

Bioreaction Quantum Computing without Quantum Diffusion

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ABSTRACT

Debate exists over whether or not adherence to quantum statistical mechanics and emulation of quantum information properties are sufficient criteria for biocomputations to be classified as quantum processes. A noteworthy example at the scale of intact life forms making social decisions can be found in “lower” eukaryotes. Ciliates learn to group Ca^{2+} -dependent behavioral strategies into heuristics which they then use to signal mating status after physical contacts from presumed suitors and rivals. The time taken by ciliates to find appropriate strategies stored within behavioral repertoires diminishes with experience. Improvements in strategy search speeds by experts resemble the root-rate performance of Grover’s quantum search algorithm over classical processes. Ciliates putatively implement fast strategy search algorithms by learning to change the reaction kinetics of mechanically activated Ca^{2+} -induced Ca^{2+} waves that travel through different cellular compartments to preferentially trigger over-learned behavioral sequences. Fire-diffuse-fire models demonstrate wave-conduction velocities most suited for quadratic increases in strategy search speeds are sensitive to limitations imposed by Ca^{2+} release times and distances between Ca^{2+} storage sites. These reaction-diffusion computations provide an interesting contrast to physicochemical quantum events described by equations containing quantum diffusion terms, as a modifiable classical diffusion coefficient solely accounts for root-rate processing efficiency. Fast chemical events underlying quantum information processing schemes in live biological systems can thus counter-intuitively exert their effects via thermodynamically vulnerable reaction parameters. The ubiquity and biological importance of intracellular Ca^{2+} -induced Ca^{2+} cascades across taxa suggests bacteria to mammals might likewise learn to use quantum-level processing when planning and executing behavioral strategies.

Key Words: autocatalytic intracellular Ca^{2+} waves, Bose-Einstein condensation, fire-diffuse-fire reactions, Grover’s quantum search algorithm, classical and quantum diffusion terms

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Introduction

Quantum biologists argue over what criteria are sufficient and necessary for bioprocesses to be considered quantum mechanical in nature (cf. Davies, 2004; Wolynes, 2009). Orthodox opinion would have the label of quantum biology applied to only those bioprocesses which exhibit physical or chemical quantum mechanical behavior. This uncompromising *a priori* decision to reject the possibility of other

kinds of quantum phenomena can lead to Type I inferential errors, since bioprocesses become excluded that obey quantum statistical mechanics, quantum information theory, and quantum game theory without necessarily manifesting physical or chemical quantum traits (e.g., Clark, 2010a-d; Flitney and Abbott, 2002; Khrennikov, 2009; Meyer, 1999; Pascual-Leone, 1970; Pothos and Busemeyer, 2009; Turner and Cho, 1999; Zabaleta and Arizmendi, 2010). Tests of the boundary conditions for quantum biological phenomena have been introduced for many systems (cf. Davies, 2004). One particular area of interest with great application for exposing distinctions between classical and quantum biology is diffusive processes (cf. Pešić 1993; Tsekov, 2011). Particle diffusion at the level of

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macromolecules and smaller scales of structural organization plays a central role in life processes, including, among other cellular events, metabolism, sensory transduction, gene expression, and cell division and repair. Because diffusion pertains to scales, times, and temperatures relevant for classical, quantum, and semiclassical/semiquantum physicochemistry, its mathematical description may incorporate terms specific to each respective mechanical regime. Thus, biologists presuppose that such individual or combined terms of a diffusion equation reasonably explain, for instance, the transfer of electrons within a catalytic chain, the trafficking of proteins through liquid-filled cell compartments, or the flow of gas molecules across semipermeable membranes. If a diffusive process falls within a certain physicochemical boundary, such as thermodynamic sensitive classical behavior, then terms relating other regimes, such as quantum or mixed behaviors, become trivial. Quantum biologists may feel secure that physicochemical equations, for all intents-and-purposes, properly correspond to the physicochemical events for which they were written.

