The quantum field theory (QFT) dual paradigm in fundamental physics and the semantic information content and measure in cognitive sciences

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Abstract. In QFT any quantum system has to be considered, as an "open" system, because always interacting with the background fluctuations of the quantum vacuum. Namely, the Hamiltonian in QFT is always including the quantum system and its inseparable thermal bath, formally "entangled" like an algebra with its co-algebra, according to the principle of the "doubling" of the degrees of freedom (DDF). This is the core of the representation theory of the cognitive neuroscience based on QFT. Moreover, in QFT the probabilities of the quantum states follow a Wigner distribution, based on the notion and the measure of quasi-probability, where negative probabilities are allowed and regions integrated under given expectation values do not represent mutually exclusive states. This means that a computing agent, either natural or artificial in QFT, against the QTM paradigm, is able to change dynamically the basic symbols of its computations. This justifies and not only supposes the definition of the information associated with a Wigner distribution as a "semantic information content", according to the definition and measure of it, defined in the Theory of Strong Semantic Information (TSSI) of L. Floridi.

1 INTRODUCTION: A CHANGE OF PARADIGM

Perhaps, the better synthesis of the actual change of paradigm in fundamental physics is the positive answer that it seems necessary to give to the following question: "Is physics legislated by cosmogony?". Such a question is the title of a visionary paper wrote in 1975 by J. A. Wheeler and C. M. Patton and published in the first volume of a fortunate series of the Oxford University about the quantum gravity [1].

Such a revolution originally amounts to the so-called *information theoretic approach* in quantum physics as the natural science counterpart of a *dual ontology* taking information and energy as two fundamental magnitudes in basic physics and cosmology. This approach started from Richard Feynman's influential speculation that a quantum computer could simulate any physical system [2]. This is the meaning of the famous posit "it from bit" principle stated by R. Feynman's teacher, J. A. Wheeler [3, p. 75]. The cornerstones of this reinterpretation are, moreover, D. Deutsch's demonstration of the universality of the Quantum Universal Turing Machine (QTM) [4], and overall C. Rovelli's development of a *relational* Quantum Mechanics QM [5]. An updated survey of such an informational approach to fundamental physics is in the recent collective book, edited by H. Zenil, and with contributions, among the others, of R. Penrose, C. Hewitt, G. J. Chaitin, F. A. Doria, E. Fredkin, M. Hutter, S. Wolfram, S. Lloyd, besides the same D. Deutsch [6].

There are, however, several theoretical versions of the information theoretic approach to quantum physics. It is not important to discuss all of them here (for an updated list in QM, see, for instance [7]), even though all can be reduced to essentially two.

1. The first one is the classical "infinitistic" approach to the *mathematical physics* of information in QM. Typical of this approach is the notion of the *unitary evolution* of the *wave function*, with the connected, supposed *infinite* amount of information it "contains", "made available" in different spatio-temporal cells via the mechanism of the "decoherence" of the wave function. Finally, essential for this approach is the necessity of supposing *an external observer* ("information for whom?" [7]) for the foundation of the notion and of the measure of information. This is ultimately Shannon's, purely syntactic, measure and notion of information in QM [5]. Among the most prominent representatives of such an approach, we can quote the German physicist H. D. Zeh [8, 9] and the Swedish physicist at the Boston MIT, M. Tegmark [10].
2. The second approach, the emergent one today, is related to a "finitistic" approach to the *physical mathematics* of information, taken as a fundamental physical magnitude together with energy. It is related to Quantum Field Theory (QFT), because of the possibility it gives of spanning the microphysical, macrophysical, and even the cosmological realms, within one only quantum theoretical framework, differently from QM [11].

In this contribute we discuss the relevance of the second approach for the theory of the *semantic information*, both in biological and cognitive sciences.

2 FROM QM TO QFT IN FUNDAMENTAL PHYSICS

The notion of quantum vacuum is fundamental in QFT. This notion is the only possible explanation at the fundamental microscopic level, of the *third principle of thermodynamics* ("The entropy of a system approaches a constant value as the temperature approaches zero"). Indeed, the Nobel Laureate Walter Nernst, first discovered that for a given mole of matter (namely an ensemble of an Avogadro number of atoms or molecules), for temperatures close to the absolute 0, T_0, the variation of entropy ΔS would become infinite (by dividing by 0). Namely,

$$\Delta S = \int_{T_0}^{T} \partial Q / T = \int_{T_0}^{T} C\, dT / T = C \ln T / T_0 ,$$

