# It from Qubit

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**In this essay I will embark on the venture of changing the realist reader's mind about the informational viewpoint for physics: "It from Bit". I will try to convince him of the amazing theoretical power of such paradigm. Contrary to the common belief, the whole history of physics is indeed a winding road making the notion of "physical object"–the "It"–fade away. Such primary concept, on which the structure of contemporary theoretical physics is still grounded, is no longer logically tenable. The thesis I advocate here is that the "It" is emergent from pure information, an information of special kind: quantum. The paradigm then becomes: "It from Qubit". Quantum fields, particles, space-time and relativity simply emerge from countably infinitely many quantum systems in interaction. Don't think that, however, I can cheat by suitably programming a "simulation" of what we see. On the contrary: the quantum software is constrained by very strict rules of topological nature, which minimize the algorithmic complexity. These are locality, unitariety, homogeneity, and isotropy of the processing, with minimal quantum dimension. What is amazing is that from just such simple rules, and without using relativity, we obtain the Dirac field dynamics as emergent.**

It is not easy to abandon the idea of a universe made of matter and embrace the vision of a reality made of pure information. The term "information" sounds vague, spiritualistic, against the attitude of concreteness that a scientist should conform to. We are all materialistic in the deep of our unconscious, we believe in "substance", and the idea of matter made of information (and not viceversa), seems inspired by a New-Age religion. It reminds us the immaterialism of bishop Berkeley. Software without hardware? Nonsense. Information *about what*? *Whose* information? A subjective information? We cannot give-up objectivity of science.

I will try to convince you that we can reconcile objectivity with subjectivity by embracing a more pragmatic kind of realism, based on *what we observe* and not on *what we believe* is out there. In the scientific process we are easily lead to consider as "ontic" entities that are instead only theoretical notions. We must separate what should be taken as "objective" from what is element of the theory, and define precisely the boundary between theory and observation. Science must make precise predictions about what everybody agree on: the observed facts, the "events".

## "Informationalism": a Realistic Immaterialism

Quantum Mechanics has taught us that we must change our way of thinking about "realism", and that this cannot be synonymous of "materialism". Likewise objectivity should not be confused with the availability of a physical picture in terms of a “visible” mechanism. We must specify which notions have the *objectivity status*, and describe the experiment in terms of them. What matters is our ability of making correct predictions, not of describing what is out there *as it is*–a nonsense, since nobody can check it for us. We only need to describe logically and efficiently what we see, and for such purpose we conveniently create appropriate “ontologies”, which nonetheless are just tools for depicting mechanisms in our mind.

Why we should bother changing our way of looking at reality? Because the old *matter-realistic* way of thinking in terms of *particles* moving around and interacting on the *stage of space-time* is literally blocking the progress of theoretical physics. We know that we cannot reconcile general relativity and quantum field theory, our two best theoretical frameworks. They work astonishingly well within the physical domain for which they have been designed. But the clash between the two is logically solved only if we admit that they are not both correct: at least one of them must hold only approximately, and emerge from an underlying more fundamental theory. Which one of the two? The answer from *It from Qubit* is: relativity theory. Indeed, the informational paradigm shows its full power in solving the conflict between the two theories (at least if we restrict to special relativity), with relativity derived as emergent from quantum theory of interacting systems–qubits at the very tiny Planck scale.

A description of a reality emerging from pure software would not provide a good theory if we were allowed to adjust the “program” to make it work. The “subroutines” must stringently derive from few very general principles, corresponding to minimize the algorithmic complexity: this is the new “elementarity” notion that will substitute the corresponding one of particle physics. What is now astonishing is that few simple topological principles–unitariety, locality, homogeneity, and isotropy–for minimal quantum dimension lead to the Dirac field theory, without assuming relativity. The only great miracle here, as it always happens with physics, is the amazing power of mathematics in describing the world. But is it really a miracle?

## The notion of *physical object* is untenable

*Matter is not made of matter.*
Hans Peter Dürr

In physics we are accustomed to think in terms of physical “objects” having “properties” (location, speed, color, ...), the value of each property depending on the object’s “state”. The object considered as a “whole”, is taken as the sum of is “parts”. The dynamics accounts for the evolution of the state, or equivalently of the properties of the object, and is described in terms of “free” dynamics for each part, along with “interactions” between the parts, each part retaining its individuality, namely being itself an object with its own properties. This bottom-up approach is called “reductionism”, and is opposed to “holism”, according to which the properties of the whole cannot be understood in terms of the properties of the parts. Holism is commonly contrasted to the mechanical "clockwork" picture of nature inherited from the scientific revolution, emphasizing it as a motivation for integrating top-down approaches. One of the unexpected features of quantum mechanics is that it incorporates a form of holism absent from classical physics. In addition, the theory entails "complementarity", namely the existence of incompatible properties that cannot be shared by an object in any possible state, nevertheless providing different kinds of information about it. The state of the object generally does not correspond to a precise value of the property, but provides the probability distribution of values of each property.

