Biological Memories and Agents as Quantum Collectives

Subhash Kak

ABSTRACT

Quantum mechanical models have been proposed for biological processes and for cognition and decision in domains that appear to be beyond the de Broglie wavelength. The basis of such quantum behavior is seen variously as quantum fields and virtual and entangled particles, and the determination that the behavior is quantum is made on coherence, order and interference effects, and non-local behavior. This paper proposes that biological memories and cognitive agents are collectives of quantum objects. Statistical and informational properties of the collectives that need to be taken into consideration are identified. Issues related to mapping of collectives into various energy states and resistance to noise are examined.

Key Words: cognition, information, learning models, neuroscience, quantum theory

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Introduction

In biology, the case has been made that quantum mechanics plays 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 canter through the FMO complex with nearly 100% efficiency even though the intermediate electronic excitations are very short-lived (~1 ns). This is the most successful example of quantum effects in biology (Ishizaki *et al.,* 2010) but this coherence may have a classical basis (Briggs and Eisfeld, 2011; Miller, 2012). In short, a process cannot be unambiguously identified as being quantum mechanical based on coherence alone.

Several proposals describe brain functioning as a classical/quantum hybrid system. Fröhlich argued (Fröhlich, 1968) those 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).

Corresponding author: Subhash Kak
Address: Department of Computer Science, OSU, Stillwater, OK 74078, USA.
Phone: + 405-744-6036
✉ subhash.kak@okstate.edu
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The dissipative quantum field model (Vitiello, 2001; 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. In our own previous consideration of this problem (Kak, 1995; 1996; 2000; 2009), the structure of the biological system itself was considered to be in a state of quantum superposition and it was argued that this made it possible for the system to adapt to the environment. The consequence of this for the brain 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 has the capacity to explain individual and social behavior.

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). More recently, quantum probability has been used in modeling cognition and decision (e.g. Busemeyer and Bruza, 2012; Khrennikov, 2010; Haven and Khrennikov, 2010) sidestepping the question of its physical basis. This line of inquiry has been motivated by the fact that human judgments do not always follow classical logic and cognition has order and interference effects. In the global workspace theory, it is consciousness that provides access to the cognitive agent to its memory sources. We are not interested in considering the question of consciousness here, but it is relevant to know how quantum theory could explain agents or memories.

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 $\lambda = h/p = h/(m_o v)$, 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.

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 their corresponding quantum space that will define agents and memories, even for a newborn. This is a possible explanation for how certain newborns –such as foals – can stand and run almost as soon as they are born.

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.

This paper considers the problem of cognitive agents and memories as collectives of quantum objects. It begins with a summary of quantum statistical distributions and then presents examples of pattern based agents that can correspond to several energy states.

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

$$|0\rangle|0\rangle, |1\rangle|1\rangle, \text{and } \frac{1}{\sqrt{2}}(|0\rangle\,|1\rangle + |1\rangle|0\rangle)\,;$$

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. We could view it as 3 particles and four boxes (distinct, quantized, energy levels) and it has $4^3 = 64$ 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 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 N = 3 and M = 4 is 20 (Figure 1a), and for fermions it is 4 (Figure 1b). The boxes in Figure 4(a) can hold more than one particle, but since they are indistinguishable, the arrangement 000 in the first box is equivalent to the arrangements of all triples. In Figure 1(b), no box can have more than one particle and the since the particles are indistinguishable, the arrangements such as 012 as shown are equivalent to its different permutations.

000			
00	1		
00		2	
00			3
0	11		
0	1	2	
0	1		3
0		22	
0		2	3
0			33
	111		
	11	2	
	11		3
	1	22	
	1	2	3
	1		33
		22	3
		2	33
		222	
			333

(a)

0	1	2	
0	1		3
0		2	3
	1	2	3

(b)

Figure 1. (a) Three bosons in four boxes; (b) three fermions in 4 boxes.

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 2 which highlights the fact that the number of arrangements decreases as we go from classical to quantum distributions.

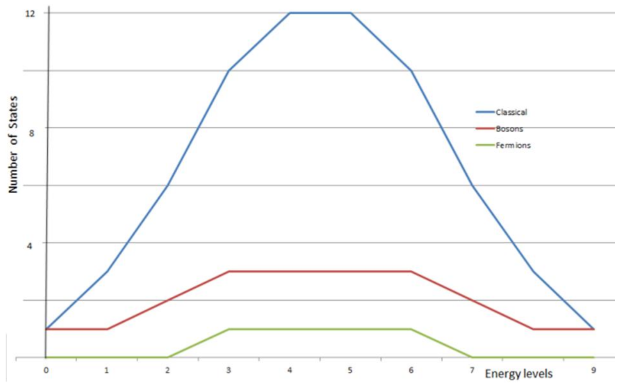

Figure 2. Number of states for different types of particles.

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 3.

