Chapter 1
Quantum Effects in Linguistic Endeavors

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1 A Methodological Premise

Any scientific description entails a complementarity between its Extension and Detail. The intrinsic limitation of a TOE (Theory Of Everything) is its inability to predict the detailed operations of single individuals, even though it provides global explanations. The two aspects of a scientific description, namely, Extension (E) and Detail (D), result mutually conflicting; this may be symbolically condensed by an uncertainty relation as

$$\Delta E \times \Delta D > C, \tag{1.1}$$

where Δ denotes the amount of uncertainty and C is a suitable constant related to the descriptive theory. For instance, a successful approach explaining the cosmic evolution from the Microwave Background to the Galaxy formation can not explain the details of planet differentiation, why e.g. the Earth has a magnetic field providing the Van Allen belt shield from solar particles, or the water necessary for life. Two different sets of foundational principles must be introduced in order to explain the two classes of phenomena, that is, the fundamental objects of Planetology and their mutual interactions must be introduced appropriately and cannot be derived from the general principles of Cosmology.

In a similar way, a general powerful QFT (Quantum Field Theory) approach has been developed to explain the brain and memory organization starting from the collective organization of water dipole quanta in living matter [1, 2].

Even though, the puzzling fact that in a human linguistic endeavor, words are mutually influencing through their meanings, so that an "infinite use emerges from

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a finite amount of resources" [3] has no explanation whatsoever in the QFT of brain and memory, that has no tools to differentiate the human brain behavior from that of other animals.

In this work, we present a specific theoretical approach that provides that sound explanation for the linguistic performances not achievable in the QFT of brain and memory.

2 Two Separate Cognitive Processes

In [4] I have analyzed two distinct moments of human cognition, namely, *apprehension* (A) whereby a coherent perception emerges from the recruitment of neuronal groups, and *judgment* (B) whereby memory recalls previous (A) units coded in a suitable language, these units are compared and from comparison it follows the formulation of a judgment.

The first moment (A) has a duration around 1 s; its associated neuronal correlate consists of the synchronization of the EEG (Electro-Encephalo-Graphic) signals in the so-called gamma band (frequencies between 40 and 60 Hz) coming from distant cortical areas. It can be described as an interpretation of the sensorial stimuli on the basis of available algorithms, through a Bayes inference.

Precisely [4], calling h ($h =$ hypothesis) the interpretative hypotheses in presence of a sensorial stimulus d ($d =$ datum), the Bayes inference selects the most plausible hypothesis h^*, that determines the motor reaction, exploiting a memorized algorithm $P(d|h)$, that represents the conditional probability that a datum d be the consequence of an hypothesis h. The $P(d|h)$ have been learned during our past; they represent the equipment whereby a cognitive agent faces the world. By equipping a robot with a convenient set of $P(d|h)$, we expect a sensible behavior.

The second moment (B) entails a comparison between two apprehensions (A) acquired at different times, coded in a given language and recalled by the memory. If, in analogy with (A), we call d the code of the second apprehension and h^* the code of the first one, now—at variance with (A)—h^* is already given; instead, the relation $P(d|h)$ which connects them must be retrieved, it represents the conformity between d and h^*, that is, the best interpretation of d in the light of h^*. Thus, in linguistic operations, we compare two successive pieces of the text and extract the conformity of the second one on the basis of the first one. This is very different from (A), where there is no problem of conformity but of plausibility of h^* in view of a motor reaction. Let us make two examples: a rabbit perceives a rustle behind a hedge and it runs away, without investigating whether it was a fox or just a blow of wind. On the contrary, to catch the meaning of the 4-th verse of a poem, we must recover the meaning of the 3-d verse of that same poem, since we do not have a-priori algorithms to provide a satisfactory answer. Once the judgment, that is, the $P(d|h)$ binding the codes of the two linguistic pieces in the best way, has been built, it becomes a memorized resource to which to recur whenever that text is presented again. It has acquired the status of the pre-learned algorithms that rule (A). However—at variance with mechanized resources—whenever we re-read the same poem, we can grasp new meanings that enrich the previous judgment $P(d|h)$. As in any exposure to a text (literary, musical, figurative) a re-reading improves our understanding. (B) requires about 3 s and entails *self-consciousness*, as the agent who expresses the judgment must be aware that the two successive apprehensions are both under his/her scrutiny and it is up to him/her to extract the mutual relation. As a fact, exploring human subjects with sequences of simple words, we find evidence of a limited time window around 3 s [5, 6], corresponding to the memory retrieval of a linguistic item in order to match it with the next one in a text flow (be it literary, or musical, or figurative).

