Communication Languages and Agents in Biological Systems

Subhash Kak

Summary. This chapter provides a general discussion of the hierarchy of languages and metalanguages that must be associated with a biological system. At the bottom of this hierarchy are physical structures whose behavior is governed by quantum mechanics. In order for this hierarchy to be valid, we postulate a language whose primitives are quantum mechanical objects. In a complementary relationship to this physical hierarchy is a hierarchy of languages where the quantum language resides at the top. We have shown how communication and cognitive agents may be conceived of as collectives of quantum particles.

INTRODUCTION

In biological systems there exist complex, non-linear structures and self-organized entities which cannot be described by models based on statistical approaches. Different scales (both spatial and temporal) must be considered when analyzing interactions and activity must be viewed as directed by agents. For example, in the processing in the human brain, there exist autonomous cognitive agents. The emergence of these agents, and the capacity for self-organization that they possess, must be viewed in the context of the evolutionary history of the biological system. Their self-organization requires strong dynamical non-linearity but this cannot be seen to occur due to macroscopic processes alone. Underlying these macroscopic processes are physical structures that have a quantum basis at the deepest level of description. The need to consider different kinds of objects, including quantum ones, in considering a general biological system from the perspectives of communication and complementarity was emphasized recently (Gautam

and Kak, 2013) and a theory to represent agents and memories as quantum collectives was also advanced (Kak, 2013a). In this chapter we review these results and also ask questions about the hierarchy of languages and metalanguages within the biological system.

The biological system may be examined at different scales and there exist layers for which a classical representation is appropriate and others for which we must choose description using quantum mechanics. The quantum formalism emerged in order to deal with fundamental complementarity in Nature and it is based on superpositions of mutually exclusive attributes with collapse to one of these upon measurement and associated with nonlocality, entanglement and coherent behavior. A determinant of nonlocality is entanglement and in certain situations the violation of Bell Inequalities identifies a process as being quantum mechanical (Kak, 2013b). In other words, there exist macroscopic, probabilistic tests that make it possible, in principle, to determine what representation is correct for the layer.

The molecular scale represents the usual divide between the classical and the quantum. Quantum effects appear if the concentration of particles $(N/V) \geq n_q$, where n_q is the quantum concentration, and the interparticle distance is indicated by the de Broglie wavelength $\lambda = h/p = h/(m_0 v)$, which for thermalized electrons in a non-metal at room temperature is about 8×10^{-9} m. The smallest molecules have size of about 10^{-10} m, but quantum effects can be exhibited at much larger distances by entangled photons and by virtual particles, which is how they have been proposed for certain biological processes. Macromolecule vibrations create quasiparticles and therefore quantum effects associated with such quasiparticles are contingent on specific macro-structures.

But the matter of the classical/quantum divide is not quite straightforward and it is not based on scale alone. While scholars upholding the orthodox Copenhagen Interpretation (CI) of quantum

mechanics assume a split between the quantum and the classical worlds, scholars not subscribing to this interpretation hold other positions. In CI, the wavefunction of the object, or the system, represents the expectations associated with the physical process and when the measurement is made there is a collapse in the expectation related to it within the mind of the observer. In this interpretation, the divide between the quantum and classical is largely based on the scale at which the system is being examined and it is appropriate to consider the biological system at the smallest-scale to be quantum mechanical.

In contrast to the above view in the Copenhagen Interpretation, the divide between the classical and the quantum is considered somewhat artificial in the many worlds interpretation (MWI) of quantum theory (Tegmark, 1998) which has become increasingly influential in many areas of physics, especially quantum computing. In this interpretation all systems are fundamentally quantum mechanical and if we do not see effects such as nonlocality and entanglement in a macroscopic system, that is a consequence of decoherence. MWI does not view the measurement process to be cause of the collapse of the wavefunction; rather this process is associated with conditions that cause decoherence (Zurek, 2003). The consideration of a biological system as fundamentally quantum mechanical is, therefore, natural in this interpretation.

In MWI the wavefunction is the primary reality and according to it a wavefunction may be assigned not only to biological and other physical systems, but to the universe itself. If CI is an inside-out view of the universe where the reality is constructed out of the perceptions of the experimenter, MWI is an outside-in view in which the mathematical function of the universe, and its sub-functions, represent the primary reality. When considering macroscopic systems, the two interpretations are very different in their assessment of the applicability of quantum theory. But in biological systems considered at the smallest scales, both the interpretations favor the application of quantum theory.

