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Bose–Einstein condensates form in heuristics learned by ciliates deciding to signal 'social' commitments

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ABSTRACT

Fringe quantum biology theories often adopt the concept of Bose–Einstein condensation when explaining how consciousness, emotion, perception, learning, and reasoning emerge from operations of intact animal nervous systems and other computational media. However, controversial empirical evidence and mathematical formalism concerning decoherence rates of bioprocesses keep these frameworks from satisfactorily accounting for the physical nature of cognitive-like events. This study, inspired by the discovery that preferential attachment rules computed by complex technological networks obey Bose–Einstein statistics, is the first rigorous attempt to examine whether analogues of Bose–Einstein condensation precipitate learned decision making in live biological systems as bioenergetics optimization predicts. By exploiting the ciliate *Spirostomum ambiguum*'s capacity to learn and store behavioral strategies advertising mating availability into heuristics of topologically invariant computational networks, three distinct phases of strategy use were found to map onto statistical distributions described by Bose–Einstein, Fermi–Dirac, and classical Maxwell–Boltzmann behavior. Ciliates that sensitized or habituated signaling patterns to emit brief periods of either deceptive 'harder-to-get' or altruistic 'easier-to-get' serial escape reactions began testing condensed on initially perceived fittest 'courting' solutions. When these ciliates switched from their first strategy choices, Bose–Einstein condensation of strategy use abruptly dissipated into a Maxwell–Boltzmann computational phase no longer dominated by a single fittest strategy. Recursive trial-and-error strategy searches annealed strategy use back into a condensed phase consistent with performance optimization. 'Social' decisions performed by ciliates showing no nonassociative learning were largely governed by Fermi–Dirac statistics, resulting in degenerate distributions of strategy choices. These findings corroborate previous work demonstrating ciliates with improving expertise search grouped 'courting' assurances at quantum efficiencies and verify efficient processing by primitive 'social' intelligences involves network forms of Bose–Einstein condensation coupled to preceding thermodynamic-sensitive computational phases.

1. Introduction

Physical particles of integer spin, termed bosons, when cooled to near absolute-zero temperatures condense into superfluids (Kapitza, 1938), supergases (Anderson et al., 1995), and perhaps supersolids (Kim and Chan, 2004) at the lowest accessible quanta of energy or ground states. These exotic states of matter showing macroscopic quantum behavior were predicted by Bose–Einstein (BE) statistics (Bose, 1925; Einstein, 1925) and first discovered for the pure vapor phase of dilute rubidium gas in the laboratory about seventy years later (Anderson et al., 1995). Condensates of fermions, arranged from bosonic Cooper pairs each with compound integer spin, have been since created at ultralow temperatures (Regal et al., 2004). And condensates of quantized spin waves or magnons now reliably develop under weaker pump-process constraints which achieve coherence in heated solids (Demokritov et al., 2006). Surprisingly, the special properties of BE condensates are not restricted to the explicit physical world. Self-organizing computational objects, such as complex technological networks ranging from the World Wide Web to science citation databases, map onto an equilibrium Bose gas obeying BE statistics (Bianconi and Barabási, 2001). When a network transitions toward BE condensation, a lone 'fittest' network node represented by a webpage, scientific publication, or another type of data structure always gains a macroscopic fraction of new connections reminiscent of true 'winner-takes-all' behavior common to competitive systems. Other topologically distinct phases, including 'fit-get-rich' and the scale-free 'first-mover-advantage', emerge as well from dynamic interactions between network nodes competing for links. As with evolving artificial

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networks, BE statistics figure to be a powerful tool for understanding operational attributes of networked biological systems. Abundant examples of dynamic computational networks exist throughout Nature, including macromolecules, intracellular control systems, multicellular organisms, and social groups. Despite the scale of organization at which biological systems may compete for resources (e.g., chemical bonds, cell–cell interactions, or community ties), the problems they encounter and solve all deal with issues of performance optimization. Establishing that biological systems mainly choose solutions involving the network analogue of BE condensation from among computational phases might explain how some biological systems improve their processing capacity and speed. Quantum superposition and tunneling properties of physical BE condensates lead some authors to anticipate that bosonic lattices made from photons or other (quasi)particles might become ideal quantum computers with enhanced performance over linear classical processors (cf. Khitun et al., 2001; Nielsen and Chuang, 2000). Informational equivalents of these same quantum properties exploited by a biological system in a network state of BE condensation could likewise increase its computational performance through processing schemes such as quantum annealing, a mathematical method useful for combinatorial optimization problems (e.g., Battaglia et al., 2005; Stella et al., 2005).