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Where Q is the heat transfer to the system, and C is the molar heat capacity, i.e., the total energy to be supplied to a mole for increasing its temperature by 1°C. Nernst demonstrated that for avoiding this catastrophe we have to suppose that C is not constant at all, but vanishes, in the limit $T \to 0$, as T^3, so to make ΔS finite, as it has to be. This means however, that near the absolute 0°C, there is a mismatch between the variation of the body content of energy, and the supply of energy from the outside. We can avoid such a paradox, only by supposing that such a mysterious inner supplier of energy is the vacuum. This implies that the absolute 0°C is unreachable. In other terms, there is an unavoidable fluctuation of the elementary constituents of matter. The ontological conclusion for fundamental physics is that we cannot any longer conceives physical bodies as isolated.

> «The vacuum becomes a bridge that connects all objects among them. No isolated body can exist, and the fundamental physical actor is no longer the atom, but the field, namely the atom space distributions variable with time. Atoms become the "quanta" of this matter field, in the same way as the photons are the quanta of the electromagnetic field» [12, p. 1876].

For this discovery, eliminating once forever the notion of the "inert isolated bodies" of Newtonian mechanics, Walter Nernst is a chemist who is one of the founders of the modern quantum physics.

Therefore, the theoretical, core difference between QM and QFT can be essentially reduced to the criticism of the classical interpretation of the QFT as a "second quantization" as to the QM. In QFT, indeed, the classical Stone-Von Neumann theorem [13] does not hold. This theorem states that, for system with a *finite* number of degrees of freedom, which is always the case in QM, the representations of the canonical commutation relations are all *unitarily equivalent to each other*, so to justify the exclusive use of Shannon information in QM.

On the contrary, in QFT systems, the number of the degrees of freedom is not finite, so that infinitely many unitarily inequivalent representations of the canonical commutation (bosons) and anti-commutation (fermions) relations exist. Indeed, through the principle of the *Spontaneous Symmetry Breaking* (SSB) in the ground state, infinitely (not denumerable) many, quantum vacuum conditions, compatible with the ground state, there exist. Moreover, this holds not only in the relativistic (microscopic) domain, but also it applies to non-relativistic many-body systems in condensed matter physics, i.e., in the macroscopic domain, and even on the cosmological scale [11, pp. 18. 53-96].

Indeed, starting from the discovery, during the 60's of the last century, of the dynamically generated long-range correlations mediated by the *Nambu-Goldstone bosons* (NGB) [14, 15], and hence for their role in the local gauge theory by the Higgs field, the discovery of these collective modes changed deeply the fundamental physics. Before all, it appears as an effective, alternative method to the classically Newtonian paradigm of the perturbation theory, and hence to its postulate of the asymptotic condition.

In this sense, "QFT can be recognized as an *intrinsically thermal* quantum theory" [11, p. ix]. Of course, because of the intrinsic character of the thermal bath, the whole QFT system can recover the classical Hamiltonian character, because of the necessity of anyway satisfying the energy balance condition of each QFT (sub-)system with its thermal bath ($\Delta E = 0$), mathematically formalized by the "algebra doubling", between an algebra and its co-algebra (Hopf algebras) [16].

The more evident difference between QM and QFT is thus the deeply different physical interpretation of the Heisenberg uncertainty principle and of the related *particle-wave duality*. In QM the Heisenberg uncertainty reads:

$$\Delta x \Delta p \geq \frac{\hbar}{2}$$

Where x is the position p the momentum of the particle and $\hbar$ is the normalized Planck constant. On the contrary, in QFT the same relation reads:

$$\Delta n \Delta \varphi \geq \hbar$$

Where n is the number of quanta of the force field, and φ is the field phase. If ($\Delta n = 0$), φ is undefined so that it makes sense to neglect the waveform aspect in favor of the individual, particle-like behavior. On the contrary if ($\Delta \varphi = 0$), n is undefined because an extremely high number of quanta are oscillating together according to a well-defined phase, i.e., within a given coherence domain. In this way, it would be nonsensical to describe the phenomenon in terms of individual particle behavior, since the collective modes of the force field prevail.

In QM the uncertainty and hence the wave-particle duality relationship is *between two representations*, particle-like and wave-like, related to a measurement operation, and accordingly the uncertainty is, respectively, on the momentum or on the position of the particle. In any case, the Schrödinger wave function in QM is not the expression of some dynamic entity like a force field, but simply the expression of different way of representing the quantum phenomenon.