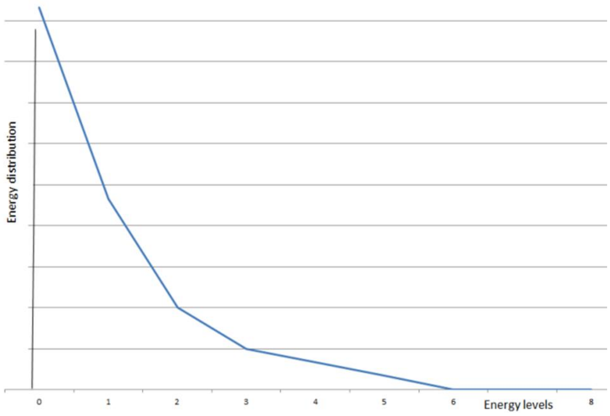

Figure 3. Bose-Einstein distribution for Example 3.

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

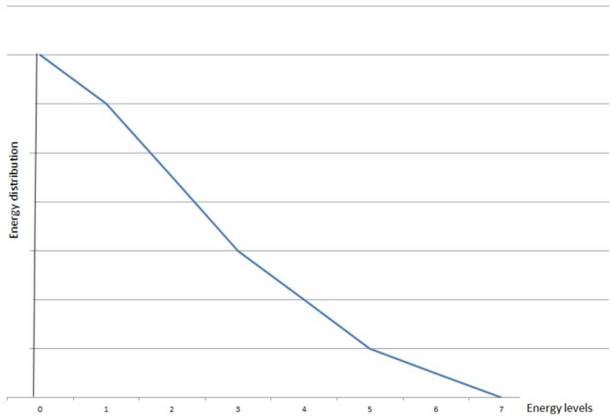

Figure 4. Fermi-Dirac distribution for Example 4.

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.

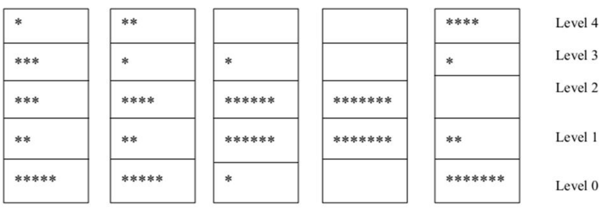

Figure 5. Fourteen quantum objects in different arrangements each with total energy of 21 (The energy of a particle in level k is equal to k).

Figure 5 shows five instances of different arrangements each of which has a total energy of 21. These arrangements from an informational content appear to be very different for there is no discernible pattern associated with them.

We propose to use 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 (Kak, 2007), and its special merit is that such structure can mimic the object of information in form.

Figure 6 presents information defined by five patterns corresponding to two agents that are easily visible to the eye. The pattern of Agent 1 is represented by 5 particles in one state and 4 particles in the next state. The patterns of Figure 6(a), (b), and (c) represent the same Agent even though their energy values are quite different, taking values of 13, 22, and 31. Likewise, the Agent 2 of Figure 6 (c) and (d), which has been shown to consist of exactly four particles in three adjacent states has energies that are 24 and 36, respectively.

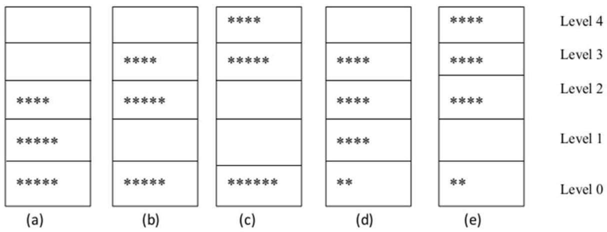

Figure 6. Fourteen quantum objects that define two different agents in 5 arrangements.

Number of Quantum Collectives

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):

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

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.

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). Does the processing in the workspace corresponding to short-term memory have a quantum component?

Conclusions

This paper has argued that cognitive agents and memories should be viewed as assemblages of quantum particles. This requires that we associate agents and memories with patterns that belong to unique classes. We have given examples of how this may be done. 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 proposal made in this paper. The evidence for order and interference effects in probability associated with cognition and decision supports the broad idea of the paper, 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.

These ideas are likely to have applicability in communication in biological systems (Gautam and Kak, 2013). In an ecological system the interactions between the components are complex. Although it is very useful to represent these interactions in a biological or social network, the graph of the interconnections does not capture many aspects of the communication between the nodes. The communication is at several levels in a hierarchy and at each level it defines a language with syntactic, pragmatic, and semantic aspects. From an operational point of view, this necessitates not only signs and codes but also interpretation within the organism (Barbieri, 2008). The investigation of the nature of the language that is associated with biological agents and memories that are quantum collectives becomes relevant. One can pose questions such as: Are quantum languages more powerful than classical languages? What is the relationship between the learning in the neural system (Kak, 2011) and in the deeper quantum memory/cognitive agent system?

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