Quantum Computation in Brain Microtubules? Decoherence and Biological Feasibility

S. Hagan a, S. R. Hameroff b,d, J. A. Tuszyński c,d

a Computational Modeling Lab, Department of Information Research, N.A.R.C.

3-1-1 Kannondai, Tsukuba, 305-8666, Japan

b Departments of Anesthesiology and Psychology and Center for Consciousness Studies

University of Arizona, Tucson, AZ 85724, USA

c Department of Physics, University of Alberta, Edmonton, Alberta, T6G 2J1, Canada

d Starlab NV/SA, Boulevard Saint-Michel 47, Brussels 1020, Belgium

The Penrose-Hameroff ('Orch OR') model of quantum computation in brain microtubules has been criticized as regards the issue of environmental decoherence. A recent report by Tegmark finds that microtubules can maintain quantum coherence for only 10^{-13} s, far too short to be neurophysiologically relevant. Here, we critically examine the assumptions behind Tegmark's calculation and find that: 1) Tegmark's commentary is not aimed at an existing model in the literature but rather at a hybrid that replaces the superposed protein conformations of the 'Orch OR' theory with a soliton in superposition along the microtubule, 2) Tegmark predicts decreasing decoherence times at lower temperature, in direct contradiction of the observed behavior of quantum states, 3) recalculation after correcting Tegmark's equation for differences between his model and the 'Orch OR' model (superposition separation, charge vs. dipole, dielectric constant) lengthens the decoherence time to $10^{-5} - 10^{-4}$ s and invalidates a critical assumption of Tegmark's derivation, 4) incoherent metabolic energy supplied to the collective dynamics ordering water in the vicinity of microtubules at a rate exceeding that of decoherence can counter decoherence effects (in the same way that lasers avoid decoherence at room temperature), and 5) phases of actin gelation may enhance the ordering of water around microtubule bundles, further increasing the decoherence-free zone by an order of magnitude and the decoherence time to $10^{-2} - 10^{-1}$ s. These revisions bring microtubule decoherence into a regime in which quantum gravity can interact with neurophysiology.

I. INTRODUCTION

In the conventional biophysical approach to understanding cognitive processes, it has been generally accepted that the brain can be modeled, according to the principles of classical physics, as a neural network [1–5]. Investigations in this field have delivered successful implementations of learning and memory along lines inspired by neural architectures and these have promoted optimism that a sufficiently complex artificial neural network would, at least in principle, incur no deficit in reproducing the full spectrum and extent of the relevant brain processes involved in human consciousness.

However, physical effects in the functioning of the nervous system that lie outside the realm of classical physics

suggest that such simulations may ultimately prove insufficient to the task. One finds ample support for this in an analysis of the sensory organs, the operation of which is quantized at levels varying from the reception of individual photons by the retina [6,7] to thousands of phonon quanta in the auditory system [8]. Of further interest is the argument that synaptic signal transmission has a quantum character [9,10], although the debate on this issue has not been conclusive [11]. We note that using the thermal energy at room temperature in the position-momentum uncertainty relation, and assuming a 1 Å uncertainty for quantal effects, Beck and Eccles [9] concluded that a particle whose mass is just six proton masses would cease to behave quantum mechanically and become classical for all intents and purposes. This seems a serious underestimate, based on the de Broglie wavelength alone. In any case, it is known that quantum modes of behavior exist in much larger structures such as peptides, DNA and proteins [12]. For instance, Roitberg et al. [13] demonstrated functional protein vibrations that depend on quantum effects centered in two hydrophobic phenylalanine residues, and Tejada et al. [14] have evidence to suggest that quantum coherent states exist in the protein ferritin.

The inadequacy of classical treatments is further suggested at the cognitive level, not only in regards to long-standing difficulties related to, for instance, accounts of semantics [15], binding [16], and the neural correlate of consciousness, but even in the rather modest goal of reproducing cognitive computational characteristics. Penrose, in particular, has argued that human understanding must involve a non-computational element [17,18] inaccessible to simulation on classical neural networks and this might be realized through a biological instantiation of quantum computation.¹ Along these lines, Penrose

¹It has been noted that fundamentally analog mechanisms, based on continuous rather than traditional discrete (Turing) computation, might also constitute non-computation in the relevant sense and equally evade Penrose's argument. It is not widely appreciated in the cognitive science community, however, that the essentially discrete nature of exocytosis implies that no such description can be framed in terms of the

and Hameroff have put forth a specific model [19–21] – orchestrated objective reduction (Orch OR) – positing quantum computation in microtubule protein assemblies in the neurons of the brain.

