropy, which is given by the traditional Boltzmann & Gibbs expression

$$S \stackrel{\text{def}}{=} -k_{\text{B}} \int\int D \ln D \; \mathrm{d}\boldsymbol{p}\mathrm{d}\boldsymbol{q}. \tag{4}$$

This can be rewritten like

$$S = -k_{\text{B}} \sum_j w_j \ln w_j + \text{const}, \tag{5}$$

where w_j is the weight of the element of phase space volume j on the state D. When the constant term is avoided, some few physicists believe that the thermodynamic entropy is related to Shannon information

$$\mathcal{I} = \sum_j p_j \ln p_j \tag{6}$$

by *assuming* that one can set $S = -k_{\text{B}}\mathcal{I}$. Moreover, they argue that entropy is a measure of ignorance because S would increase when $\mathcal{I}$ decreases. Some physicists ignore the dimensions of the the universal constant k_{B} and refer to $-\mathcal{I}$ as «Shannon *entropy*» or «*informational entropy*» and to $\mathcal{I}$ as «*negentropy*». Again nice if it were not for all this being incorrect. Besides the dimensions of the universal constant, w_j and p_j are two different concepts, which implies that $S \neq -k_{\text{B}}\mathcal{I}$.

The main difference between w_j and p_j is that the weight w_j is *independent* of the information that the observer has of the physical system; however, p_j depends of the observer and can vary even for a given observer! The value p_j is defined as the probability of that the system *is in the state* j, whereas w_j is only an element of a concrete mathematical superposition used to represent the *physical state* D. Consider an electron e^- in the water molecule; the *physical* state D_{e^-} of the electron can be expanded as a mathematical superposition of different wavefuntions ψ_j and their conjugates ψ_j^*, each one participating with a weight w_j [4]. The electron cannot be found in any of those wavefunctions due to the existence of quantum correlations; the impossibility to describe the physical state of the electron in the molecule using a wavefunction ψ_j is completely unrelated to the information or ignorance of observers.

This confusion between w_j and p_j is very typical in one part of the physical literature and closely related to the confusion between the *physical* density matrix introduced by Lev Davidovich Landau & Paul Adrien Maurice Dirac in quantum mechanics and the informational (statistical) density matrix introduced by John von Neumann. Only the former matrix is fundamental.

This differentiation between the physical entropy introduced by thermodynamics and the anthropomorphic 'entropy' of the theory of information allows the elimination of additional paradoxes from science, such as those associated to the irreversibility of physicochemical and biological processes. A discussion of such topics would require an entire Essay and will be discussed elsewhere.

The importance of the bit

When we set $\hbar = 0$ and consider a DIRAC Delta [6] state $D = D_{\mathrm{cl}} = \delta(\boldsymbol{p} - \boldsymbol{p}(t))\delta(\boldsymbol{q} - \boldsymbol{q}(t))$ in (1) we obtain a classical equation

$$\frac{\partial D_{\mathrm{cl}}}{\partial t} = \mathcal{L}_{\mathrm{cl}} D_{\mathrm{cl}}, \tag{7}$$

which becomes equivalent to the HAMILTON equations of classical mechanics

$$\frac{\mathrm{d}\boldsymbol{q}}{\mathrm{d}t} = \frac{\partial H_{\mathrm{cl}}}{\partial \boldsymbol{p}} \tag{8}$$

$$\frac{\mathrm{d}\boldsymbol{p}}{\mathrm{d}t} = -\frac{\partial H_{\mathrm{cl}}}{\partial \boldsymbol{q}}. \tag{9}$$

Integrating this pair of equations, or its equivalent (7), with the help of the initial condition $(\boldsymbol{p}_0, \boldsymbol{q}_0)$ provides a deterministic description of all the mechanical properties of the system. The role of the **bit** is trivial in classical mechanics.

Its role is also trivial in the molecular thermodynamics of equilibrium. For simple systems, at constant composition and volume, the state is given by $D_{\mathrm{eq}} = (1/Z)\exp(-H/k_{\mathrm{B}}T)$; here Z is an integration constant, the so-called «*partition function*», and T the temperature. One of the main properties of an equilibrium state is its inherent universality: molecular differences between diverse systems do not impede a complete characterization of the equilibrium state by energy, volume, and composition alone. The situation changes drastically when we move beyond equilibrium. In the words of ILYA PRIGOGINE: «*we can say that matter at equilibrium is 'blind', but far from equilibrium it begins to 'see'*».

Far-from-equilibrium systems are non-integrable in the POINCARÉ sense [5], and their state D cannot be obtained from solving the classical HAMILTON equations or the quantum SCHRÖDINGER equation. In the nonlinear regime, irreversible processes and the boundary conditions do not uniquely specify the nonequilibrium state to which the system will evolve; driven by internal fluctuations or other small influences, the system evolves to one of many possible new states, each one of which has to be discovered, characterized, and cataloged, revealing the true importance of the bit D in modern science.

Away from linear regime, the certainty of Newtonian and SCHRÖDINGER motion begin to fade in favor of a complex non-geometrical, 'living', conception of Nature: an «***it and bit***» conception.

References and notes

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[5] The Liouville Space Extension of Quantum Mechanics **1997:** *Adv. Chem. Phys. 99, 1–120*. Petrosky, T.; Prigogine, I.

[6] We use the following representation for the Dirac Delta function

$$\delta(z) = \frac{1}{\pi} \lim_{\epsilon \to 0} \frac{\epsilon}{\epsilon^2 + z^2}$$