In recent years, experiments and theory both have come out on the side of quantum mechanics playing a direct or indirect role in photosynthesis (Collini *et al*, 2010) olfaction (Turin, 1996), vision (Polli, 2010), long-range electron transfer (Gray and Winkler, 2005), and bird navigation (Ritz *et al*, 2004). In some of these areas the evidence is not concerning coherence but rather on quantization and discrete energy levels (Lambert et al, 2013). In photosynthesis, the light-harvesting chlorosome of green-sulphur bacteria collects and then transfers energy to the reaction center through the FMO complex with nearly 100% efficiency even though the intermediate electronic excitations are very short-lived (~ 1 ns)**.** Although alternative explanations for this coherence have been advanced (Briggs and Eisfeld, 2011; Miller, 2012), this is considered the most successful example of quantum effects in biology (Ishizaki et al, 2010). In many situations, probabilistic tests to separate quantum from classical behavior are quite complicated due to the effects of decoherence on the quantum process.

Several proposals describe brain functioning as a classical/quantum hybrid system. Fröhlich argued (Fröhlich, 1968) that electric and elastic forces within the dense arrangement of dipolar molecules of the biological cells will interact leading to vibrations at characteristic frequencies that couple electrical displacements to physical deformations. These vibrations may be viewed as collective behavior of phonons that extends correlations across macroscopic distances within the organism. Ricciardi and Umezawa proposed (Ricciardi and Umezawa, 1967) a mechanism of memory storage and retrieval in terms of virtual bosons associated with the physiological structures of the brain in which long term memory is related to the ground state and short-term memory to the meta-stable excited states. Jibu, Yasue and Pribram further developed these ideas and considered implications for consciousness (Jibu, Yasue, and Pribram, 1996).

The dissipative quantum field model (Freeman and Vitiello, 2006)

associates memory with the non-zero energy states coupled to the infinitely many minimal energy states of the system. This model is different from the model (Hameroff and Penrose, 2003) that takes microtubules to be the place where quantum coherence is maintained. It has been recently proposed that extended CaMKII kinases can potentially encode synaptic Ca^{2+} information via phosphorylation as ordered arrays of binary bits and candidate sites for CaMKII phosphorylation-encoded molecular memory include microtubules (Craddock et al., 2012).

In our own previous consideration of this problem (Kak, 1995; Kak, 1996; Kak, 2000), the structure of the biological system itself is taken to be in a state of superposition in the sense that it is in one of many metastable states based on internal and external conditions. In particular, in brain dynamics state transitions occur when the cortex switches abruptly from one metastable state to another. These metastable states are like the component states of a superposition but they form a discrete spectrum and not a continuous set of values. Brain dynamics can be seen either from the perspective of these discrete states or, complementarily, from the perspective of attractive basins associated with nonlinear dynamics.

The actual brain state cannot be identified excepting in its linguistic projection in the mind, which may be non-verbal or verbal. When the state is quizzed by the conscious mind, it can do no better than speak of a transition state that may be one spatial pattern from which it goes to another as frames in a cinema film. The existence of the many metastable states makes it possible for the system to adapt to the environment. The consequence of this is that the cognitive system is quantum at a deeper level but it is coupled to the conscious system which is classical: the quantum system is defined by collectives of quasiparticles; the classical system comprises of the neural networks of the brain. This dual system of the cognitive system can thus describe individual and social behavior. We also propose that the linguistic mind

creates local explanations for phenomena, and since quantum processes are nonlocal, this is a consequence of a principle of veiled nonlocality (Kak, 2014).

Recently, quantum probability has been used in modeling cognition and decision (e.g. Busemeyer and Bruza, 2012) sidestepping the question of its physical basis. This line is an offshoot of the proposal made early by the pioneers of the Copenhagen Interpretation that the unconscious mind is quantum mechanical and different from classical mind of the internal dialog within the individual. As stated by Niels Bohr: "[T]he quantum postulate implies that any observation of atomic phenomena will involve an interaction with the agency of observation not to be neglected. Accordingly, an independent reality in the ordinary physical sense can neither be ascribed to the phenomena nor to the agencies of observation. After all, the concept of observation is in so far arbitrary as it depends upon which objects are included in the system to be observed. Ultimately, every observation can, of course, be reduced to our sense perceptions. The circumstance, however, that in interpreting observations use has always to be made of theoretical notions entails that for every particular case it is a question of convenience at which point the concept of observation involving the quantum postulate with its inherent *irrationality* is brought in." (Bohr, 1928)