Microtubules are hollow cylinders whose walls consist in 13 columns (protofilaments) of the protein tubulin arranged in a skewed hexagonal lattice. Along with other structures, microtubules comprise the internal scaffolding - the 'cytoskeleton' - in cells including neurons. Determinants of both structure and function, cytoskeletal structures are dynamically active, performing a host of activities instrumental to cellular organization and intelligence [22]. Earlier models (see, for instance, [23–29]) proposed classical information processing among the tubulin 'dimers' composing microtubules - molecular-level automata regulating real-time cellular behavior. More recently, arguments have been made for quantum computation at the level of individual proteins [30]. In particular, functional protein conformational states are mediated by quantum van der Waals forces [31], the relevance of which is demonstrated by the mechanism of action of the general anesthetic gases that reversibly ablate consciousness. Anesthetics act by disturbing such forces in the hydrophobic pockets of various brain proteins [32,33]. Microtubules are thus poised to mediate between a tubulin-based quantum computation and the classical functioning of neurons.

The Penrose-Hameroff proposal suggests that coherent superpositions of tubulin proteins are inherently unstable and subject to self-collapse under a quantum gravitational criterion. Calculations indicate that decoherence due to such a quantum gravitational mechanism might allow coherence to survive for milliseconds, even up to a second, in the context of the brain [19,20,34,35]. According to the Orch OR model, quantum coherent states that persist over such a neurophysiologically relevant time frame could influence cognitive processes, in a manner accounting for the non-computational element, by 'orchestrating' state vector reductions to perform quantum computation.

Recently, Tegmark [36] has responded to this and other models of brain function invoking a quantum element by contending that the relevant degrees of freedom cannot reasonably be sufficiently shielded from environmental, and particularly thermal, influence to maintain quantum coherence until self-collapse. It is well-known that technological quantum devices often require extremely low temperatures to avoid decoherence through environmental interaction. The survival of a delicate quantum coherence in the 'warm, wet and noisy' milieu of the brain long enough for quantum computation to play a neurophysiological role therefore seems unlikely to many observers. Tegmark maintains that orthodox mechanisms of deco-

neurochemical basis of synaptic function.

herence would collapse a microtubule-associated quantum state on a timescale of the order of 10^{-13} seconds, much shorter than that associated with decoherence by quantum gravitational means, thus apparently superseding the possibility of an orchestrated reduction relevant to neurophysiology.²

In the following, we critically review Tegmark's assumptions, calculations, and claims to ascertain whether they accurately reflect the potential for quantum computation in the brain.

II. DECOHERENCE RATES

Tegmark considers in his paper [36] two different scales at which quantum computation might occur in the brain – one involving superpositions of neurons firing and not firing (with calculated decoherence times of 10^{-20} seconds), and another involving microtubules (calculated decoherence times of 10^{-13} seconds). We agree that superpositions at the level of neural firing are unlikely, and in fact play no role in the Orch OR or any other contemporary quantum model. We therefore focus our attention on Tegmark's assertions regarding decoherence times for microtubule-associated quantum states.

Though Tegmark specifically implicates Penrose, his criticisms target neither the Penrose-Hameroff Orch OR model nor any other that is currently or has been under investigation. It appears to be directed against a spuriously quantum version of a classical model, put forth by Sataric *et al.* [26], to treat lossless energy transfer in microtubules in terms of kink solitons travelling along their length.

Tegmark considers a model in which kink soliton solutions, like those of Sataric et al. [26], exist in a quantum superposition of different positions along the microtubule. The actual Orch OR model, on the other hand, is framed in terms of superpositions of the conformational state of a tubulin dimer. The fact that this state is coupled to a delocalized electron residing in the hydrophobic pocket of the tubulin dimer protein points to a process of conformational change in the dimer controlled by quantum level events. There is thus a considerable conceptual disparity between this model and that considered by Tegmark. Nevertheless, it is equally critical to the

²Tegmark also maintains that the original motivations for the modifications to the Schrödinger equation implicit in a reduction postulate are obviated by the Everett relative state interpretation of quantum theory [37,38]. As has been previously noted [39,40], however, Everett's determination that the probability interpretation of the diagonal elements in the density matrix automatically holds for most observers depends on the prior assumption of a probability interpretation for the measure over the space of observers, and so itself constitutes an additional postulate.

actual model that the mechanisms of decoherence analyzed do not destroy quantum coherence before a quantum gravity-induced self-collapse can come into play. Below, we consider both numerical and theoretical concerns that bear on the results presented by Tegmark.

In the microtubule case, Tegmark determines the time to decoherence, τ , due to the long-range electromagnetic influence of an environmental ion to be:

$$\tau \sim \frac{4\pi\epsilon_0 a^3 \sqrt{mkT}}{Nq_e^2 s},\tag{1}$$

where T is the temperature, m is the mass of the ionic species, a is the distance to the ion from the position of the quantum state, N is the number of elementary charges comprising that state, and s is the maximal 'separation' between the positions of the tubulin mass in the alternative geometries of the quantum superposition. Since any difference in the mass distributions of superposed matter states will impact upon the underlying spacetime geometry, such alternative geometries must presumably be permitted to occur within the superposition.