At variance with (A), (B) does not presuppose an algorithm, but rather it builds a new one through an ***inverse Bayes procedure*** [7]. This construction of a new algorithm is a sign of *creativity and decisional freedom*. Here the question emerges: can we provide a computing machine with the (B) capacity, so that it can emulate a human cognitive agent? [8]. The answer is NOT, because (B) entails non-algorithmic jumps, insofar as the inverse Bayes procedure generates an ad hoc algorithm, by no means pre-existent.

The five figures that follow and their captions explore in detail these aspects [4] (Figs. 1.1, 1.2, 1.3, 1.4 and 1.5).

After having shown evidence of this short term memory window bridging successive pieces of a linguistic text, we formulate a quantum conjecture. This conjecture fulfills two needs, namely, (1) explaining the fast search in a semantic space, whose sequential exploration by classical mechanisms would require extremely long times, incompatible with the cadence of a linguistic presentation [9]; (2) introducing a fundamental uncertainty ruled by a quantum constant that yields a decoherence time fitting the short term memory window. The memory enhancement associated with linguistic flows is an exclusively human operation, not applicable to a cognitive agent that operates ***recursively***, exploiting algorithms already stored in the memory. If the conjecture will be confirmed, the quantum mechanism would explain the a-posteriori construction of novel interpretational tools.

Classifying the information content of spike trains, an uncertainty relation emerges between the bit size of a word and its duration. This uncertainty is ruled by a quantum constant that can be given a numerical value and that has nothing to do with Planck's constant. A quantum conjecture might explain the onset and decay of the memory window connecting successive pieces of a linguistic text. The conjecture here formulated is applicable to other reported evidences of quantum effects in human cognitive processes, so far lacking a plausible framework since no efforts to assign a quantum constant have been associated.

Models of quantum behavior in language and decision taking have already been considered by several Authors but without a dynamical basis, starting from 1995 [10, 11]; and over the past decade [12]. Most references are collected in a recent book [13]. None of these Authors worries about the quantum constant that must replace Planck's constant. However, a quantum behavior entails pairs of incompatible variables, whose measurement uncertainties are bound by a quantization constant, as Planck's in the original formulation of Heisenberg. One can not apply a quantum formalism without having specified the quantum constant rul-

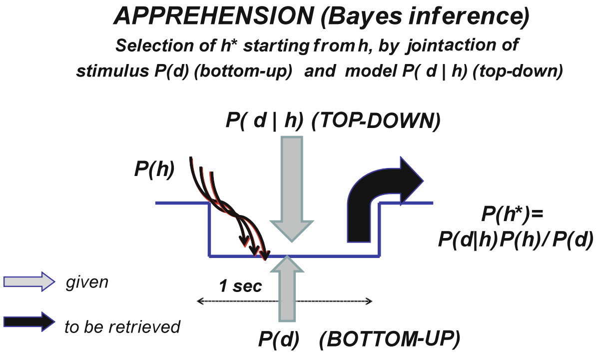

Fig. 1.1: Apprehension as a Bayes inference. One formulates a manifold of hypotheses; each one provides a datum through the top-down conditional probability; only the hypothesis that generates the actual datum (bottom-up) is the plausible one