Contrary to some popular accounts (cf. Lee and Johnson, 2002), however, accumulating evidence indicates a similar strict correspondence may not always exist between physicochemical parameters of a biological system and its information processing capabilities. A good example of this incongruity concerns the information processing of eukaryotic microbes, broadly known as contractile ciliates. These single-celled organisms display both classical and quantum information processing when experiencing socially valuable situations. Ciliates capable of quantum information processing show greater social aptitude and, consequently, survival and reproductive fitness. As discussed below, one of the hypothesized mechanisms of ciliate information processing is the classical reaction-diffusion of intracellular Ca^{2+} messenger pathways. Autocatalytic Ca^{2+} reactions parsimoniously describe both classical and quantum traits of ciliate social decision making via subtle modifications to the diffusion coefficient and other reaction parameters. The significance of Ca^{2+} response regulator pathways for bacteria, fungi and molds, plants, and animals suggests that the

same sort of mechanism might mediate both classical and quantum biocomputations across phylogeny, a finding that would radically change our understanding about what types of criteria should define quantum biology.

Social Decision Making by Ciliates

Contractile ciliates are among the most sophisticated social decision makers near or below the animal-fungal divergence. For instance, similar to “higher” eukaryotes, they learn to use courtship and dominance displays to help attract mates and deter rivals (Clark, 2010a-d, 2011a, b, 2012). Perimating events used by ciliates to convey mating availability and fitness are typically initiated upon detection of peptide pheromones secreted by nonself mating types (cf. Miyake, 1981; Vallesi *et al.*, 2005). Circulating gradients of pheromones and cell-tethered pheromones advertise the spatial position and type of mate(s) available. Attracted individuals may try to engage one or more compatible partners in sexual-like conjugation producing up to eight daughter cells per reproductive pair at lifecycle’s end (Lynn, 2008). In different ciliate genera, stereotypic courtship dances, dominance displays, and preconjugal changes in cell structure allowing partner docking and gene exchange result from specific pheromone binding to G-protein-associated paracrine receptors (Bishop, 1923; Cronkite, 1975; Lynn, 2008; Miyake, 1981; Ricci, 1990; Seshachar and Padmavathi, 1959; Vallesi *et al.*, 2005). Activation of sexual pheromone transduction pathways in ciliates, as with other eukaryotic microbes (Baneutt, 1998; Lombardi *et al.*, 2008; Muller *et al.*, 2004; Yoshimura *et al.*, 2004), is further modified by cell-cell contacts and related events that activate intracellular Ca^{2+} -induced Ca^{2+} cascades and phosphatase- and protein-kinase-dependent feedback regulation of mechanosensation and Hebbian-like learned motility (Clark, 2010a, b; Miyake, 1981).

Quantum Information Processing by Ciliates

Ciliates, and possibly cells of different phylogenetic origin, learn to guide the planning, selection, and execution of cellular decisions, such as mating signals and behavioral sequences, with heuristics. Heuristics embody patterns of action which evolve into topologically invariant



computational networks. The combinatorial and computational dynamics of heuristics are dictated by Hebbian-like preferential attachment rules that obey quantum Bose-Einstein, quantum Fermi-Dirac, and classical Maxwell-Boltzmann statistical mechanics (Clark, 2010b-d, 2011a-c, and 2012). Because each node of a heuristic contains socially relevant bitwise content, they are used to search for social strategies stored within behavioral repertoires (Clark, 2010a, b, d), adjust levels of potential net reproductive payoffs via social honesty and deception (Clark, 2010a), diagnose and correct errors in mating signals (Clark, 2010c), solve mating dilemmas with insight or analysis schemes (Clark, 2011b), control bioenergetics expenditures (Clark, 2010b, d), and make social inferences (Clark, 2012). When ciliates employ heuristics to search for mating strategies, search patterns through respective computational networks generally differ between ciliates and social contexts. However, the algorithmic times or numbers of operations needed to search for and select appropriate behavioral strategies improve with learning over separate mating encounters, often reaching a rate comparable to finding target solutions from superposed states with Grover's quantum search algorithm (Clark, 2010a-d, 2011a-c, 2012). In other words, search times decrease by the square-root of the total number of search elements, N , stored in an evolving computational network after determination of path connectedness.