**Reconciling Holism with Reductionism.** Quantum theory entails a strong instance of holism, with the existence of properties of the whole that are incompatible with any property of the parts. Correspondingly, there are states of the whole with determinate values of a property of the whole, but having no determinate value of any property of the parts. Thus, differently from classical mechanics, we have the seemingly paradoxical situation that we can have perfect knowledge of the whole having no knowledge of the parts. Such holistic states of the whole describe correlations between properties of the parts that cannot be interpreted as shared randomness, namely they do not correspond to a joint probability distribution of random values of the properties of the parts. This is what we call "quantum nonlocality", and it is signaled by the violation of the celebrated Bell's bound for shared randomness [1], which has been breached in numerous experiments in quantum optics and particle physics.

The holism of quantum theory has resulted in the popular credo that quantum theory is logically inconsistent with the bottom-up approach of physics. On the contrary, the structure of the theory is fully consistent with it. How the theory reconciles with the bottom-up approach? The answer relays on the fact that the theory satisfies the principle of "local discriminability" [2, 3], namely the possibility of discriminating between any two states of the whole by performing only observations on the parts. This means that we can still observe a holistic reality in a reductionistic way by observing only the parts of the whole.

**The Bell test supports a deeper epistemological realism.** The Bell result changes dramatically our way of looking at reality, and for this reason it shows the epistemological power of physics in guiding our knowledge well beyond the mere appearance. We can tell whether the deep conceptual framework of the theory is in focus, and be well aware of its reliability and theorizing perspectives, a step essential to objectivity. At first glance, Bell's theorem seems to be against realism, for the inescapable holism that proves the inextricable interconnectedness of parts that blurs their individual images. Instead, the Bell test supports a deeper epistemological realism, providing a strong positive case for our ability to go beyond the appearance. Things are not the way we naively believed they are: realism cannot mean that we should be able to see sharply defined parts the way we believe they exist out there. Contrarily to what Einstein thought, such an intrinsic unsharpness is not the incapability of quantum theory to go beyond the veil that blurs our observation: it is the way things are. The lesson spelled loud and clear by the Bell theorem is that we should trust observations, even against our intuition, and ground our knowledge on the logic of the experiment, focusing theoretical predictions on what we actually observe. In a word: being *operationalist*.

**The Plato's cave and the shadows of physical ontologies.** We are like the prisoners in Plato's cave who can see objects only through the shadows they cast. The "true" object may have properties in addition to what we see, e.g. three dimensional shape and color–properties that are seemingly irrelevant for the casted shadows. The detractor of operationalism would say that the doctrine rejects as unphysical those hidden variables with no immediate empirical consequences. However, pragmatically such restriction should be taken only as long as the hidden variables have no additional explanatory power, e.g. in describing the dynamics of the shadows overlapping each other on the walls of the cave. We can create a three-dimensional ontology corresponding to the shadows, but we should not forget that this is an explanatory tool, not "what is really out there". The ontology can be extremely powerful in describing a large number of different phenomena, as it is the case of the modern notion of atom, on which the whole chemistry relies, and which allows us understanding a great deal of physics. Nowadays we can almost "see" the atoms using a tunnel-effect microscope, even though we shouldn't forget that these images are just a suitable mathematical representation of electric signals. Ernst Mach was stubbornly against the idea of atoms, but he was proven wrong.

**The elementary-particle ontology.** An evolution of the notion of atom is the modern concept of elementary particle, which has marked the greatest successes of modern physics. Unfortunately, we have not only successes, but also failures in explaining relevant phenomena–e.g. gravity or dark matter and other astrophysical observations–phenomena that even a reasonable revision of the particle notion seems unable to explain. An ontology that works perfectly well in accounting for a large class of phenomena may later prove having not the same power in explaining other phenomena, e.g. those occurring at scales that are much larger or much smaller than those where the ontology is successful. Ultimately the ontology may turn out to be even logically inconsistent within the theoretical framework, and a new more powerful ontology later will emerge, which can account for mechanisms within a much larger physical domain, and without suffering the logical inconsistencies of the old ontology. We must always keep in mind that the motivations for adopting the new ontology must always be its additional explanatory power in accounting for the behavior of the observed shadows on the cave walls, and, more important, the logical solidity and consistency of the theoretical principles embodied by the ontology. Unfortunately, some colleagues followers of Einstein's realism got so fond of the Plato's cave paradigmatic tale, to the extent that they believe that quantum mechanics only describes the shadows on the cave walls, whereas they are convinced that there exists a veiled reality made of particles like three-dimensional marbles: this is what they call the "true reality". But here the Bell's theorem comes to help us, proving that, whatever outside the cave the object are made of, they cannot be constituted of "parts" of which we can have perfect knowledge in all cases. Quantum nonlocality is not a feature of the shadows only: it holds for any possible object projecting the shadow. This is the amazing epistemological power of physics.