On the contrary, in QFT the duality is between *two dynamic entities*: the fundamental force field and the associated quantum particles that are simply the quanta of the associated field that is different for different types of particles. In such a way, the quantum entanglement does not imply any odd relationship between particles like in QM, but simply it is an expression of the unitary character of a force field. To sum up, according to such more coherent view, Schrödinger wave function of QM appears to be only a rough statistical coverage of a finest structure of the dynamic nature of reality.

3 QFT OF DISSIPATIVE STRUCTURES IN BIOLOGICAL SYSTEMS

a. Order and symmetry breakdown in condensed matter

It is well-known that the first domain of successful application of QFT is the study of the microphysics of condensed matter, that is in systems displaying at the macroscopic level an high degree of coherence related to an *order parameter*. In crystals, the "order parameter", that is the macroscopic variable characterizing the new emerging level of matter organization, is related to the *matter density distribution*. In fact, in a crystal, the atoms (or the molecules) are "ordered" in well-defined positions, according to a *periodicity law* individuating the crystal lattice.

Other examples of such ordered systems in condensed matter realm are the magnets, the lasers, the super-conductors, etc. In all these systems the emerging properties related to the respective order parameters, are neither the properties of the elementary constituents, nor their "summation", but new properties depending on *the modes in which they are organized*, and hence on *the dynamics controlling their interactions.* In this way, at each new macroscopic structure, such a crystal, a magnet or a laser, corresponds a new "function", the "crystal function", the "magnet function", etc.

Moreover, all these emerging structures and functions are controlled by *dynamic parameters,* that, with an engineering terminology, we can define as *control parameters.* Changing one of them, the elements can be subject to different dynamics with different collective properties, and hence with different collective behaviors and functions. Generally, the temperature is the most important of them. For instance, crystals beyond a given critical temperature — that is different for the different materials — lose their crystal ordering, and the elements acquire as a whole the macroscopic structure-functions of an amorphous solid or, for higher temperatures, they lose any static structure, acquiring the behavior-function of a gas.

So, any process of *dynamic ordering,* and of *information gain,* is related with a process of *symmetry breakdown.* In the magnet case, the "broken symmetry" is the rotational symmetry of the magnetic dipole of the electrons, and the "magnetization" consists in the correlation among all (most) electrons, so that they all "choose", among all the directions, that one proper of the magnetization vector.

To sum up, whichever dynamic ordering among many objects implies an "order relation", i.e., a *correlation* among them. What, in QFT, at the *mesoscopic/macroscopic* level is denoted as *correlation waves* among molecular structures and their chemical interactions, at the *microscopic* level any correlation, and more generally any interaction, is mediated by *quantum correlation particles.* They are called "Goldstone bosons" or "Nambu-Goldstone Bosons (NGB)" [17, 14, 15], with mass — even though always very small (if the symmetry is not perfect in finite spaces) —, or *without mass at all* (if symmetry is perfect, in the abstract infinite space). Less is the inertia (mass) of the correlation quantum, greater is the distance on which it can propagate, and hence the distance on which the correlation (and the ordering relation) constitutes itself.

However, an important *caveat* is necessary to do about the different role of the "Goldstone bosons" as quantum correlation particles, and the "bosons" of the different energy fields of quantum physics (QED and QCD). These latter are the so-called *gauge bosons*: the photons γ of the electromagnetic field; the gluons g of the strong field, the bosons $W^{\pm}$ and the boson Z of the electroweak field; and the scalar Higgs boson H^0 of the Higgs field, common to all the precedent ones.

The gauge bosons are properly mediators of the *energy exchanges,* among the interacting elements they correlate, because they are effectively quanta of the energy field they mediate (e.g., the photon is the quantum of the electromagnetic field). Hence, the energy quanta are bosons able to change the *energy state* of the system. For instance, in QED of atomic structures, they are able to change the fundamental state (minimum energy), into one of the excited states of the electronic "cloud" around the nucleus.

