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The Doubling of the Degrees of Freedom in Quantum Dissipative Systems, and the Semantic Information Notion and Measure in Biosemiotics †

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1. The Semantic Information Issue and Non-Equilibrium Thermodynamics

In the recent history of the effort for defining a suitable notion and measure of semantic information, starting points are: the "syntactic" notion and measure of information H of Claude Shannon in the *mathematical theory of communications* (MTC) [1]; and the "semantic" notion and measure of *information content or informativeness* of Rudolph Carnap and Yehoshua Bar-Hillel [2], based on Carnap's theory of intensional modal logic [3].

The relationship between H and *the notion and measure of entropy S* in Gibbs' statistical mechanics (SM) and then in Boltzmann's thermodynamics is a classical one, because they share the same mathematical form.

We emphasize that Shannon's information measure is the information associated to an event in quantum mechanics (QM) [4]. Indeed, in the classical limit, i.e., whenever the classical notion of probability applies, S is equivalent to the QM definition of entropy given by John Von Neumann. Indeed, he prompted Claude Shannon to call "entropy" the statistical measure of information H. As emphasized by Shannon himself [1] (p. 3), the "syntactic" and not "semantic" character of H and its connection with entropy S in SM and QM, is that the "informativeness" is associated with the "uncertainty removal". This is determined with the occurrence of a symbol in MTC and/or of an event in SM or in QM [4].

Another point is the *classical semantic information* (CSI) theory in the logic of Carnap and Bar-Hillel [2]. There the intension of a given sentence corresponds to the set of "possible worlds" (or "contexts", defined according to Carnap's intensional modal logic [3]) that make the sentence true. This theory leads to the famous Carnap and Bar-Hillel paradox, separating the semantic information content of a given declarative sentence from the notion of logical truth. In fact, because a logical truth is true in all possible worlds, $w \in W$, i.e., it does not exclude any world, it is empty of any semantic content (effectively, it is a tautology). Therefore, the information content of a sentence s, Cont(s), is defined in CSI as the set of all sentences (possible worlds) belonging to the same universe W of the theory excluded by s.

The paradoxical conclusion is that the maximum semantic content is always a false (i.e., a contradictory) sentence, because it excludes any possible world. In other words, "a self-contradictory sentence asserts too much: it is too informative for being true" ([2], p. 229).

To correct this separation between truthfulness and informativeness in CSI, by vindicating that a consistent theory of semantic information must concern "well-formed, meaningful, and truthful data", Luciano Floridi proposed his *theory of strong semantic information* (TSSI) [5]. This measure is based on a "contingency requirement of informativeness", and then on the notion of *c*ontingent truth in modal logic (= true for some possible worlds $(w_i \in W)$), so that, "a declarative sentence *s* is informative if *s* individuates at least some (possibly one: the actual world w_0) but not all w_i from W [6]. Now, the probabilistic measure of informativeness σ associated with a sentence *s* proposed by Floridi ([5], p. 55ff.) is a measure of some sort of "distance" θ of σ from the actual world w_0, so that it is possible to calculate the degree of informativeness $\iota(\sigma) = 1 - \theta(\sigma)^2$, where the maximum of informativeness is of course when $\theta(\sigma) = 0$. In this way, both for the "always true" proposition ($s \lor \neg s$) or a tautology of CSI, for which $\theta(\sigma) = 1$, and for the "always false" proposition of CSI ($s \land \neg s$), for which $\theta(\sigma) = -1$, the degree of informativeness is null, i.e., $\iota(\sigma) = 0$, while it is maximum, i.e., $\iota(\sigma) = 1$, only for the "contingently true" proposition*s* where $\theta(\sigma) = 0$, because it refers to the actual world w_0.

The problem of the TSSI measure of informativeness is twofold.

On the one hand, it supposes the existence of negative probabilities (between −1 and 0) or "pseudo-probabilities", violating the first axiom of the three ones of Andrey N. Kolmogorov's axiomatic theory of probabilities[1] [7].

On the other hand, TSSI effectively proposes a theory of semantic information independent of the entropy measure in physics and of the information-theoretic approach to universal computations. This second limitation of TSSI is emphasized by Pieter Adriaans [8], who suggests that more interesting would be the development of a theory of "non-equilibrium entropy" ([8], p. 45). Namely, the study of the entropy (the information, and then the universal computations) associated with the thermodynamics of dissipative systems moving through different phases and staying persistently in far-from-equilibrium conditions [9,10].