Grover's quantum search algorithm, alternately called the square-root algorithm, shows quadratic acceleration over classical processes with $N^{1/2}$ operations required to find a suitable solution. The increase in search rates exceeds the Church-Turing thesis, stating the probabilistic Turing machine is the most efficient computational device. Information processing speeds of classical algorithms searching networked data structures may also quicken following network reorganization independent of quantum influences. However, reorganizing or encapsulating computational networks into modules based on categorical descriptions denoting different levels of social information content is an unsatisfactory explanation for observed ciliate strategy search performances. Heuristics used by ciliates link $5 \leq n \leq 8$ strategies without combinatorial restructuring and encapsulate $3 \leq r \leq 6$ connected groups or modules with

combinatorial restructuring (Clark, 2010a). A probability distribution or "database", $\rho(\Pi)$, of search elements containing either upper-limit n^2 or r^2 entries indexes the likelihood of each strategy or group of strategies in the network to acquire new connections corresponding to decisions over s_N learning trials or algorithmic steps (cf. Clark, 2010a, b). Imposing such constraints, optimal search patterns for strategies follow Hebbian-like preferential attachments rules determined by an annealing parameter proportional to associative learning strength (Clark, 2010b). The relations $N = n^2$ for individual strategies and $n^2 > r^2$ for grouped strategies then become the smallest possible numbers of operations for complete classical strategy searches by ciliates performing the traveling salesman problem (cf. Clark, 2010a, b). Because often $N^{1/2} = n < r^2$, ciliates use some type of quantum mechanism rather than classical recombination to improve strategy search speeds beyond the capabilities of classical algorithms (Clark, 2010a). This conclusion is further supported by the finding that ciliate decisions to switch between strategies of higher or lower ecological fitness conforms to linear and nonlinear Arrhenius kinetics during respective classical and quantum information processing phases (Clark, 2010d).

Another intriguing computational feature of ciliate mating heuristics is the emergence of the computational analogue of Bose-Einstein condensation (Clark, 2010b). Self-organizing computational objects, such as evolving complex technological networks, map onto an equilibrium Bose gas following Bose-Einstein statistics (Bianconi and Barabási, 2001). Mappings occur whether or not the network itself is in equilibrium or reversible. Network nodes correspond to energy levels and connections between nodes correspond to particles. As a network transitions toward Bose-Einstein condensation, a lone fittest node or energy level always gains a macroscopic fraction of new connections or particles reminiscent of true "winner-takes-all" behavior common to competitive systems. Distributions of network connections for all known computational phases depend to some extent on thermodynamic limits set by the fitness level for each node contained within a network. But only network nodes forming "winner-takes-all" Bose-Einstein condensates continue to maintain time-independent portions of links as they approach energetic



ground states. Ciliate heuristics, like technological networks, condense onto fittest mating strategies during decision making. Ciliates that show the fastest strategy search rates and that later learn to signal brief periods of either easier-to-get or harder-to-get mating assurances begin mating encounters condensed on fittest courting solutions. When these ciliates switch from their first strategy choices, Bose-Einstein condensation of strategy use abruptly dissipates into a Maxwell-Boltzmann computational phase no longer dominated by a single fittest strategy. Recursive trial-and-error strategy searches anneal strategy use back into a condensed phase consistent with performance optimization. These results verify efficient information processing by ciliates involves network forms of Bose-Einstein condensation coupled to preceding thermodynamic sensitive computational phases.

Rates of Quantum Search Algorithms and Autocatalytic Ca^{2+} Reactions

Grover's quantum search algorithm relies on an initial superposition of arbitrary N eigenstates to later execute nonclassical "subroutines" involving unitary phase shifts on eigenstates and to produce a root-rate gain in the algorithmic time (i.e., $O(N^{1/2})$) needed to arrive at some "target" variable x (cf. Grover, 1996; Nielsen and Chuang, 2000). Occurrence of a quantum square-root algorithm in ciliate strategy search performances indicates that the biomechanism(s) essential for expression of the phenomenon might also approximate operational characteristics of known quantum algorithms. Many components of a cell's computational machinery may be involved in producing noticeable quantum operational characteristics in the decision processes of cells. For example, cytoskeletal lattices (Craddock *et al.*, 2009; Hameroff, 1994; Matsuno, 2006), photosynthetic protein complexes (Hu *et al.*, 1998; Sener *et al.*, 2005; Trevors and Masson, 2010), the citric acid cycle (Matsuno, 2006) and metabolism (Demetrius, 2003), molecular ratchets (Cooper, 2009; Matsuno, 1999, 2006; McFadden and Al-Khalili, 1999; Patel, 2001), molecule folding (Cieplak and Hoang, 2003; Gutin *et al.* 1996), and genetic logical switches (Mayo *et al.*, 2006; Möbius *et al.*, 2005; Sudarsan *et al.*, 2006) have been previously associated with quantum-level biological activity. Quantum effects at both informational

and physical degrees of freedom thus seem to appear in every major aspect of cell structure and function, from sensory transduction to gene expression to cellular metabolism to cell motility.