In the quantum cognition field (e.g. Busemeyer and Bruza, 2012; Khrennikov, 2010; Haven and Khrennikov, 2010) it has been argued that human judgments do not always follow classical logic and cognition has order and interference effects. If it is accepted that there exist nonclassical aspects to human cognition and decision, there is then need to discuss how these nonclassical agents and memories are structured. In the global workspace theory, it is consciousness that provides access to the cognitive agent to its memory sources.

If subsystems within biological systems are quantum mechanical, what is the nature of communication between these subsystems? In analogy

with classical systems, one would expect that the communication will have syntactic, pragmatic, and semantic aspects. We also stress that biocommunication includes associative (classical) and reorganizational (adaptive) elements in addition to those that are quantum (Kak, 1996). Here the associative language is the ordinary language of communication for which the medium is chemical in terms of a variety of neurotransmitters and electrical in the manner in which signals are transmitted; the reorganizational language is the one in which the subsystems reorganize and in doing so change their modes of communication; and the quantum language is the one that is characterized by a quantum process (see e.g. Ball, 2011).

REPRESENTATIONS AND LANGUAGES

From an operational point of view, we need to speak not only signs and codes and their representation but also interpretation within the organism, which requires an appropriate metalanguage. Proper linguistic expressions are different from noise and this has important implications in that it makes it possible for the organism to recognize self from non-self (Sanabria et al., 2008). Furthermore, unlike a formal language and quite like natural languages, the biocommunication language is adaptive. The biological organism cannot be seen in isolation. It shares an identity with others in a group, it uses signs in a coherent manner, it belongs to a habitat where it shares space with other organisms, its signs have meanings that can be interpreted differently based on context, and its semiotic rules evolve based on the nature of interactions with other organisms. The nature of intra-level interaction, together with the governing grammar, has implications for the capacity of the organism to operate within its ecological environment.

One can see limitations of representations from a variety of perspectives, including that of information and computability (Kak, 2012). No representation can be looked at in isolation because interactions occur both within a hierarchy and across hierarchy. For example, top-down influences shape cortical and thalamic processing of sensory information

in highly interconnected ways. Cortical structures work as adaptive processors subject to attention and expectation related to the perceptual task, and brain states are a consequence of complex interactions between multiple structures and the modulation of intrinsic circuits by feedback connections.

Representations are not static but context-sensitive, which context is provided by the appropriate top-down signals and expectations. The cumulative repertoire of behaviors at all the levels has infinite variety. The communications between different nodes within the system must therefore have all the elements of the hierarchy of Figure 1, where it is remembered that for biological systems it is the subsets of the elements under certain internal and external conditions that define the boundaries. We call the highest level quantum (Kak, 1996) to stress that it comes with identification of wholeness and awareness of self as distinct from non-self. The three languages interface with each other adding to the complexity of the interaction between the communicating elements. The languages are also in a complementary relationship with their respective metalanguages. Note that this hierarchy is different from the Chomsky hierarchy of formal languages although the two hierarchies may very well have points of convergence. For example, recursively enumerable languages (Type-0 in the Chomsky hierarchy) could very well correspond to what we call quantum mechanical-type languages since they are associated with unrestricted grammars, but this is a matter that requires additional research.
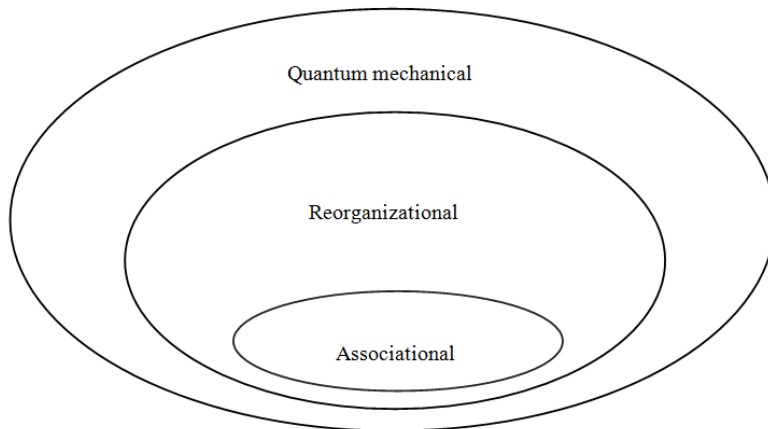
Figure 1. The language hierarchy with adaptive subsets