## The evaporation of the notion of object

Quine in his *Whither Physical Objects?* [4] made a thorough attempt to arrive at a very comprehensive concept of "object", but he end up with a progressive evaporation of the notion, from the "body", toward "space-time region", up to mere "set of numerical coordinates" with which he ends.

What is a "physical object"? Independently on the specific context, an object must be located in space and time. Its persistence through time is a fundamental feature to grant its individuality. What if we have two identical objects A and B that disappear and suddenly reappear somewhere else? How can we know which one is A and which is B? This is exactly what happens with identical quantum particles, which are literally indistinguishable. And, indeed, they cannot be followed along their trajectories, even in principle. "Particles", i. e. "small parts", are the minimum "part" of which every material object is made up. But can we consider particles as objects themselves?

Take the "atom" as the ancestor notion of particle. Since its birth with Democritus and Leucippus, the idea of atom was devised to solve precisely the problem of individuality of objects. Is an object something different from the stuff it is made of? Heraclitus said that "we could not step twice into the same river", to emphasize that the river is never the same water, contrarily to appearance. The river is not the collection of water drops: it is a bunch of topological invariants in the landscape: the two sides, the flow of water in between. Thus the notion of physical object resorts to a set of invariants. And the atoms are invariants, eternal entities within the river flow.

**The Theseus' ship paradox and teleportation: *It* becomes *State*.** In a popular tale Plutarch raised the following paradox: the Theseus' ship was restored completely, by replacing all its wooden parts. After the restoration, was it the same ship? The problem of the Theseus' ship can be posed more dramatically in modern terms, using the thought experiment in which a human is teleported between two places very far apart, e. g. Earth and a planet of Alpha Centauri. From quantum theory we know the basic principles of teleportation. Each atom, electron, proton, neutron, etc. of the human body undergoes a quantum measurement that completely destroys its quantum state. A huge file containing all measurement outcomes is sent to the arrival place (to cover the distance between the two planets it will take 4.37 years traveling at the speed of light). At the arrival the quantum state is rebuild over local raw matter.

Technically a so-called entangled resource is needed, namely a bunch of previously prepared particle states of the same kind of those used to experimentally prove violation of the Bell's bound. According to quantum theory the protons (neutrons, electrons, etc.) at the departure point are indistinguishable, even in principle, from those at the arrival point: matter is the same everywhere. The quantum measurement while destroying the quantum state of the human's molecules, literally kills the person, reducing him to raw matter. Then, the rebuilding of the human at the arrival is made by re-preparing the matter available there in the same original state that the human had at the departure point: teleportation literally resurrects the human. The question now is: are the human before and the human after teleportation the same individual? The two are indeed perfectly indistinguishable: they are made of the same matter, and even share the same thoughts, since the molecules of the brain are in the same physical state as they were before teleportation (indeed, the teleported guy will feel to be the same individual, and had experienced just a sudden change of his surrounding).

What is then the teleported human? He is certainly not identifiable with his constituent matter: matter is everywhere the same. The human is the shape along with all the properties of the matter that is made of. Apart from a space translation, the human is a "state" of matter–a very complicate state indeed, involving many particles. But with this reasoning we have reached an inconsistency with the original notion of object, since the state is not the object itself, but is a catalog of all its properties. This means that what we considered an object was instead a "state"–as the shape of the river, the shape of the Theseus' ship–whereas the physical objects are now the particles, the stuff.

**Quantum field theory: the particle becomes a state.** We enter now quantum field theory, and what we discover? We realize that, differently from the non relativistic quantum mechanics, particles are themselves states of something else: the quantum field. Thus, electrons are states of the electron field, photons are states of the electromagnetic fields, neutrinos of the neutrino field, and so on. The process of demoting particles to states and introducing the notion of quantum field as the new "object" for such states is known as "second quantization".