With the exception of ciliate strategy search performances, however, the only reported instance of quantum searches by a biological system is for DNA polymerases that sample and sort nucleotide base pairs during DNA replication and proofreading. Such biocomputations are believed to exploit the quantum superposition of mutational genetic states (Cooper, 2009; Patel, 2001). It is improbable that observed ciliate quantum information processing utilizes this sort of mechanism. Chromosomal functions expressed via mRNA translation and protein synthesis exert major effects on traditional long-term (and not short-term) dual-process learned behaviors in animals. Protein synthesis is needed to consolidate encoded information into memories lasting days or longer. But the briefer time frame of comparable learning and memory by short-lived ciliates (cf., Eisenstein *et al.*, 1982) supports the idea that genetic processes may be only involved in a more-or-less peripheral or supportive way in microbes. Instead, the reaction kinetics of chemical processes mediating the Ca^{2+} -dependent behavioral planning and execution of ciliates offer a better explanation for the expression of fast strategy searches. In particular, Ca^{2+} -induced Ca^{2+} waves initiated by activated mechanosensitive Ca^{2+} channels serve as a likely mechanism for ciliate quantum information processing and perhaps similar cellular information processing across all systematics levels (Clark, 2010a-d, 2011a-c, 2012).

Mechanical stimulation felt by ciliates during mating contacts, for example, cause Ca^{2+} influx via cooperative G-protein-coupled mechanoreceptors and voltage-gated channels. Rising Ca^{2+} concentrations next liberate further Ca^{2+} from intracellular stores that form networks throughout cortical and subadjacent endoplasmic compartments. These cellular regions contain cytoskeletal contractile myonemes and ciliary axonemes vital for cell motility and many social interactions. Due to their importance in cellular response regulation (cf. Dominguez, 2004; Nowycky and Thomas, 2002; Plattner and Klauke, 2001; Plieth, 2005), networks of intracellular Ca^{2+}



release sites present an excellent substrate for single cells to store associatively learned information into memory circuits and to retrieve that same information with fast search algorithms capable of eliciting stored behavioral strategies of assorted fitness (Clark, 2010a, b, 2011c). Variable spatiotemporal patterns of activated/inactivated intracellular Ca^{2+} stores putatively crosstalk with other response regulator systems, including epigenetic, genetic, and somatic regulatory networks, to “bind” salient information into internal representations that provide a physical basis for heuristics. Such internal representations may be later selectively activated and modified by additional extero- and/or interoceptive sensations and the subsequent differential spread and speed of autocatalytic Ca^{2+} waves linking storage sites. Factors that affect the dynamics of intracellular Ca^{2+} waves include free Ca^{2+} buffering and uptake, periods of Ca^{2+} mobilization, distances between calcium storage sites and effector systems, and phosphatase- and protein-kinase-dependent feedback control over Ca^{2+} -conducting receptor complexes, transporters, and exchangers (cf. Chen *et al.*, 2008, 2009; Clark, 2010a, b, 2011c; De Pitta *et al.*, 2008, 2009; Matsuno, 1999; Siso-Nadal *et al.*, 2009).

If modifiable operation of linked intracellular Ca^{2+} storage sites and associated affector/effector systems function as computational networks and heuristics, then reaction-diffusion equations should reveal classical and quantum properties of strategy search algorithms and patterns selectively applied to those networks. One such reaction-diffusion equation, the fire-diffuse-fire model of Ca^{2+} propagation, defines Ca^{2+} waves by the evolution equation (Ponce-Dawson *et al.*, 1999):

$$\partial[\text{Ca}^{2+}]/\partial t = D(\partial^2[\text{Ca}^{2+}]/\partial^2 x) + (\sigma/d^2\tau)\sum \delta(x - x_i)H(t - t_i)H(t_i + \tau - t), \quad (1)$$

where $[\text{Ca}^{2+}](x,t)$ is the average concentration of calcium in directions perpendicular to the direction x of propagation, $\delta(\zeta)$ is the δ function, $H(\zeta)$ is the Heavyside step function, D is the classical Ca^{2+} diffusion coefficient, t_i is the first time the i th Ca^{2+} release site reaches threshold value, σ is the total number of Ca^{2+} ions released per storage site, and τ is the