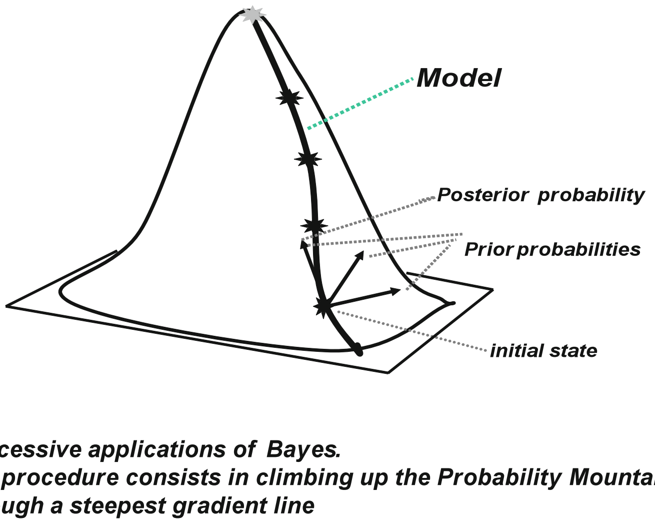

Fig. 1.2: Recursive application of Bayes is equivalent to climbing a probability mountain, guided by the Model, that is, the conditional probability that an hypothesis generates a datum. This strategy is common e.g. to Darwin evolution and to Sherlock Holmes criminal investigation; since the algorithm is unique, it can be automatized in a computer program (expert system)

ing the formalism. For this reason, all reported quantum attempts must be considered flawed, because (1) either they overlook the need for a quantization constant [10–12], or (2) use Planck constant and consequently arrive to very short decoherence times, incompatible with cognitive processes [13–16].

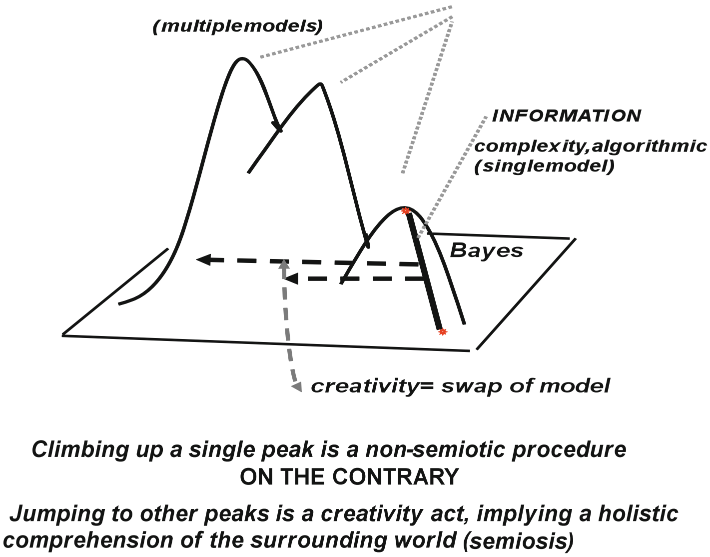

Fig. 1.3: Comparison of two different complexities, namely, (1) the algorithmic complexity, corresponding to the bit length of the program that enables the expert system to a recursive Bayes; and (2) semantic complexity, corresponding to the occurrence of different models (provided they are countable); in fact they are not, because we will see that different meanings result from a quantum exploration

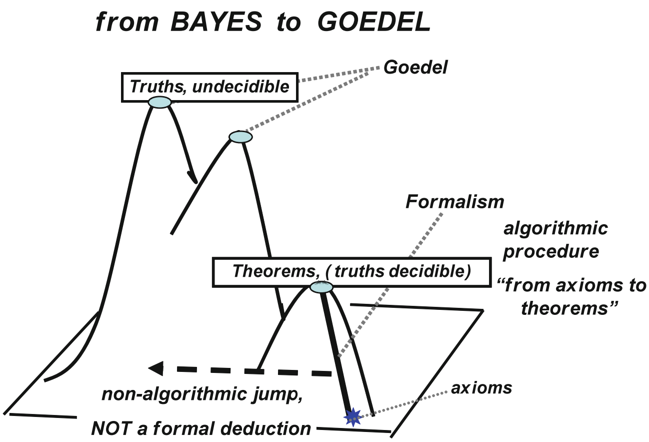

Fig. 1.4: The semantic complexity explains the criticism of K. Gödel to Hilbert's formal deduction of theorems as the only way to extract truths from a body of axioms