**The field is not an "object".** But is now the field an object in the usual sense? Not at all. The field is everywhere. And it is not made of matter: its states are. What is it then? It is a collection of infinitely many quantum systems. But the "quantum system" is an abstract notion: it is an *immaterial support* for quantum states, exactly in the same fashion as the "bit" in computer science is the abstract system having the two states 0 and 1. The analogous system of the bit in quantum theory is the "qubit", having not only the two states 0 and 1, but also all their superpositions, corresponding to the possibility of having complementary properties which are absent in classical computer science. Therefore, we are left with states of qubits, namely pure quantum software:

objects, matter, hardware, completely became vaporized.

## *It from Qubit:* space-time emerging from a web of interactions.

**A game on the web.** Consider the following game on the web. There is an unbounded number of players: Alice, Bob, Carol, David, Eddie, . . . . Each player has the same identical finite set $S = \{e, h_1, h_2, \ldots, h_M, h_1^{-1}, h_2^{-1}, \ldots, h_M^{-1}\}$ of colored buttons to press. When pressing button $e$ one connects with himself, and experiences audio feedback. When pressing button $h_1$ Alice speaks with Bob, whereas when Bob presses the button $h_1^{-1}$ he speaks to Alice. If Alice presses $h_1$ and Bob presses $h_1^{-1}$ they both will experience audio feedback. After trying many connections, Alice realizes that when she presses $h_1$ and Bob presses $h_2$ connecting to Carol, and Carol presses $h_3$, all of them experience audio feedback, meaning that Carol is connected back to Alice. The same happens if anybody else presses $h_1$, and the connected player presses $h_2$, and the third connected player presses $h_3$: the same feedback loop holds starting from any player, namely from the network perspective all players are perfectly equivalent. Also the feedback delay in the two-person round-trip communication is the same for every player and for every pressed button: it is $2t_P$. Then the delay for each feedback loop is a multiple of $t_P$, e.g. the delay of the Alice-Bob-Carol-Alice loop is $3t_P$. Each players doesn't know where the other players are: they can only try to figure it out from the feedback loop structure and the delays.

It is easy to realize that the above structure is that of a *group*, which we will call $G$: $e$ is the identity element, $h_j$ the group generators, $h_j^{-1}$ the respective inverses, whereas the feedback loops are relations among group elements, e.g. $h_3h_2h_1 = e$, or $h_2h_1 = h_3^{-1}$. Each player corresponds to an element of the group. The fact that all players are equivalent corresponds to the *homogeneity* of the group network (this network is precisely a Cayley graph of the group). Thus, by playing the game and by knowing that the network is homogeneous, we come out with a group $G$ which is given by the so-called *group presentation*, i.e. via *generators* and *relators*. Generally even though the group is finitely generated, it grows unbounded. This is the case, for example, of a lattice, as those of crystals. For example, in the simple-cubic lattice there are only three generators (the translations along $x, y, z$), and along with their respective inverses they make a total of six elements, corresponding to the coordination number of the lattice. The time-delay of the feedback loops is a way of measuring the distance between the players: it is a metric for the group: the socalled "word-metric" (the numbers of letters of the word denoting the group moltiplication, e. g. for $h_3h_2h_1$ the length is 3). From the feedback loops we figure out the shape of the network, e. g. a simple-cubic lattice. We then imagine the network immersed in the usual Euclidean space $\mathbb{R}^3$. There is, however, a mismatch between the distances measured in $\mathbb{R}^3$ and those measured with the word-metric: they are exactly proportional when measured along a fixed direction, but the proportionality constant differs depending on direction, e.g. it is 1, $\sqrt{2}$, or $\sqrt{3}$ if measured along the sides, the face-diagonals or the main diagonals of the cubes, respectively.

This mismatch has been noted by Weyl [5], who argued that we cannot have a continuous geometry emerging from a discrete one, since we could never get the irrational numbers as $\sqrt{2}$ or $\sqrt{3}$ coming from the Pythagoras' theorem. Then, we cannot immerse the lattice in $\mathbb{R}^3$ by preserving the metric, since the word-metric and the Euclidean metric cannot be matched. In mathematical terms we say that the lattice cannot be *isometrically* embedded in $\mathbb{R}^3$. But here a new outstanding branch of mathematics comes to help: the *geometric-group theory* of Gromov [6]. It states that we only need a *quasi-isometric* embedding, namely the two metrics should match modulo additive and multiplicative constants. (Geometric-group connects algebraic properties of groups with topological and geometric properties of spaces on which these groups act).