period that receptors remain open to release Ca^{2+} in a single event. The dynamics of this equation depend on two dimensionless parameters, Γ and β (Ponce-Dawson *et al.*, 1999). The former parameter is the ratio of released $[\text{Ca}^{2+}]$ to the difference between basal and threshold $[\text{Ca}^{2+}]$, while the latter parameter is the ratio of the Ca^{2+} release time to the Ca^{2+} diffusion time between storage sites. The parameter Γ acts as a multiplicative variable governing wave velocity. When chemical processes, such as the duration of Ca^{2+} mobilization, become rate-limiting over interstore distances, Ca^{2+} waves transition from slow saltatory to fast continuous wave fronts. Thus, the value of parameter β defines whether a Ca^{2+} wave front propagates in a slow saltatory, fast continuous, or intermediate mixed fashion. Moreover, slow saltatory wave propagation travels at a rate proportional to the Ca^{2+} diffusion coefficient (Ponce-Dawson *et al.*, 1999), $v \approx (D/d)(g^{-1})(\Gamma)$, where d is the distance between Ca^{2+} release sites and g^{-1} is an inverse function. The velocity of fast continuous waves is proportional to the square-root of the Ca^{2+} diffusion coefficient (Ponce-Dawson *et al.*, 1999), $v \approx (D/\tau)^{1/2}(f^{-1})(\Gamma)$, where f^{-1} is an inverse function. Fire-diffuse-fire models of Ca^{2+} propagation are remarkably robust, explaining the diffusive characteristics of store-operated Ca^{2+} regulation in a wide variety of eukaryotic cell types, including oocytes, cardiac myocytes, and neurons.

Importantly, the leading edge of intracellular Ca^{2+} gradients are comparatively slow, being experimentally recorded to often travel at velocities ranging from 20 to 70 $\mu\text{m/s}$ (Jaffe, 1993). But when N and D are numerically related (Clark, 2010a), the quadratic disparity between the speeds of saltatory and continuous Ca^{2+} waves is nevertheless consistent with expression of a square-root quantum algorithm that increases strategy searches in living cells beyond the bounds of classical algorithms (Clark, 2010a, b, 2011c). In the algorithmic sense, the properties of classical Ca^{2+} diffusion therefore successfully describe the phenomenon (cf. Clark, 2010a, b). A physical manifestation of quantum mechanics via a quantum diffusion term is unnecessary to produce quantum-efficient searches. This result is perhaps counter-intuitive for most quantum biologists because diffusive processes may be classical, quantum, or semiclassical/semiquantum in



nature. The diffusion coefficient or diffusivity, D , in Eq. 1 is a purely classical one generally derived from Fick's laws and the Einstein-Smoluchowski relation as $D = \mu k_B T$, where μ is particle mobility or the inverse drag coefficient, k_B is Boltzmann's constant, and T is temperature in degrees Kelvin. This equation, via the Einstein-Sutherland relation, becomes the Einstein-Stokes equation in one dimension, $D = k_B T / 2\pi\eta r$, and in three dimensions, $D = k_B T / 6\pi\eta r$, for spherical particles of radius r moving through a fluid of viscosity η at a low Reynolds number. If the density of the diffusing material affects D , then the diffusion equation is nonlinear and D is taken to be variable. When independent of thermodynamic influences, $D = h / 4\pi m$, where h is Planck's constant and m is the mass of the diffusing particle. This latter definition of the diffusion coefficient is quantum mechanical.

At the biologically pertinent subsecond times, warm temperatures, and micrometer scales described for the conditions of Ca^{2+} fire-diffuse-fire reactions (cf., Ponce-Dawson *et al.*, 1999), quantum diffusive processes produce negligible effects without thermodynamic shielding, such as in the case of bacterial photosynthetic reaction cores (Hu *et al.*, 1998; Sener *et al.*, 2005; Trevors and Masson, 2010), or pump-process energy transfer, such as in the possible case of actomyosin polymerization (Matsuno, 1999). Neither thermodynamic shielding nor pump-process constraints must be invoked for classical fire-diffuse-fire reactions. In view that classical diffusion terms satisfy the quadratic improvements needed for Grover's quantum search algorithm, it is interesting that search selectivity by such an algorithm in single cells is probably enhanced, rather than impaired, by diffusion barriers causing unstable Ca^{2+} gradients. Anisotropic patterns of Ca^{2+} diffusion due to free cytosolic chaperons and buffers (Chen *et al.*, 2008, 2009) and frequency and amplitude modulated Ca^{2+} liberation (De Pitta *et al.*, 2008, 2009) have been reported to help improve the specificity of encoding sensory information transmitted by intracellular Ca^{2+} cascades. The storage and retrieval of that information is expected to be further refined by recursive phosphorelays affecting Ca^{2+} permeability to extracellular sources (Clark, 2010a-d, 2011c). In addition, intracellular spaces are filled with Ca^{2+} traps, such as immobile binding sites. Traps lower the effective diffusion coefficient below that