On the contrary, NGB correlating quanta are not mediators of the interactions among the elements of the system. They determine only the *modes of interaction* among them. Hence, any symmetry breakdown in the QFT of condensed matter of chemical and biological systems has one only gauge boson mediator of the underlying energy exchanges, the photon, since they all are electromagnetic phenomena. Therefore, the phenomena here concerned, from which the emergence of *macroscopic* coherent states derives, implies the generation, effectively the *condensation,* of correlation quanta with negligible mass, in principle null: the NGB, indeed. They acquire a different name for the different mode of interaction, and hence of the coherent states of matter they determine – *phonons* in crystals, *magnetons* in magnets, *polarons* in biological matter. Indeed, what characterizes the coherent domains in living matter is the phase coherence of the *electric dipoles* of the organic molecules and of the water, in which only the biomolecules are *active.* This is the basis of the fundamental "Goldstone theorem" [18, 19]. Therefore, despite the correlation quanta are real particles, observable with the same techniques (diffusion, scattering, etc.), not only in QFT of condensed matter, but also in QED and in QCD like the other quantum particles, wherever we have to reckon with broken symmetries [15], nevertheless they do not exist *outside* the system they are correlating. For instance, without a crystal structure (e.g., by heating a diamond over 3,545 °C), we have still the component atoms, but no longer phonons. Also and overall in this aspect, the correlation quanta differ from energy quanta, like photons. Because the gauge bosons are *energy* quanta, they cannot be "created and annihilated" as the correlation quanta are.

Better, in any quantum process of particle "creation/annihilation" in quantum physics, what is conserved is the energy/matter, mediated by the energy quanta (gauge bosons), not their "form", mediated by the NGB correlation quanta. Also on this regard, a dual ontology is fundamental for avoid confusions and misinterpretations as to the notion of "information" in quantum physics, as *neghentopy.*

Moreover, because the mass of the correlation quanta is in any case negligible (or even null), *their condensation does not imply a change of the energy state of the system.* This is the fundamental property for understanding how, not only the stability of a crystal structure, but also the relative stability of the living matter structures/functions, at different levels of its self-organization (cytoskeleton, cell, tissue, organ…), can depend on such basic *dynamic* principles. In fact, all this means that, if the symmetric state is a fundamental state (a minimum of the energy function corresponding to a *quantum vacuum* in QFT of dissipative systems), also the ordered state, after the symmetry breakdown and the instauration of the ordered state, remains *a state of minimum energy,* so to be *stable* in time. In kinematics terms, it is a *stable attractor* of the dynamics.

b. The Doubling of Degrees of Freedom (DDF) in QFT and in neuroscience

We said that the relevant quantum variables in biological system are the *electrical dipole vibrational modes* in the water molecules, constituting the oscillatory "dynamic matrix" in which also neurons, glia cells, and the other mesoscopic units of the brain are embedded. The condensation of massless NGB (polarons) — corresponding, at the mesoscopic level, to the long-range correlation waves observed in brain dynamics — depends on the triggering action of the external stimulus for the symmetry breakdown of the quantum vacuum of the corresponding brain state. In such a case, the "memory state" corresponds to a coherent state for the basic quantum variables, whose mesoscopic order parameter displays itself as the amplitude and phase modulation of the carrier signal.

In the classical Umezawa's model of brain dynamics [20], however, the system suffered in an "intrinsic limit of memory capacity". Namely, each new stimulus produces the associated polaron condensation, by cancelling the precedent one, for a sort of "overprinting". *This limit does not occur in dissipative QFT where the many-body model predicts the coexistence of physically distinct patterns, amplitude modulated and phase modulated*. That is, by considering the brain as it is, namely an "open", "dissipative" system continuously interacting with its environment, there not exists one only ground (quantum vacuum) state, like in thermal field theory of Umezawa where the system is studied at equilibrium. On the contrary, in principle, there exists infinitely many ground states (quantum vacuum's), so to give the system a potentially infinite capacity of memory. To sum up, the solution of the overprinting problem relies on three facts [21]:

1. In a dissipative (non-equilibrium) quantum system, there are (in principle) infinitely many quantum vacuum's (ground or zero-energy) states, on each of which a whole set of non-zero energy states (or "state space" or "representation states") can be built.
2. Each input triggers one possible irreversible time-evolution of the system, by inducing a "symmetry breakdown" in one quantum vacuum, i.e., by inducing in it an ordered state, a coherent behavior, effectively "freezing" some possible degrees of freedom of the constituting elements behaviors (e.g., by "constraining" them to oscillate on a given frequency). At the same time, the input "labels" dynamically the induced coherent state, as an "unitary non-equivalent state" of the system dynamics. In fact, such a coherent state persists in time as a ground state (polarons are not energetic bosons, are Goldstone bosons) so to constitute a specific "long-term" memory state for such a specific coupling between the brain dynamics and its environment. On the other hand, a brain that is no longer dynamically coupled with its environment is, either in a pathological state (schizophrenia), or it is simply dead.
3. At this point emerges the DDF principle as a both physical and mathematical necessity of such a brain model. Physical, because a dissipative system, even though in non-equilibrium, must anyway satisfy the *energy balance*. Mathematical, because the 0 energy balance requires a "doubling of the system degrees of freedom". The *doubled* degrees of freedom, say $\tilde{A}$ (the tilde quanta, where the non-tilde quanta A denote the brain degrees of freedom), thus represent the environment to which the brain state is coupled. The environment (state) is thus represented as the "time-reversed *double*" of the brain (state) on which it is impinging. The environment is hence "modeled on the brain", but according to the finite set of degrees of freedom *the environment itself elicited*.