The elements of this communication are in directed relationships amongst its components. A cortical state engenders expectations about the subsequent state, and the expectation affects the way the incoming sensory information is processed. This broadens the functional diversity of each area and makes the way information is exchanged across areas more important than the contents of any specific area. The exchange of information across areas increases the capacity of the structures. It has been "proposed that this interaction is manifest in the way that feedback connections address subsets of intrinsic cortical connections, and the functional properties of a neuron depend on which subset is gated at any given time. The mechanism of perceptual learning may involve the setting up of this addressing, such that both the encoding and recall of learned information involves the appropriate selection of the inputs that convey information about the stimulus being discriminated." Gilbert and Sigman, 2007) In genetic information, the situation is similarly complex (Witzany and Baluska, 2012).

Now consider the complementarity between the neural and linguistic processing in the brain. The processing in neural networks, which are defined in a hierarchical sense with complex interaction amongst structures, is associated with what one might call *neuronal concepts*. On the other hand, there is the system of logic and language at work within systems that informs cognitive agents in their higher-order processing.

The human mind creates linguistic models of reality whose elements are interconnected grammatically and logically. Paralleling the structure of the brain, language is organized hierarchically. The functional elements of the linguistic system are *logical or linguistic concepts*. The neuronal concepts are nonlinguistic as contrasted from the logical concepts of the linguistic objects (Figure 2).
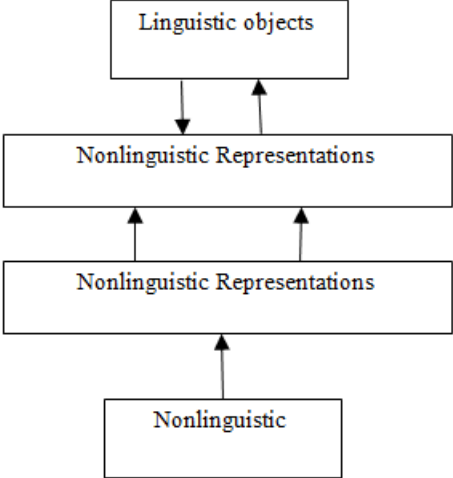
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Figure 2. Language and reality

The neuronal and the linguistic systems are interconnected. The linguistic system is a product of the brain, but, in turn, the linguistic dialog also influences the functioning of the brain. The relationship between neuronal and logical concepts is an important problem. Neuroscience provides clues about the lowest levels of the neuronal hierarchy; about the higher levels we don't possess knowledge that is independent of language. Since language is a behavior associated with the brain, a close relationship should exist between the highest levels of the neuronal hierarchy and the lowest stages of linguistic concepts. The logical structure of an object must have a neuronal correlate. The initial skeleton of the concepts that a child comes to have is a consequence of interaction with caregivers that is essentially before the use of speech. But this skeleton is filled out as the child learns additional concepts that are language-dependent. Thus the problem of the mutual relations of

neuronal and logical concepts has an interesting developmental side since the more complex concepts in the child emerge under the influence of language.

The complementarity of the neuronal and the linguistic concepts has significant implications for structure and performance. The nature of language and the subject's proficiency of it play a role in the understanding of reality. Indeed, this should have an influence even in the manner in which the brain reorganizes itself based on experience and activity.

Since linguistic objects become a part of social reality that play a role not very different from material objects, it becomes necessary to create other linguistic objects that describe this reality of which linguistic objects are components necessitating a metasystem transition (Turchin, 1977). Such transitions can occur at many different hierarchical levels thus leading to a variety of nested metalanguages.

An example of metasystem transition is the one from unicellular to multicellular organisms. A different transition is the emergence of eusociality or symbolic thought (Costa and Fitzgerald, 2005). A metasystem is formed by the integration of a number of initially independent components and the collective of components becomes a new, goal-directed individual, capable of acting in a coordinated way. This metasystem is more complex, more intelligent, and more flexible in its actions than the initial component systems. One can also speak of a metasystem transition in the development of a language.