expected for free diffusion. But the propagation of information moves faster than single particle diffusion (Pando *et al.*, 2006).

Additional Properties of Quantum Search Algorithms and Ca^{2+} Response Regulator Pathways

Although learned quadratic changes in the kinetics of autocatalytic Ca^{2+} reactions meet the critical lower-bound speed requirements of a quantum search algorithm, other basic features of quantum search algorithms should be considered as well. If making comparisons with Grover's quantum search algorithm, then an initial superposition of search elements and Grover's iteration (cf. Grover, 1996; Nielsen and Chuang, 2000) must be accounted for by ciliate biocomputations. An initial superposition state, in a macroscopic form of the network analogue of Bose-Einstein condensation, appears during the early stages of heuristic-guided ciliate decision making (Clark, 2010b). As with Grover's quantum search algorithm, this superposition seems to place heuristics into a configuration that enables faster computations to be performed across the set of search elements, as ciliates that fail to initialize their heuristics into Bose-Einstein condensates never attain quantum search efficiencies (Clark, 2010b). Ciliates then apply iterative searches, reminiscent of Grover's iteration, until a Maxwell-Boltzmann computational phase abruptly occurs, corresponding to a switch in mating strategy preferences and determination of path connectedness between heuristic nodes. The interruption of quantum computations by classical computations is difficult to resolve with a straightforward interpretation of Grover's quantum search algorithm. However, this event may help to energetically drive, similar to an energy pump (e.g., Fröhlich, 1968, 2004; Matsuno, 2006), heuristics toward another subsequent Bose-Einstein condensation state and a reversal of strategy preferences (Clark, 2010b) after repeated strategy searches. Whatever the purpose, ciliates fail to achieve a quadratic improvement in search efficiencies without prior appearance of Maxwell-Boltzmann computational phases.

While biochemical feedback loops might process information in a manner similar to Grover's iteration, there remains the question of how an initial superposition of



search elements is physically accomplished for ciliate search performances. Changes in the kinetics of autocatalytic Ca^{2+} reactions provide some tentative explanations (Clark, 2010b). When chemical processes, such as the duration of Ca^{2+} mobilization, become rate limiting over interstore distances, intracellular Ca^{2+} waves evolve into transitional states of charged vortices or spiral waves that show characteristics of both slow saltatory and fast continuous wave fronts (Reas and Ballaró, 2004). cursory inspection of this effect suggests fluctuating mesoscopic collections of Ca^{2+} ions bring about dynamic phenomena comparable to the quantum behavior of quasiparticles at physiological temperatures. But exactly how Ca^{2+} ions under biological conditions assemble into a physical Bose-Einstein condensate remains unknown. For instance, the most stable and common Ca^{2+} isotope with its even atomic number and mass possesses no nuclear spin for the formation of magnons. Being a cation with few outer-shell electrons, Ca^{2+} ions also are unable to emit photons as an outcome of biologically important reactions. Macroscopic Brownian motion can readily cohere individual Ca^{2+} ions into larger scale waves. Yet the kinetic or vibrational energy of individual Ca^{2+} ions do not resonate in the same ground state without strong environmental coupling, strictly constraining the probability of Bose-Einstein condensation for phonon-type liquid lattices. Perhaps the emergence of a Maxwell-Boltzmann computational phase serves to facilitate environmental coupling. Nonetheless, as noted above, entrained synchronous activity between stores discharging localized Ca^{2+} puffs may bind social information into computational networks and heuristics. Synchronous activity of store-operated Ca^{2+} release increases the conduction velocity of Ca^{2+} waves to a level supporting fast search algorithms. Hebbian-like associative learning may further pare the number and distribution of activated Ca^{2+} release sites to enhance metabolic and information processing efficiency to some critical threshold, such as that defined by optimal annealing and associative strength, where one strategy becomes favored over another. Taken together, recurrent feedback, networked cellular substrate(s), and fast intracellular Ca^{2+} waves realistically cooperate to condense a ciliate's courting decisions onto preferred mating strategies.