Antonio Damasio connected the intentional aboutness, or reference-to-object typical of the phenomenological approach, to meaning in psychology [11], primarily to biology, and more specifically to the fundamental notion of *homeostasis* [12], which expresses much more than the simple "equilibrium" in thermodynamics. He recalls very appropriately that equilibrium in biology is a synonym of "death" and of the simple linear "energy balance". In fact, homeostasis refers in biology to the non-linear phenomena of "self-regulation", ranging from the molecular, to the cellular, to the tissue levels, and so on, till it involves the whole organism and its environment (see the I part of [12], pp. 11–69 for a review of this notion). For instance, the complex self-regulation processes collected under the term *epigenetics*, studying "heritable changes caused by the activation and deactivation of genes without any change in the underlying DNA sequence of the organism" [13], evidently depends on the interaction between DNA/RNA sequences and the inner/outer chemical environment of cells. This confirms that whichever organism is a dissipative system, not only for its metabolism, but in its most basic component, the genome. This makes the relationship between dissipative systems and semantic information even more interesting, as well as for a proper understanding of the notion of "genetic code", or more properly of "epigenetic code", or "organic code" in *biosemiotics* [14,15].

2. Dissipative Systems, the Doubling of the Degrees of Freedom, and the Semantic Information Measure in QFT

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[1] Let $(\Omega, \mathcal{F}, P)$ be a "measure space" with *P* being a probability of some event *E* denoted as $P(E)$ and $P(\Omega) = 1$. Then, $(\Omega, \mathcal{F}, P)$ is a "probability space", with sample space Ω, event space $\mathcal{F}$, and probability measure *P*. (1) *First axiom*: "The probability of an event is a non-negative real number: $P(E) \in \mathbb{R}, P(E) \geq 0; \quad \forall E \in \mathcal{F}$. (2) *Second axiom*: "The probability that at least one of the elementary events in the whole sample space will occur is 1 ('unit measure' assumption, or 'unitarity' in physics)": $P(\Omega) = 1$. (3) *Third axiom:* "Any countable sequence of disjoint (mutually exclusive) events $E_1, E_2, \ldots$ satisfies $P(\cup_{i=1}^{\infty} E_1) = \sum_{i=1}^{\infty} P(E_i)$ (= 'σ-additivity' assumption). We note that *quasi-probability distributions* relax this axiom. In quantum physics they are typical of coherent states (phases*): $P(|\alpha_0\rangle)$, where *P* is a delta function: $P(\alpha, \alpha^*) = \delta^2(\alpha - \alpha_0)$, e.g., in the Wigner function in QM and QFT systems.

Since the publication of its preprint at the end of 2019, a paper just published on *Nature Communications* [16] excited the debate among scientists because it demonstrated, in an experiment of matter-wave interferometry, quantum self-interferences, similar to the most famous "double-slit" experiment in QM, of a natural polypeptide, the *gramicidin A1*, a linear antibiotic polypeptide composed of 15 amino acids. The novelty is that, despite the wave-like behavior already being demonstrated for large molecules, such a behavior was demonstrated here for fragile biomolecules, "the building blocks of life", at room temperature. The excited comment published on the site of *MIT Technology Review* was that:

> This work paves the way for the study of the quantum properties of biomolecules and sets the scene for experiments that exploit the quantum nature of enzymes, DNA, and perhaps one day simple life forms such as viruses [17].

The two theoretical questions that ignited the debate are how to justify the quantum wavelike properties of *macroscopic* complex objects, such as fragile biomolecules, and how to justify the quantum nature of biological processes evidently occurring at *room temperature*. We propose that the proper theoretical framework for an answer to the questions, giving at the same time a measure of semantic information, is provided by QFT [18–20] and specifically by the QFT formalism of the *doubling of the degrees of freedom* (DDF) for finite temperature [21] and dissipative systems [22].