Of the DDF we have illustrated elsewhere its logical relevance, for an original solution of the reference problem (see [22, 23] and below).

There exists a huge amount of experimental evidence in brain dynamics of such phenomena, collected by W. Freeman and his collaborators. It found, during the last ten years, its proper mathematical modeling in the dissipative QFT approach of Vitiello and his collaborators, so to justify the publication during the last years of several joint papers on these topics (see, for a synthesis, [24, 25]).

To sum up [26], Freeman and his group used several advanced brain imaging techniques such as multi-electrode EEG, electrocorticograms (ECoG), and magneto-encephalogram (MEG) for studying what neurophysiologist generally consider as the *background activity* of the brain, often filtering it as "noise" with respect to the synaptic activity of neurons they are exclusively interested in. By studying these data with computational tools of signal analysis to which physicists, differently from neurophysiologists, are acquainted, they discovered the massive presence of patterns of AM/FM phase-locked oscillations. They are intermittently present in resting and/or awake subjects, as well as in the same subject actively engaged in cognitive tasks requiring interaction with the environment. In this way, we can describe them as features of the background activity of brains, modulated in amplitude and/or in frequency by the "active engagement" of a brain with its surround. These "wave packets" extend over coherence domains covering much of the hemisphere in rabbits and cats [27, 28, 29, 30], and regions of linear size of about 19 cm in human cortex [31], with near zero phase-dispersion [32]. Synchronized oscillations of large-scale neuron arrays in the β and γ ranges are observed by MEG imaging in the resting state and in the motor-task related states of the human brain [33].

4 SEMANTIC INFORMATION IN LIVING AND COGNITIVE SYSTEMS

a. QFT systems and the notion of neghentropy

Generally, the notion of information in biological systems is a synonym of the *negentropy* notion, according to of E. Schrödinger's early use of such a term. Applied, however, to QFT foundations of dissipative structures in biological systems, the notion of negentropy is not only associated with the *free energy*, as Schrödinger himself suggested [34], but also with the notion of *organization*, as the use of this term by A. Szent-György first suggested [35]. The notion of negentropy it is thus related with the constitution of *coherent domains* at different space-time scales, as the application of QFT to the study of dissipative structures demonstrates, since the pioneering H. Frölich works [36, 37].

On this regard, it is important to emphasize also the key-role of the notion of *stored energy* that such a multi-level spatial-temporal *organization* in coherent domains and sub-domains implies, as distinct from the notion of *free energy* of classical thermodynamics [38]. Namely, as we know from the precedent discussion, the constitution of coherent domains allows chemical reactions to occur at *different time-scales*, with a consequent energy release, that so becomes immediately available exactly *where/when it is necessary*. For instance, resonant energy transfer among molecules occurs typically in 10^{-14} sec., whereas the molecular vibrations themselves die down, or thermalize, in a time between 10^{-9} and 10^{1}sec. Hence, it is a 100% highly efficient and highly specific process, being determined by the frequency of the vibration itself, given that resonating molecules can attract one another. Hence, the notion of "stored energy" is meaningful at every level of the complex spatial-temporal structure of a living body, from the single molecule to the whole organism.

This completes the classical thermodynamic picture of L. Szilard [39] and L. Brillouin [40] according to which the "Maxwell

demon", for getting information so to compensate the entropic decay of the living body must consume free energy from the environment. This means an increasing of the global entropy according to the dictate of the Second Law. However, this must completed in QFT with the evidence coming from the Third Law discussed in this paper.
This occurs at the maximum level in the biological realm in the human brain dynamics. For illustrating this point as to the DDF applied in neuroscience, Freeman and his collaborators spoke about "dark energy" as to the extreme reservoir of energy hidden in human brain dynamics. Human brain indeed has 2% of the human body mass, but dissipates 20-25% of resting energy. This depends on the extreme density of cells in the cortices ($10^5/mm^3$), with an average of 10^4 connections [41].