Phylogenetic Relevance of Ca^{2+} -mediated Quantum Information Processing

Two *in situ* biological systems, intracellular Ca^{2+} signaling cascades (Clark, 2010a, b, 2011c) and polymerase-mediated DNA replication and proofreading (Patel, 2001), are currently known to fulfill many of the exacting computational requirements of producing Grover's quantum search algorithm at the scale of a single cell. Free intracellular Ca^{2+} serves as an intermediate between sensory input and response output for all known cellular life (cf. Dominguez, 2004; Nowycky and Thomas, 2002; Plattner and Klauke, 2001; Plieth, 2005). It aids in controlling stress responses, cell fate and death, synaptic plasticity, cell motility and growth cone extension, cell energetics, host-pathogen and pathogen-pathogen interactions, changes in cell morphology, and many other cellular events. While there is some debate over whether intracellular Ca^{2+} messenger systems act as a chemical switch and/or as a digital information channel (Hameroff *et al.*, 2010; Plieth, 2005), no doubt exists about the importance and ubiquity of Ca^{2+} signaling pathways across phylogeny. Specific details of signaling pathways, such as the evolutionary origins, structure, and function of Ca^{2+} -conducting channels, may differ between prokaryotes and eukaryotes (Martinac *et al.*, 2008) and even among eukaryotes (Martinac *et al.*, 2008; Wheeler and Brownlee, 2008). Yet the basic principles of Ca^{2+} -induced Ca^{2+} reactions remain the same (Ponce-Dawson *et al.*, 1999). An initial entry or release of Ca^{2+} excites further localized Ca^{2+} release from compartmentalized networks of intracellular Ca^{2+} stores. Depending on parameters involving Ca^{2+} concentrations, Ca^{2+} release times, interstore distances, and other variables, Ca^{2+} waves arise, extinguish, and propagate at differential speeds, patterns, and distances. These properties fit the properties required of Grover's quantum search algorithm, such as search speeds, regardless of what afferent and efferent systems are involved. And they do so without need of quantum diffusion or other manifest quantum physicochemical behavior.

Although currently untested, examples of Ca^{2+} -dependent quantum-efficient information processing should be readily found for a number of well-studied biological systems besides aneural ciliates. Central and



peripheral nervous systems of animals are just one set of possibilities, indicating that Ca^{2+} -dependent quantum information processing might have evolved to improve the information storage capacity, processing speeds, and error diagnosis and correction of whole multicellular organisms as well as their systems, tissues, and cells. For instance, Ca^{2+} response regulation affects induction and/or maintenance of certain forms of animal learning by modulating synaptic efficacy between pre- and postsynaptic neuronal terminals. Sensitization, a nonassociative response increment to repeated exposures to the same stimulus, depends on Ca^{2+} influx through voltage-gated channels which, in turn, increases presynaptic transmitter mobilization and release. Augmented transmitter release causes synaptic enhancement, technically referred to as heterosynaptic facilitation. Associative forms of learning, such as classical conditioning, are also dependent upon Ca^{2+} mechanisms. Long-term potentiation, the change in synaptic efficacy and configuration thought to underlie some associative forms of learning and memory, requires entry of Ca^{2+}

into neurons via selective ligand and/or voltage gated channels. Postsynaptic Ca^{2+} influx induces long-term potentiation by activating protein kinases, while presynaptic Ca^{2+} influx, mediated by retrograde messengers, maintains long-term potentiation by enhancing transmitter release. Structural changes in synaptic terminals accompanying improved synaptic transmission also are brought about by free intracellular Ca^{2+} . In each of these cases, Ca^{2+} -induced Ca^{2+} reactions, often during a “post-tetanic” potentiation period, contribute to messenger cascades that regulate mechanisms of learning and memory. Therefore, whether one considers Ca^{2+} -dependent nonassociative or associative animal learning and memory, the ecological impact of quantum-efficient processing seems quite predictable. As with ciliates, animals capable of elevating their information processing to quantum levels figure to be better learners, adapting their behaviors and social strategies more quickly and accurately to meet environmental demands.

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