The "two-slit experiment", to which the just quoted paper on the polypeptide refers to, has been indeed described by using the Wigner function $W(x, p)$ which provides an immediate example of the powerfulness of the DDF formalism. Use of $W(x, p)$ requires in fact the doubling of the canonical set of coordinates (x, p) by introducing $x_+ = x + y/2$ and $x_- = x - y/2$, so that the doubled set of coordinates (x_+, p_+) and (x_-, p_-) (or (x, p_x) and (y, p_y)) describes the system. The result [9,23] is that the diffraction pattern, displaying the quantum wave-like behavior, occurs only when the particle goes forward (in time) through one slit and backward (in time) through the other one, namely $|x_+(t) - x_-(t)| > 0$. On the contrary, when $x_+(t) = x_-(t)$, then no diffraction pattern appears on the screen, i.e., the particle behaves classically.

The DDF plays a crucial role in the QFT of dissipative systems and whenever one deals with *phase transitions in non-equilibrium systems*. The "phases", or space of the states, through which these systems, including biological ones, evolve in time, are physically *inequivalent representations* of the canonical commutation relations (for bosons, or anticommutation relations for fermions; CCR or CAR, respectively), and therefore unitarily inequivalent representations of the CCR (or CAR) (the QFT *foliation* of the space of the states). The study of dissipative systems thus cannot be carried on within QM since there all the representation of the CCR (CAR) are *unitarily equivalent* (as stated by the von Neumann theorem). The proper framework is the one of QFT [9,24], more precisely *finite temperature QFT*.

This leads us again to DDF, as realized in *Thermo Field Dynamics* (TFD) formalism [21,25] (see also [9], chs. 5–6; [6]). In TFD it appears clearly that the role played by the DDF is to include in the description the thermal bath, or environment, in which the system is embedded. In this way, the global system (the system under study and its environment) is a closed system and the canonical formalism of QFT can be used. This is a central point in our discussion: the *openness* of finite temperature (equilibrium) systems, of dissipative systems (finite temperature non-equilibrium systems, including biological systems), and of the semantic information measure *all require* the inclusion of the *environment* (the *context* in CSI and/or the *actual world* in TCSSI) in the formalism, in order to be formulated within the available canonical formalism. This one is, indeed, devised to account only for *closed* systems. Without entering technical questions, we only mention that the DDF is realized by adopting the *non-commutative Hopf algebra* – recalling that the *non-commutativity* of the algebras is essential for granting logical *ordering* in topological computer science [10] –, and by introducing the tensor product of the system Hilbert space and the environment Hilbert space. It can be also shown that the equilibrium TFD is equivalent to the C* algebra formalism.

Schematically, we can say that pillars of QFT [9,21,25] are:

1. *The Haag theorem* [26] stating the unitary inequivalence between the interacting field representations of the CCR (CAR) and the physical field representations in terms of which observables are described. It implies that, within the resulting non-perturbative formalism, the same basic dynamical interaction may be realized in infinitely many unitarily (i.e., physically) inequivalent representations. Of course, this constitutes a necessary condition for a QFT modelling of non-equilibrium systems evolving over trajectories through different phases (phase transition processes).

2. The use of the *Bogoliubov transformations* [27] mapping one representation into another unitarily inequivalent one, and thus a boson condensate into another physically inequivalent one. Substantially, this shows the isomorphism of the realizations of the CCR (CAR) in the different representations including their respective topologically non-trivial properties (the corresponding C* algebras).

3. The *spontaneous breakdown of symmetry* (SBS), by which the system ground state is not invariant under the full continuous symmetry group of the basic dynamical equations (the Lagrangian). In such a case, the Goldstone theorem [28–30] states the dynamical formation of long-range correlations among the system elementary constituents. The associated boson quanta are called Nambu-Goldstone (NG) quanta. Their condensation in the vacuum (the system ground state) manifests itself in the observable ordered patterns (vacuum structure). For example in ferromagnets, NG are the spin wave quanta or magnons; in crystals, NG bosons are the phonons, quanta of the elastic waves; in polar systems, NG are dipole wave quanta, as e.g. in biological systems where dipole waves span the system [18–20,31]; in superconductors, NG are the Cooper pairs, etc. These NG quanta do not appear in the spectrum of physical excitations in the case that a gauge field (e.g., the electromagnetic field) is present, although they are still responsible of the vacuum structure (the Anderson-Higgs-Kibble mechanism) [9,21]. Different condensates are identified by different values of the "order parameter" (e.g., the magnetization in the ferromagnetic case), which thus acts as a *label* for the unitarily inequivalent representations corresponding to the different condensates. Therefore, the order parameter identified with the condensation density N turns out to be a dynamic robust memory code in complex systems, biological [18,32] and neural systems before all [19,20].