QUANTUM MECHANICS IN MEMORY

Now we consider how quantum mechanical and linguistic structures may be correlated. Specifically, we consider linkages between neuronal structures and the specific linguistic concept of memory. Several years ago, the Bose-Einstein quantum probability distribution was proposed as model of human memory and shown to describe experimental results

related to Piaget's developmental stages (Pascual-Leone, 1970). This approach was taken further and it was shown how such memories might be structurally conceived (Kak, 2013a).

The starting point of this approach was to conceptualize Piaget's cognitive-developmental variable as a processor with capacity M, which was the maximum number of chunks of information or schemes that can be controlled or integrated in a single act. M was supposed to grow with age and therefore it became a quantitative measure of each developmental stage.

Particles and quasiparticles cannot be agents or memories in themselves because they are too numerous and also indistinguishable. In physics the property of most interest concerning particles or quasiparticles is energy, but going from physics to chemistry and biology, molecular structure and shape play an increasingly significant role in processes. When considering cognitive agents, informational attributes of these collectives can be expected to play a part in their identity. We assume that bosonic quasiparticles or fermions are assembled in different arrangements to become cognitive agents. The three-dimensional structures of the brain will come with corresponding quantum space that will define agents and memories.

Agents and memories should be set apart by number, structure and informational content. In classical computers, they are both represented by binary sequences and they are differentiated by context. Agents, unlike memories, are linked to sensors and actuators. As sequences shorn of context, they ought to be very similar. An agent (or a memory) must be invariant to certain types of transformation and it should be resistant to noise so long as the noise is within a certain limited range.

Quantum objects and quasiparticles associated with macro-structures, in collectives representing different cognitive agents and memories, have long range correlations. The property of resistance to noise implies that

there is a minimum *separation* between patterns representing them. This distance must be defined in an abstract space that is different from the three-dimensional geometry associated with the particles. To study such agents one needs to go beyond statistics related to energy distributions as the properties of collectives should be invariant with certain translations of energy.

STATISTICAL CONSIDERATIONS

Classical and quantum objects may be differentiated based on their statistics. Indeed the very search for a quantum theory began as statistics associated with black-body radiation were different from that of classical thermodynamics. The Planck radiation formula is an example of the distribution of energy according to Bose-Einstein statistics.

Classical objects are distinguishable whereas quantum objects are not. For N classical particles distributed over M single-particle distinct states (which could be energy states), the number of possible arrangements is n $= M^N$, and this is the basis of the Maxwell-Boltzmann distribution. Quantum statistics must be considered in cognitive processes if cognitive agents are collectives of quasiparticles.

As there are two different classes of quantum particles, bosons and fermions, we have two different quantum statistics. Bosons are governed by the Bose-Einstein statistics and fermions by the Fermi-Dirac statistics. For N bosons associated with M single-particle states, the number of arrangements is

$$n_{bosons} = \frac{(N+M-1)!}{N!(M-1)!}$$

For fermions, the number of arrangements is reduced further due to the Pauli Exclusion Principle according to which no two such particles can be in the same state, and we obtain:

$$n_{fermions} = \frac{M!}{N!(M-N)!}$$

The probability of observing any particular state is determined by the number of copies of that state divided by the total number of arrangements. The number of permissible arrangements goes down as we move from classical to bosonic to fermionic states. In statistical distributions we are interested in the probability of arrangements corresponding to specific energy values since these either represent temperature or some other measurable characteristic of the ensemble.

Example 1. Given two particles, the classical state can be one of the following four: 00, 01, 10, and 11. The bosonic states will be $|0\rangle|0\rangle, |1\rangle|1\rangle,$ and $\frac{1}{\sqrt{2}}(|0\rangle|1\rangle + |1\rangle|0\rangle)$; and the fermionic state will be $\frac{1}{\sqrt{2}}(|0\rangle|1\rangle - |1\rangle|0\rangle)$. The probability of finding different outputs for the three situations is summarized as shown below:

Table 1. Probability of different outputs for two particles

	Classical	Bosons	Fermions
Both 0	0.25	0.33	0
Both 1	0.25	0.33	0
One 0 and one 1	0.50	0.33	1

Example 2. Consider N = 3 and M = 4. This may be viewed as 3 particles in four boxes (distinct, quantized, energy levels) that corresponds to $4^3 = 64$ classical arrangements. Let us label the four boxes 0, 1, 2 and 3 (with energy levels equal to the index) and each of the three balls can be shown at a different location. The 64 arrangements will then be the sequences 000, 001, 012, …, 222,…333. Here the arrangement 000 means that all the three particles are in the energy state

216

0. Each of these sequences has the probability 1/64 of being observed. The energy in the system will vary from a minimum of 0 (corresponding to the arrangement 000) to a maximum of 9 (arrangement 333). For bosons, the number of arrangements with the same number of particles and boxes is 20, and for fermions it is 4.