After summarizing in Sect. 3 the main difference between (A)-perception and (B)-linguistic processes, we devote Sect. 4 to the quantum aspects of an interrupted

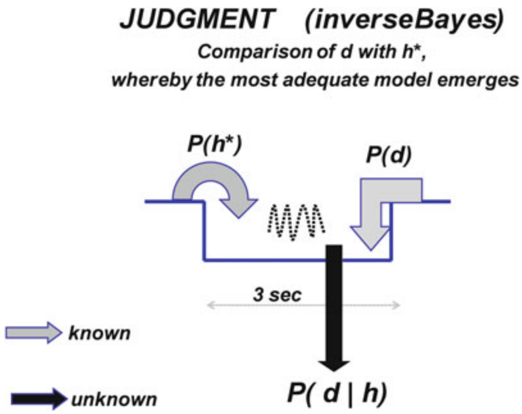

Fig. 1.5: The inverse Bayes procedure that occurs in linguistic endeavors, whereby a previous piece of a text is retrieved by the short term memory and compared with the next one: the appropriate conditional is no longer stored permanently but it emerges as a result of the comparison (judgment and consequent decision)

spike train, that provide a non-Newtonian quantization suitable for the foundation of quantum linguistic processes.

3 Perceptions vs Linguistic Processes

To summarize the previous arguments, we have distinguished between two different cognitive processes, namely,

- (A) *perception*, whereby a sensorial stimulus is interpreted in terms of "models", or behavioral patterns, already stored in the long term memory; the interpreted stimulus elicits a motor reaction; duration from a few hundred milliseconds up to 1 s; adequately described as a Bayesian procedure; common to all animals, and
- (B) *linguistic processes*, only human, whereby a sequence of pieces, coded as words of the same language, are sequentially presented to the cognitive agent; each piece is interpreted in terms of the previous one recovered by the short term memory; such a comparison must be performed within 3 s; otherwise, the sequence must be repeated.

Focusing on (B), a decision, or *judgment*, is the interpretation of the last piece based upon the meanings of the previous one. Scanning all possible meanings of each piece entails a fast search process that requires a quantum search.

Plenty of approaches have tackled quantum-like aspects of language processing [10–13]; however these approaches either did not discuss limitations due to a quantum constant, hence, they are purely formal without a physical basis or they refer to the quantum behavior of Newtonian particles [14, 15] and hence are limited by a coherence time estimated around 10^{-14} s, [16, 17] well below the infra-sec scale of the cognitive processes [18].

4 A Novel Aspect of Quantum Behavior

Standard quantum physics emerges from the Newtonian physics of a single particle. Refer for simplicity to 1-dimension. The uncertainties of position x and momentum p obey the Heisenberg condition

$$\Delta x \Delta p \geq \hbar. \tag{1.2}$$

All quantum formalism is a consequence. For instance, comparison with the Fourier condition

$$\Delta x \Delta k \geq 1. \tag{1.3}$$

suggests the De Broglie relation

$$k = \frac{p}{\hbar}, \tag{1.4}$$

whence the single particle interference, which contains the only quantum mystery [19] and Schrödinger wave equation. In the x, p space, instead of Euclidean points $\Delta x = 0$, $\Delta p = 0$, we have uncertainty rectangles; thus the uncertainty areas of two separate particles can overlap: this is the origin of *entanglement*.