4. The *coherent* vacuum structure *dynamically* generated in the condensation of long-range NG boson modes (therefore as an effect of SBS, see point 3). Coherence is observed to occur in a wide range of temperatures; diamond crystals at atmospheric pressure burn in absence of oxygen at about 3545 °C; in the presence of oxygen at 800 °C; the critical temperature (Curie temperature) for the loss of magnetization of iron is about 770 °C; $T_c = -252$ °C is the critical temperature for some superconductors. The observed high stability of ordered patterns and their dynamical origin in the SBS phenomenon thus shows that the coherent vacuum structure is protected by the unitarily inequivalence among representations in QFT (in QM the decoherence phenomenon may occur since, due to the von Neumann theorem, all the representations may be related by unitary transformations washing out coherent properties). Moreover, coherence is responsible of the transition from the *microscopic* behavior of the system components to the *macroscopic* behavior. This means that the notion of *macroscopic quantum system* may be thus introduced by considering that characteristic macroscopic properties have their necessary physical justification at the *microscopic level* of QFT. For example, the order parameter is a classical field since its value is independent of quantum fluctuations. In a coherent state the ratio of quantum fluctuations to the condensate number is indeed proportional to $1/|\alpha|$, where $|\alpha|$ is the modulus of the coherence strength. A further property of coherence manifest as *entanglement* among the condensate components [9,22,33].

All of this leads us again to consider the *quantum field-particle duality* considered above. The observed macroscopic properties of quantum origin are manifestations of "the in-phase behavior" of long-range NG boson condensation. These NG modes enter in the formal mathematical description as "phase modes" and coherence consists in a very much reduced phase uncertainty $\Delta\varphi$, which due to the number-phase uncertainty relation, corresponds to a huge value on the number uncertainty ΔN, which is only possible when N is very large (infinite in the limit $\Delta\varphi \to 0$). This brings us back to the need to use *fields*, which, by definition, are infinite number of degrees of freedom systems. The

suggestion is thus that a possible answer to the issues recently addressed in [16] must be searched in the framework of QFT, being out of reach in QM.

3. Conclusions

To conclude, the entropy measure associated with the DDF modeling of dissipative quantum systems can be defined as a measure of the *system-environment entanglement* ([9], pp. 212–215) to be the measure of *semantic information* we are searching for. See [6,10] for a discussion about this notion and its relationship with the non-commutative deformed Hopf coalgebras. Along the lines there depicted, an information-theoretic approach to quantum computing based on a "doubled" and then "semantic" qubits may be formulated. By the help of Pauli matrices, integer numbers and therefore Krönecker delta (not Dirac delta) may be dealt with [10]. On these matrices, we can implement directly the "quantum *Eigenlogic*" [34]. That is, a logic of operators where the truth-table semantics is provided directly by the eigenvalue structure of Pauli matrices. As recently demonstrated, this can be directly related to the *universality* of the quantum gates [34], so to grant that the semantic information according to the DDF approach, satisfies not only in *a physical* but also in a *logical consistent way* the TSSI requirement of a "well-formed, meaningful, and truthful" information processing. As a first step, to implement this approach toward the realization of a QFT processor, a group of researchers (at the Labs of the Institute of Microelectronics and Microsystems (IMM) of the Bologna Research Area of the Italian National Research Council (CNR)) has developed a patented electro-optical microchip. This is a fully programmable micro-diffraction grating (PMDG), based on the control over the coherent light waveforms produced by one mini-laser. The control is exerted by electric fields through electrodes on the top of the waveguides (till 10^3 (or actually 10^2) guides in 2 cm^2), hollowed into the electro-optical crystal substrate, and deposited in planar technology on a silicon plate. In this way, it is possible to perform *full control over the electromagnetic waveforms,* their phase shifts (see [35,36]), and their phase interferences to obtain qubits without the use of statistics of entangled single photon polarization states. Indeed, by using suitable DAC devices, it is possible "to depict" any classical or quantum logical port [34] directly on the dynamic substrate of entangled photon condensates, i.e., of interfering electromagnetic waves.

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