Let the energy of a particle in a box be determined by the label of the box (0 has energy of 0; 1 has energy of 1; 2 has energy of 2; 3 has energy 3), then the distribution is through a spectrum of values ranging from 0 to 6 of Table 2.

Table 2. Distribution of energy in three different distributions

Energy level	Number of arrangements in Maxwell-Boltzmann distribution	Number of arrangements in Bose-Einstein	Number of arrangements in Fermi-Dirac
0	1	1	0
1	3	1	0
2	6	2	0
3	10	3	1
4	12	3	1
5	12	3	1
6	10	3	1
7	6	2	0
8	3	1	0
9	1	1	0

The probability that the state will be one of these arrangements has gone up to 1/20 for bosons and 1/4 for fermions from the 1/64 for classical particles.

The distribution of Table 2 is shown in Figure 3 which highlights the fact that the number of arrangements decreases as we go from classical to quantum distributions.
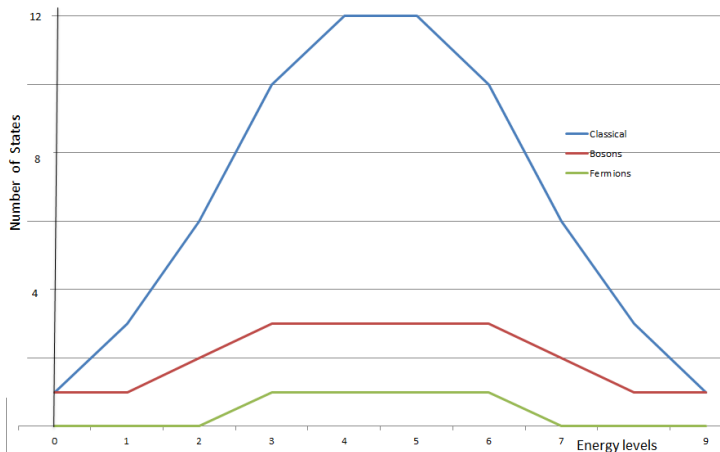

Figure 3. Number of states for different types of particles

The specific quantum probability distribution is obtained by choosing a certain energy value associated with the system in equilibrium and then seeing how many of the arrangements correspond to each of the energy levels.

In principle, the statistics can reveal if quantum modeling of a cognitive phenomenon is correct. It is significant that Pascual-Leone found the Bose-Einstein statistics to be the correct model for memory in the Piaget's developmental model on the compound-stimuli visual information tasks (Pascual-Leone, 1970). This work assumed that the tasks solved at about the same age by normal children involve formulas of equal maximum complexity, which was denoted by m = a + k, where a stands for the processing space required, and k is the number of independent cognitions required by the task. The value k varied with

each Piagetian stage: i.e., a+ 2, a + 3, a + 4, a + 5, . . . The value m was a measure of the computing space M, which was taken to depend on the subject's representation of the task instructions, the testing situation, and the information needed to generate the correct logical response.

Cognitive tasks require that the representation be done in one space and binding be done in another higher dimensional space and the requirements for this seem particularly matched to quantum representation models. Furthermore, quantum dissipation models are associated with fractal behavior that has been observed in brain states (Vitiello, 2009).

Example 3. Consider 9 bosons that are associated with 6 energy states (ranging from values 0 through 5) for a total energy of 8 units. The arrangements associated with this are shown in Table 3. Each indexed value is a unique representation of the energy partition for the total value of 8, where the level 0 serves to account for the particles that do not contribute to the energy total. The 18 cases of Table 3 represent the different partitions of number 8.