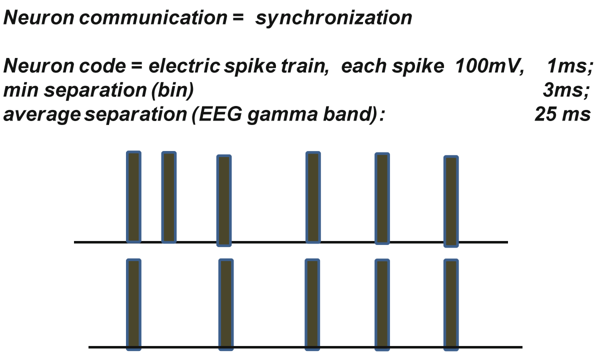

Fig. 1.6: Two neural spike trains; synchronization missed for an extra-spike in the upper train

Now, let us consider a non-Newtonian phenomenon consisting of a temporal train of identical spikes of unit area and duration $\tau_b = 3$ ms (bin) positioned at unequal times. This is a sound model for the electrical activity of a cortical neuron [20, 21]. The corresponding signal is a binary sequence of 0's and 1's, depending on whether a given bin is empty or filled by a spike. Spike synchronization, i.e. temporal coincidence of 0's and 1's, is considered as the way cortical neurons organize in a collective state [22] (Fig. 1.6).

Each cortical neuron has two ways to modify its spike occurrence, namely, either coupling to other cortical neurons or receiving signals from extra-cortical regions.

Let us take a processing time $T = 300\,\text{ms}$, then, the total number of binary words that can be processed is $P_M = 2^{300/3} \cong 10^{33}$. At the end of a computational task a decision center (called GWS = global workspace [23, 24]) picks up the information of the largest synchronized group and—based upon it—elicits a decision.

In the ***perceptual*** case (A), the cognitive action combines a bottom-up signal provided by the sensorial organs with a top-down interpretation provided by long term memories stored in extra-cortical areas [25].

In the ***linguistic*** case (B), the comparison occurs between the code of the second piece and the code of the previous one retrieved by the short term memory. Here, we should consider a fact which so far had escaped a full explanation. Namely,spikes occur at average rates corresponding to the so called EEG gamma band (say, around 50 Hz, that is, average separation 20 ms) [20]. However, superposed to the gamma band, there is a low frequency background (theta band, around 7 Hz), which controls the number of gamma band bursts [26]. We show that interruption of a spike train introduces a quantum uncertainty, hence an entanglement among different words. This entanglement provides a fast quantum search of meanings, that in classical terms would take a much longer time.

The theta-gamma cross-modulation corresponds to stopping the neural sequence at $\Delta T \leq T$. As a result, all spike trains equal up to ΔT, but different by at least one spike in the interval $T - \Delta T$, provide an uncertainty cloud ΔP such that [27, 28]

$$\Delta P = 2^{(T-\Delta T)/\tau} = P_M\, 2^{-\Delta T/\tau} \tag{1.5}$$

Thus we have a peculiar uncertainty of exponential type between spike information P and duration T, that is,

$$\Delta P \cdot 2^{\Delta T/\tau} = P_M \tag{1.6}$$

By a variable change

$$y = 2^T \tag{1.7}$$

we arrive to a product type uncertainty relation

$$\Delta P \Delta y = P_M \tag{1.8}$$

In the space (P, y) we have a Heisenberg-like uncertainty relation. Following the standard procedure of a quantum approach, we expect single particle interference and two particle entanglement in such a space.

For $\Delta P = 1$ (minimal disturbance represented by 1 spike) we have the *decoherence* pseudo time $\Delta y_d = P_M$. The corresponding decoherence time (in bins) is

$$decoherence\ time = \log_2\, P_M = 100\ (bins) \tag{1.9}$$

and going from bins to sec:

$$decoherence\ time = 0.3\,\text{s} \tag{1.10}$$

very far from the naive value of 10^{-14} s evaluated for Newtonian particles disturbed by the thermal energy $k_B T$ at T = room temperature [16].