Now you would ask: why such a construction for having space-time as emergent? The answer is that we want to have space-time and relativity emerging from just quantum systems in interactions. In the game on the web, the players $g \in G$ label the quantum systems $\psi(g)$, which is a vector/spinor quantum field evaluated at $g \in G$. The player connections $h_i \in S$ label their local interactions in terms of transitions matrices $A_h$. The whole quantum network of systems is a Quantum Cellular Automaton, our quantum software. The single-step of the run is described by the unitary operator [7]

$$A = \sum_{h \in S} T_h \otimes A_h,$$

where $T_h$ is a unitary faithful representation of the group $G$. Thanks to its quantum nature, the automaton *physically achieves* the quasi-isometric embedding, and on the large scale we recover the relativistic quantum field theory.

**The Quantum Cellular Automata.** One can ask: what is the minimal field vector dimension $s$ of a nontrivial automaton quasi-isometrically embeddable in $\mathbb{R}^3$ and isotropic? For $s = 1$ the automaton is trivial. For $s = 2$ it turns out that there are two automata that are reciprocally connected by chirality [all results that follow have been presented in the joint work with P. Perinotti [7]]. The groups that are quasi-isometrically embeddable in $\mathbb{R}^3$ must be commutative, and these are the Bravais lattices, and the only lattice that achieve unitariety and isotropy is the BCC (body cubic centered). The eigenvalues of $A$ have unit modulus, and their phases as a function of the wave-vector $\vec{k}$ in the Brillouin zone are the dispersion relations. For $|\vec{k}| \ll 1$ (the so-called relativistic regime) the two automata approaches the Weyl equation. Coupling such Weyl automata in the only possible localized way, one gets two different automata with $s = 4$ that are reciprocally connected by the CPT symmetry. Thus, the CPT symmetry is broken, and is recovered in the relativistic limit, where both automata become the Dirac equation, with the rest-mass being the coupling constant. Therefore, the simplest cellular automata satisfying unitariety, locality, homogeneity, and isotropy are just those achieving the Weyl and Dirac equations in the limit of small wave-vectors. For general $\vec{k}$ the automata can be regarded as a theory unifying scales from Planck to Fermi, with Lorentz covariance distorted [13] a la Amelino-Camelia [9, 10] and Smolin/Maguejo[11, 12], i.e. with additional invariants in terms of energy and length scales. They exhibit relative locality [14], namely event coincidence depending on the observer and on the momentum of the observed particles. The generalized energy-momentum Lorentz transformations are those that leave the dispersion relations invariant [13]. Thus, relativistic quantum field theory is obtained without assuming relativity, as a theory emergent at large scales from a more fundamental theory of information processing. This has also been shown in Ref. [13] for the one-dimensional Dirac automaton earlier derived by heuristic arguments [15]. For technical details of the Dirac automata in $\mathbb{R}^d$ with $d = 1, 2, 3$ the reader can see Refs. [16, 7, 13].

## The many bonuses of the It-from-Qubit

In addition to emergence of relativistic quantum field and space-time without assuming relativity, the quantum automaton theory has a number of very desirable features that are not possessed by quantum field theory. The theory is quantum *ab-initio*, and is the natural scenario for the holographic principle, two dreamy features for a microscopic theory of gravity a la Jacobson[17] and Verlinde[18]. It extends field theory by including localized states and measurements, solving the issue of localization of quantum field theory. It has no violation of causality and no superluminal tail of the wave-function. It is computable and is not afflicted by any kind of divergence. Its dynamic is stable, allowing analytical evaluations of the evolution for long times, a feature that is crucial for deriving observable phenomenology. Despite its simplicity it leads to unexpected interesting predictions, e. g. it anticipates a bound for the rest-mass for the Dirac particle, simply as a consequence of unitariety, and without invoking mini black-hole general-relativity arguments [16].

The predicted violation of Lorentz covariance and space-isotropy affect physics at huge energies, many order of magnitude above that of UHECRs (ultra-high-energy cosmic rays). Planck-scale effects are possibly visible from light coming from quasars at the boundary of the universe [19, 20].

The quantum nature of the automaton is crucial for the emergence of space-time, since continuous isotropy and all continuous symmetries are recovered from the discrete ones in the relativistic limit thanks to quantum interference between paths [21] (Lorentz covariance from classical causal networks conflicts with homogeneity, and needs a random topology [22]). The classical dynamics also emerges from the automaton, with the particle trajectories being the "typical paths" of narrow-band superpositions of single-excitations, whereas the field Hamiltonian is derived from the unitary operator $A$ [16].

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