b. Syntactic *vs.* semantic information in quantum physics

It has been emphasized the Shannon nature of the notion and measurement of information that can be associated to decoherence in QM, overall in the relational and hence computational interpretations of QM illustrated above [5]. In fact, in both cases the "information" can be associated to the uncertainty H removal, in the sense that "more probable" or "less uncertain" an event/symbol is, less informative (or, psychologically, less "surprising") its occurrence is. Mathematically, in the Mathematical Theory of Communication (MTC), the information H associated with the i^{th} symbol x among N ones (= alphabet), can be defined as:

$$H = \sum_{i=1}^{N} p(x_i)\, I(x_i) = \sum_{i=1}^{N} p(x_i) \log \frac{1}{p(x_i)} = -\sum_{i=1}^{N} p(x_i) \log p(x_i)$$

Where $p(x_i)$ is the relative probability of the i^{th} symbol x as to the N possible ones, I is the information content associated with the symbol occurrence, that is the inverse of its relative probability (less probable it is, more informative its occurrence is). The use of probability logarithms is only for granting that the amount of the total probability of a set of elements (symbols in our case) is equal to the summation of the probabilities of the single elements, and not to their product.
The information amount H has thus the dimensions of a statistical *entropy* that is very close to the thermodynamic entropy S of statistical mechanics:

$$S = -k_B \sum_i p(x_i) \log p(x_i)$$

Where x_i are the possible microscopic configurations of the individual atoms and molecules of the system (microstates) which could give rise to the observed macroscopic state (macrostate) of the system, and k_B is the Boltzmann constant. Based on the correspondence principle, S is equivalent in the classical limit, i.e. whenever the classical notion of probability applies, to the QM definition of entropy by John Von Neumann:

$$S = -k_B \mathrm{Tr}(\rho \log \rho)$$

Where ρ is a density matrix and Tr is the trace operator of the matrix. Indeed, who suggested Claude Shannon to denote as "entropy" the statistical measure of information H he discovered, was the same Von Neumann. The informativeness or the "uncertainty (removal)" associated with (the occurrence of) a symbol in MTC (or with an event in statistical classical and quantum mechanics) is (are) only "syntactic" and not "semantic" [42, p. 3]. Effectively, the symbol (the event) occurs as *uninterpreted* (context-independent) and *well-formed* (determined), according to the *rules* of a *fixed* alphabet or code (i.e., according to the *unchanged laws* of physics.
Anyway, starting from the pioneering works of D. M. Mackay [43], and of R. Carnap & Y. Bar-Hillel [44], it is a *leit-motiv,* in almost any work dealing with the notion of information in biological and cognitive systems, the vindication of the *semantic/pragmatic* character of it. Particularly, because information concerns here self-organizing and complex process, in them the evolution of the coding, and the notion of contingent truth (semantics), in the sense of *adequacy* for an optimal fitting with the environment (pragmatics), are essential [45, 46, 47]. More specifically, in QFT differently from QM, it is significant the pragmatic information content, defined as the ratio of the rate of energy dissipation (power) to the rate of decrease in entropy (neghentropy) [47]. A measure generally considered in literature as the proper information measure of self-organizing systems. Evidently, in the DDF formalism of QFT, the relationship between a quantum system and its thermal bath (environment), and specifically, in neuroscience, the relationship between the brain and its contextual environment, the notion and measure of pragmatic information, as described in [47], plays an essential role [41].
What is here to be emphasized is that in QFT the Wigner function (WF), on which the probabilities of the physical states are calculated, are deeply different from the Schrödinger wave function of QM, not only because the former, differently from the latter, is defined on the phase space of the system. What is much more fundamental is that the WF uses the notion of *quasi-probability* [48], and not the notion of probability of the classical Kolomogorov axiomatic theory of probability [49].
Indeed, the notion of quasi-probability, not only violates the third axiom of the classical theory, because *negative probabilities* are allowed. It also violates the fifth axiom, because regions integrated under given expectation values do not represent *mutually exclusive states* – i.e., the separation of variables in such distributions is not fixed, but, as it is the rule in the case of phase transitions, can evolve dynamically. From the computability theory standpoint, this means that a physical system in QFT, against the TM and QTM paradigms, is able to change dynamically "the basic symbols" of its computations, since new collective behaviors can emerge from individual ones, or vice versa. In this way, this justifies the definition of the information associated with a WF as a "semantic information content".
The semantic information in QFT computations hence satisfies, from the logical standpoint, the notion of "*contingent (not logical) truth*", so to escape the Carnap & Bar-Hillel paradoxes (CBP) [44], just like the "Theory of Strong Semantic Information" (TSSI) does in L. Floridi's approach, with which it shares the same notion of quasi-probability [50]. Let us deepen shortly this point.
Following the critical reconstruction of both the theories (CSI and TSSI), by S. Sequoiah-Grayson [51], CSI approach is based on Carnap's theory of intensional modal logic [52]. In this theory, given n individuals and m monadic predicates, we have 2^{nm} possible worlds and 2^m Q-predicators, intended as individuations of possible type of objects, given a conjunction of primitive predicates either un-negated or negated. A full sentence of a Q-predicator is a Q-sentence, hence a possible world is a conjunction of n Q-sentences, as each Q-sentence describes a possible