Table 3. Arrangements for 6 energy levels and 9 bosons for total energy=8
(Columns are energy levels 0 through 5 and rows are arrangements 1 to 18)

Index ↓	0	1	2	3	4	5
1	5	3	0	0	0	1
2	6	1	1	0	0	1
3	7	0	0	1	0	1
4	4	4	0	0	1	0
5	5	2	1	0	1	0
6	6	0	2	0	1	0
7	6	1	0	1	1	0
8	7	0	0	0	2	0
9	3	5	0	1	0	0
10	4	3	1	1	0	0
11	4	0	1	2	0	0
12	5	1	2	1	0	0
13	5	2	0	2	0	0

14	2	6	1	0	0	0
15	3	4	2	0	0	0
16	4	2	3	0	0	0
17	5	0	4	0	0	0
18	1	8	0	0	0	0
Averages→	4.66	2.33	1	0.5	0.33	0.17

The averages for the different columns are according to the Bose-Einstein distribution which is shown in Figure 4.
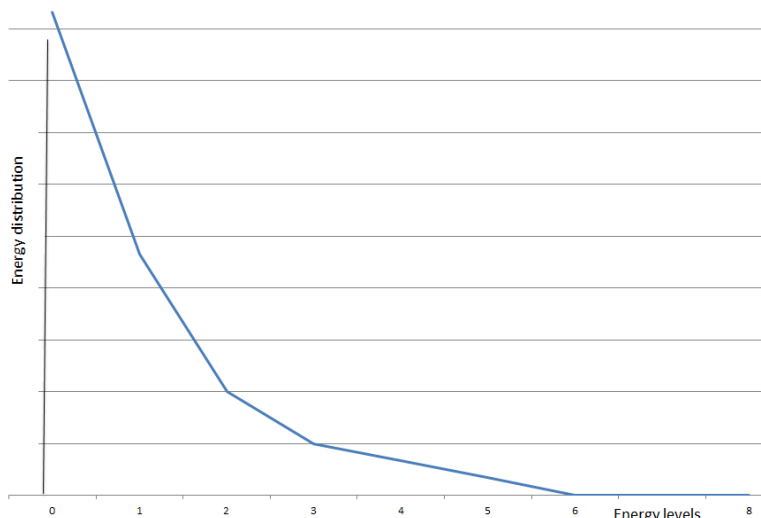

Figure 4. Bose-Einstein distribution for Example 3

Example 4. Consider 6 fermions of spin-½ with 7 energy states (ranging from values 0 through 6) for a total energy of 10 units. The arrangements associated with this are shown in Table 4. The 8 cases of Table 4 represent the different unique partitions of number 10. Since each particle can be either in spin-up or spin-down, each energy state can have at most 2 particles.

Table 4. Arrangements for 7 energy levels and 6 fermions for total energy = 10
(Columns are energy levels 0 through 6 and rows are arrangements 1 to 8)

Index ↓	0	1	2	3	4	5	6
1	2	2	1	0	0	0	1
2	2	1	2	0	0	1	0
3	2	2	0	1	0	1	0

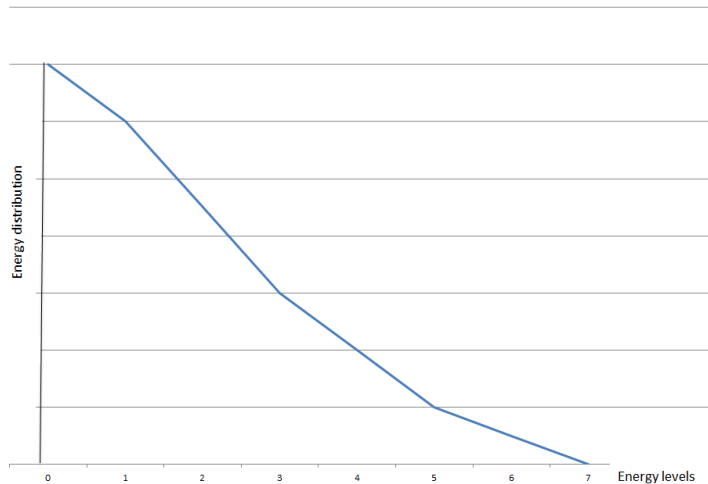| 4	2	1	1	1	1	0	0
5	1	2	2	0	1	0	0
6	2	0	2	2	0	0	0
7	1	2	1	2	0	0	0
8	2	2	0	0	4	0	0
Averages	1.75	1.50	1.12	0.75	0.50	0.25	0.12

Figure 5. Fermi-Dirac distribution for Example 4

Low energy states are more probable with the Bose-Einstein statistics and less probable with the Fermi-Dirac statistics as compared to the Maxwell-Boltzmann statistics. At very low energies, bosons can condense into the lowest energy states.