Although BE statistics promise a well-developed means to tackle tough problems related to computational performance, its application to intelligent life forms and so-called intelligent machines constructed of either inanimate (e.g., Albus and Barbera, 2005; Krichmar and Edelman, 2002; Rzevski, 2003) or live biointerfaced media (e.g., Chao et al., 2008; DeMarse et al., 2001; Reger et al., 2000) remains largely overlooked. Interests in how BE condensation affects information processing by intelligent systems began with modeling of cells and neural networks long before actual pure physical condensates and their network analogue were demonstrated by physicists (cf. Fröhlich, 1968, 2004; Marshall, 1989). It is now an unremarkable fact that bizarre quantum traits of BE condensates, and quantum phenomena in general, appeal to fringe brain, engineering, and computer sciences as a physical basis for ‘psyche’ and brain function (e.g., Beck and Eccles, 1992; Bohm, 1971; Jung and Pauli, 1955; Penrose, 1989; Schrödinger, 1944) popularized in psychoanalytic Noetic Field Theory (Amoroso and Martin, 1995), Quantum Brain Dynamics of biological and artificial intelligences (Ricciardi and Umezawa, 1967; Pribham, 1991), and other controversial ‘mind theories’ (cf. Amoroso, 1997). But many of these second-generation frameworks struggle to craft and validate an eccentric ‘scientific’ jargon to describe complex cognitive phenomena that otherwise elude empirical corroboration and consensus mathematical formalism. A great impediment to this goal has been the inability to resolve debates over the coherence of chemical processes needed for soft matter to function in a quantum regime at physiologically important times, lengths, and temperatures (Davies, 2004; Hagan et al., 2002; Matsuno, 1999, 2006; Rosa and Faber, 2004; Tegmark, 2000; Thaheld, 2005). Putting aside these debates, much still can be learned about the quantum mechanical nature of computations performed by soft matter. In principle, perceptions, social decisions, and related cognitive-like processes may uniformly ‘condense’ on learned solutions supporting optimal organization and operation for both strategizing individuals and interacting groups of organisms. Networks of game players, for instance, evolving under preferential attachment rules weighted by rewarded fitness parameters enrich their benefits through improved cooperation when confronting social dilemmas (e.g., Jiménez et al., 2008; Nowak, 2006; Poncela et al., 2008; Santos et al., 2006). Learning to laterally inhibit the activity of neural networks also organizes neurons into groupings of ‘winner-takes-all’ attractors useful for memory storage (e.g., Willshaw et al., 1969; Hopfield, 1982; Xie et al., 2002). Findings from these modeling studies hint some sort of skewed statistical distribution corresponding to intelligent actions is achieved without directly testing if BE statistics (or for that matter, quantum Fermi–Dirac (FD) or classical Maxwell–Boltzmann (MB) statistics) are obeyed. An important next step, addressed by the present study, is to determine the computational relationship statistical mechanics might have with social decisions made by individual live organisms and if the network analogue of BE condensation precipitates their choice behavior.

2. A living computational model

2.1. Heuristic-guided ‘Social’ decisions learned by ciliates

A good model to investigate the role played by computational phases, including BE condensates, in the development of perception and decision making can be found in the sexual-like conjugative behavior of the large contractile ciliate, *Spirostomum ambiguum*. Some microbes display primitive intelligences capable of choice behavior (e.g., Hellingwerf, 2005; Nakagaki et al., 2000) and this particular ciliate is capable of heuristic-guided ‘social’ reciprocity (Clark, in press). In simulated social trials, *S. ambiguum* learns to advertise different levels of mating fitness to a mixed population of perceived ‘suitors’ and ‘rivals’ by contracting or ciliary reversing at rates that signal either conspicuous consumption or prudent savings (Clark, in press). Those ciliates flaunting conspicuous consumption proclaim their fit reproductive status through the extravagant rates at which they signal avoidance. Only highest quality mating candidates are capable of metabolically wasteful displays. Because conspicuous consumers make it difficult for required preconjugate contacts to occur between ‘courting’ couples, they play ‘harder-to-get’ when replying to the presumed advances of fellow ciliates. In contrast, prudent savers conserve their resources until circumstances become more favorable for attracting a partner. Prudent savers respond with comparatively lower frequencies of avoidance reactions which assure possible nearby conspecifics of their likelihood of being ‘easier-to-get’ during ‘courtship ritual’. By deciding to switch from an initial behavioral strategy that signals conspicuous consumption to one that signals prudent savings, fitter ciliates learn to altruistically sacrifice net payoffs to persuade ‘suitors’ to engage them in paired reproduction. Less fit ciliates unable to sustain long periods of high response rates may switch their initial behavioral strategy of prudent savings to briefly emit conspicuous consumption and thus learn to opportunistically cheat superior ‘rivals’. The competency of each *S. ambiguum* to appropriately stay with the same reply or to switch its reply from one behavioral strategy to another depends on the type of dual-process nonassociative learning expressed (i.e., sensitization or habituation), the duration of learning (i.e., longer- or shorter-term), and the efficiency of heuristics formed from recursive strategy searches and use. Heuristics represent stored patterns of action taken by a ciliate. They evolve into ordered computational networks of strategic serial escape behaviors organized around centers of smaller, local strategy groups supporting ‘courting’ assurances of ‘harder-to-get’ and ‘easier-to-get’ (see Supplementary Material). As ciliates expand their signaling skill over many trials, connectivity between different strategies often strengthens, like that expected of Hebbian learning (Hebb, 1949), leading to faster decisions about the appropriateness of certain mating replies. The speeds at which the best experts master signaling decisions approach efficiencies that resemble finding target solutions from superposed states with Grover’s quantum search algorithm (Grover, 1996).