existing individual. The *intension* of a given sentence is taken to be the set of possible worlds that make true the sentence, i.e., included by the sentence. This is in relation with the notion of *semantic information* in CSI, here referred as *content* of a declarative sentence *s* and denoted by 'Cont(*s*)'. Of course, larger is the sub-set of possible worlds that a sentence is able to exclude, richer is its semantic content. 'Cont(*s*)' is taken thus as the set $\{x\}$ of all possible worlds making *s* false, i.e., the set of all possible worlds that make true $\neg s$:

$$\mathrm{Cont}(s) := \{x \in W : x \vDash \neg s\}$$

Where W is the set of all possible worlds. So, for any *logically true* sentence $\top$ (=true for all the possible worlds), $\neg\top$ (false) will exclude any possible world:

$$\mathrm{Cont}(\top) = \varnothing$$

Then, for any contradictory sentence $\perp$, $\neg\perp$ will include *any possible world*, so that BCP holds, i.e.,

$$\mathrm{Cont}(\perp) = W$$

In Carnap & Bar Hillel terms, "a self-contradictory sentence asserts too much: it is too informative for being true" [44, p. 229]. Effectively, it is well-known also to common-sense that tautologies have no information content. What is paradoxical for common-sense is that contradictions have the maximum information content. For logicians, however, who know the famous Pseudo-Scotus law, according to which anything can be derived from contradictions, this conclusion is not surprising, once we have defined the information content of a sentence *s*, Cont(*s*), as the set of all sentences (possible worlds) belonging to the same Universe W of the theory excluded by *s*.

Of course, the limit of CSI consists in its abstraction, namely in the *logical* notion of truth and on the *a priori* probability that it supposes. Surprisingly, but not contradictorily, it is just a supposition of *a logical notion of truth* (= true in all possible contexts, or "worlds" in modal logic terms) that makes impossible using truth as a necessary condition of meaningfulness in CSI.

What makes interesting the TSSI of Floridi and followers is that it offers a theory and measures of the semantic information for *contingent* and not *necessary* propositions. Namely, for propositions that are not *logically* true, i.e., true for all possible worlds, like, on the contrary, both the tautologies (i.e., the logical laws) and/or the general ontology propositions are – i.e., true for whichever "being as being". Namely, both the propositions of all empirical sciences, and the propositions of specific ontologies are *true* for objects *actually* existing (or *existed*, or that *will exist*) only in *some* possible worlds – in the limit *one*: the actual, "present" world. In other terms, the scientific and ontological theories are "models" (i.e., theories true only for a limited domain of objects), precisely because both have a semantic content, differently from tautologies. I developed elsewhere [53, 54] a formal ontology of the QFT paradigm in natural sciences, in which this notion of truth is logically and ontologically justified, alternative to Carnap's logical atomism. I.e., alternative to the formal ontology of Newtonian paradigm in natural sciences, on which both CSI and BCP depend.

Hence, it is highly significant developing a *theory* and a *measure* of information content such as TSSI, compatible with what S. Sequoiah-Grayson defines as the *Contingency Requirement of Informativeness* (CRI), supposed in TSSI. Unfortunately, a requirement such as CRI cannot be *supposed*, but only *justified*, as G. Dodig-Crnkovich indirectly emphasizes in her criticism to TSSI [55], and this is the limit of TSSI. In fact, the CRI states [51]: «A declarative sentence *s* is informative *iff* *s* individuates at least some but not all w_i from W (where $w_i \in W$)». Sequoiah-Grayson recognizes that CRI in TSSI is an idealization. However, he continues,

> «Despite this idealization, CRI remains a convincing modal intuition. For a declarative sentence *s* to be informative, in some useful sense of the term, it must stake out a claim as to which world, out of the entire modal space, is in fact the actual world».