QUANTUM STATES AS MEMORIES AND AGENTS

Classical objects are uniquely defined in terms of their many attributes. On the other hand, since quantum objects are indistinguishable, they must be defined in terms of arrangements (or patterns) associated with quantum states. A memory or cognitive agent as a collective of quantum particles must have a unique structure. In biological systems the structure is likely to be three dimensional, but here, for simplicity, we consider structure for one-dimensional sequences.

As example, consider three particles in four energy levels. Let the agents (or memories) be defined in terms of whether all the particles are same (Agent 1); there are two of one kind and one of another (Agent 2); and

they are all different (Agent 3). If each of the arrangements occurs with equal probability, the frequencies of the three agents would be as given below by the number of elements of each set:

Agent 1: 4 cases – 000, 111, 222, 333
Agent 2: 12 cases – 001, 002, 003, 011, 022, 033, 112, 113, 122, 133, 223, 233
Agent 3: 4 cases – 012, 023, 023, 123

Each of these maps several energy values to a single agent.

Energy alone cannot be a marker of memory or agent. To see this, consider now a quantum system that is associated with 5 energy levels, which we label as Level 0 through Level 5, where the energy of a particle in Level k is taken to be k. The quantum objects will belong to one of these 5 levels and the arrangements would correspond to the energy associated with the system. There can be many instances of different arrangements each with the same total energy. These arrangements from an informational content appear to be very different for there is no discernible pattern associated with them.

We propose than an algorithmic approach to information content in which the length of the program required to generate the patterns is a measure of the information (Li and Vitanyi, 1997). This is equivalent to a structural view of the problem, and its special merit is that such structure can mimic the object of information in form.

The number of quantum collectives in a system with n energy levels may be computed in a manner analogous to sphere-packing arguments. In linear codes, the number of elements of the collective, M, is given by the following relation (van Lint, 1975):

$$M \leq \frac{q^n}{\displaystyle\sum_{i=0}^{s} \binom{n}{i}(q-1)^i}$$

where q is the number of energy states (or quantization levels), n is the size of the collective, and s is a measure of the noise-resistance that the collectives possess. In the example of Figure 5, q=5 and n =14. Therefore, for small noise-resistance the number of collectives can be very many. The number of agents (that may well be equivalent to the number of chunks of memory) can grow in number as the neuronal structures grow and mature.

In number of chunks of short-term memory, the numbers four to six has been given (Cowan, 2000), although that of chimpanzees seems to be much higher (Inoue and Matsuzawa, 2007; Matsuzawa, 2013). It is interesting to speculate if the processing in the workspace corresponding to short-term memory has a quantum basis and whether the number of its chunks can help determine its physical structural correlates.

CONCLUSIONS

This chapter has provided a general discussion of the hierarchy of languages and metalanguages that must be associated with a biological system. At the bottom of this hierarchy are physical structures whose behavior is governed by quantum mechanics. In order for this hierarchy to be valid, we must postulate a language whose primitives are quantum mechanical objects. In a complementary relationship to this physical hierarchy is a hierarchy of languages where the quantum language resides at the top.

We have shown how communication (and cognitive) agents may be conceived of as collectives of quantum particles. We associate agents and memories with patterns that belong to unique classes of quantum collectives. The structural approach to the definition of memory has the

good property that it can mimic features of the two- or three-dimensional original it seeks to represent. It is plausible that the fundamental character of agents and memories is different and that agents are fermion collectives whereas memories are boson collectives. If agents reside in quantum physical structures, that supports the view that they are fermion collectives.

It should be possible to devise experiments to test the theory advanced in this chapter. The evidence for order and interference effects in probability associated with cognition and decision supports the broad idea discussed here, but additional tests concerning quantum statistics must be devised. These tests will reveal the nature of the particles in the underlying physical structures and they will raise new questions on the physical basis of the quantum collectives.

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Subhash Kak, Ph.D., is with the School of Electrical and Computer Engineering at Oklahoma State University, Stillwater

E-mail addresses: subhash.kak@okstate.edu