5 Conclusions

To conclude, we stress the revolution brought about by the linguistic processes in the brain:

1. The quantum constant for spike number-duration uncertainty has nothing to do with Planck's constant, a new type of quantum behavior has to be considered; spike synchronization is a peculiar physical process that cannot be grasped in terms of Newtonian position-momentum.
2. The energy disturbance which rules the decoherence time is by no means $k_B T$ (k_B being Boltzmann constant and T the room temperature), but it is replaced by the minimal energy necessary to add or destroy a cortical spike. This energy corresponds to the opening along the axon of about 10^7 ionic channels each one requiring an $ATP \rightarrow ADP + P$ reaction involving 0.3 eV, thus the minimal energy disturbance in neural spike dynamics is around $10^8\, k_B T$ [29]. This is the

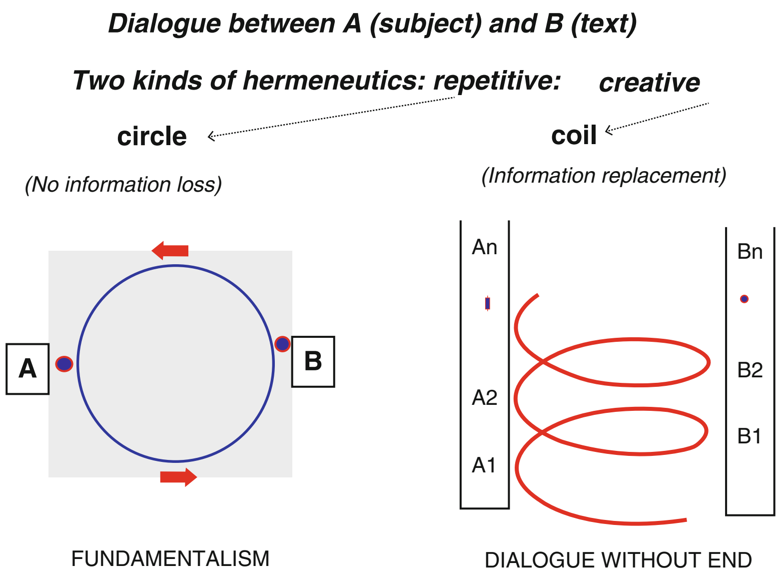

Fig. 1.7: Visual comparison between two kinds of interpretation of a text, or hermeneutics, namely, the CIRCLE, whereby the interpreter A attributes a finite and fixed set of meanings to the text B, and the COIL, whereby A captures some particular aspects of B and—based on that information—A approaches again the text B discovering new meanings

evolutionary advantage of a brain: to live comfortably at room temperature and be barely disturbed, as it were cooled at 10^8 the room temperature.

As for the interpretation (hermeneutics) of a cognitive experience (be it perceptual or linguistic), we represent in Fig. 1.7 the procedural interpretation by a computing machine (CIRCLE) against that of any human language (COIL).

As for the CIRCLE, in information science, an ***ontology*** is a formal definition of the properties, and interrelationships of the entities that exist for a particular domain of discourse. An ontology compartmentalizes the variables needed for some set of computations and establishes the relationships between them. For instance, the booklet of the replacement parts of a brand of car is the ontology of that car. The fields of artificial intelligence create ontologies to limit complexity and to organize information. The ontology can then be applied to problem solving. Nothing is left out; we call this cognitive approach "finitistic" as nothing is left out beyond the description.

On the contrary, in any human linguistic endeavor (be it literary, or musical or figurative) A starts building a provisional interpretation $A1$ of the text; whenever A returns to B, he/she has already some interpretational elements to start with, and from there A progresses beyond, grasping new aspects $B2$, $B3$ and hence going to $A2$ and so on (COIL). If B is not just a linguistic text, but another human subject, then B undergoes similar hermeneutic updates as A; this is a picture of the dialogical exchange between two human beings.

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