This requirement is explicitly and formally satisfied in the formal ontology of the "natural realism" as alternative to the "logical atomism" of CSI [53, 54]. Effectively the main reason, Floridi states, leading him to defend the TSSI is that only such a theory having truthfulness as *necessary condition* of meaningfulness can be useful in an epistemic logic. In it, indeed, the entire problem consists in the justification of the passage from belief as "opinion" to belief as "knowledge", intended as a *true* belief.

That in TSSI is operating a CRI it is evident from the "factual" character of the semantic information content in it, and of its probabilistic measure. Starting from the principle that semantic information σ has to be measured in terms of distance of σ from w, we have effectively four possibilities. Using the same example of Floridi [50, p. 55ff.], let us suppose that there are exactly three people in the room: this is the situation denoted in terms of the actual world w. The four possibilities for σ as to w are:

(T) There are *or* there are not people in the room;
(V) There are some people in the room;
(P) There are three people in the room;
(F) There are *and* there are not people in the room.

By defining θ as the distance between σ and w, we have: $\theta(\mathrm{T}) = 1$; $\theta(\mathrm{V}) = 0.25$ (for the sake of simplicity); $\theta(\mathrm{P}) = 0$; $\theta(\mathrm{F}) = -1$. From this relations it is possible to define the *degree of informativeness* ι of σ, that is:

$$\iota(\sigma) = 1 - \theta(\sigma)^2$$

The graph generated by the equation above (see Figure 1) shows as θ ranges from the necessary false (F) (= contradiction), to the necessary true (T) (= tautology), both showing the maximum distance from the contingent true (P).

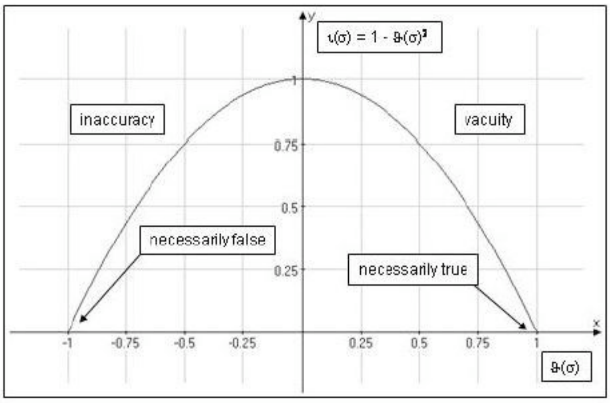

Figure 1. Degree of informativeness. From [50, p. 56].

To calculate the quantity of semantic information contained in σ relative to $\iota(\sigma)$ we need to calculate the area delimited by the equation above, that is, the definite integral of the function $\iota(\sigma)$ on the interval [0, 1]. The maximum amount of semantic information we denote as α is of course carried by (P) whose $\theta = 0$, that is, generalizing to σ, we have:

$$\int_0^1 \iota(\sigma)dx = \alpha = \frac{2}{3}$$

On the contrary, the amount of vacuous information, we denote as β, is also a function of θ. More precisely it is a function of the distance of θ from w, i.e.:

$$\int_0^\theta \iota(\sigma)dx = \beta$$

It is evident that in the case of (P) $\beta = 0$. From α and β, it is possible to calculate the amount of semantic information carried by σ, i.e. γ, as the difference between the maximum information that can be carried in principle by σ and by the vacuous information carried effectively by σ, that is, in bit:

$$\gamma(\sigma) = \log(\alpha - \beta)$$

Of course in the case of (P):

$$\gamma(\mathrm{P}) = \log(\alpha)$$

That confirms CRI in TSSI, that is, the proposition contingently true, namely, denoting the actual situation w and/or expressing the true knowledge of w, is carrying the maximum of semantic information about w.

5 CONCLUSION

It is evident that the WF, defining in QFT the matching between the double force field elicited in the brain by the external stimulus according to the DDF principle described above, can be superposed to the graph of Figure 1, *being both defined on quasi-probabilities*. At the same time, a computation based on DDF in QFT corresponds to a dynamic procedure for redefining the "basic symbols" for matching a given singular situation. In this way, not only it is confirmed what we said that the information associated to WF is a *semantic information* and not purely syntactic, as it is the case of TM, and of its implementation in QM systems (QTM). This is much more significant today, when an artificial simulation of brain "natural computation" based on phase coherent domains, and hence on QFT principles, has been successfully implemented in the so-called "fractal-frequency computing" approach, probably inaugurating a new, exciting age in computing theory and applications [56].

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