It is worthy of immediate note that the decoherence time given by Tegmark in equation (1) is manifestly incorrect with respect to its temperature dependence. As absolute temperature increases, the opposite should happen to the decoherence time as a result of the increasing influence of environmental fluctuations on the quantum rate. This will be further elaborated in section II D, but we first consider those corrections required by the current formulation that do not alter the theoretical foundation of the derivation.

A. Superposition 'separation'

Superposition occurs not only at the level of a mass distribution separated from itself, but concomitantly at the level of the underlying spacetime geometry. According to Penrose's quantum gravitational criterion for objective reduction, superpositions involving different spacetime geometries are considered inherently unstable, with the rate of collapse determined by a measure of difference in the geometries. As this measure approaches the order of a Planck length, it becomes problematic to determine a consistent standard by which to match up points in the superposed geometries. Yet if the superposed spaces cannot be resolved into one and the same space, then the different matter states in the superposition must occur in separate spaces and the meaning of 'superposition' in this context becomes obscure. Thus the rate of collapse in Penrose's suggestion for objective reduction must become significant before the measure of difference in superposed spacetime geometries grows to the Planck scale. Since gravitational forces are inherently weak, however, the mass distributions of the superposed matter states can be substantially 'separated' before incurring a large measure of difference in the associated spacetime geometries.

Tegmark assumes that this separation, s, must be at least as large as the diameter of a microtubule, D=24 nm, for superpositions spanning many tubulin dimers. This estimate is based on a picture of tubulin dimers literally 'beside themselves' in superposition. However, in the Orch OR theory, the authors contemplate separation only at the level of the individual atomic nuclei of amino acids comprising the protein.

Assuming that a conformational movement of tubulin displaces its mass by roughly one tenth the radius of a tubulin monomer, Hameroff and Penrose [41] surveyed three different levels at which separation might occur: 1) partial separation (10%) of protein spheres, 2) complete separation of atomic nuclei, and 3) complete separation of nucleons. The gravitational self-energy in each instance is taken to be inversely proportional to the decoherence time according to the energy-time uncertainty relation. In the case of protein spheres, the energy, E, for partial separation is obtained from:

$$E = \frac{GM^2s^2}{2r^3} \left(1 - \frac{3s}{8r} + \frac{s^3}{80r^3} \right),\tag{2}$$

where M is the monomer mass of 55 kDa, r is the radius of a monomer sphere, and $s=\frac{1}{10}r$ is the superposition separation. For complete separations at the level of either atomic nuclei or nucleons, the contribution to the self-energy determined in separating the mass distributions to a distance of one diameter (the contact position in a spherical approximation of the masses) is of the same order as that determined by increasing the separation further, even to infinity, so the contribution in moving from coincidence to contact is a good order of magnitude estimator of the self-energy for complete separations.

Mass separation of granular arrays of atomic nuclei yields the highest energies of the three cases, and hence the shortest decoherence times, and it is this level that will thus dominate in an orchestrated reduction.³ Thus mass separation is effected already at separations the size of the nucleus, on the order of femtometers, some seven orders of magnitude smaller than Tegmark's estimate.

 $^{^3\}mathrm{Estimates}$ of the time to decoherence due to such a quantum gravitational mechanism will depend on the number of tubulin subunits participating in the quantum state. For example, calculating energies based on a separation at the level of atomic nuclei, a decoherence time of 500 ms is obtained for 10^9 participating tubulin, or about 10^3 neurons if it is assumed that 10% of the tubulin contained becomes coherent. Larger quantum states will collapse more rapidly.

B. Polarization and charge

In his analysis of the polarization associated with the microtubule, Tegmark defines p(x) to be the average component, in the direction parallel to the microtubule axis, of the electric dipole moment due to the tubulin dimers, a polarization function given in units of charge \times length. He then claims that -p'(x) represents the net charge per unit length along the microtubule, which, on dimensional grounds alone, cannot be well-founded. Nevertheless, on this basis, he integrates over the length of the microtubule across the kink to obtain a net charge that incorrectly bears the units of an electric dipole moment. This, in effect, treats the microtubule as a line of uniform charge rather than a polarized line, and this is how he obtains the magnitude of the polarization function by simply summing the *charge* of the ions arrayed around the microtubule at the level of the kink-like propagation. The value of N that figures in his estimate of the decoherence time is then this sum expressed in units of the electron charge, q_e . Aside from the dimensional incongruities in this procedure, Tegmark accounts only for the presence of 18 Ca²⁺ ions, bound to the C-terminus of the tubulin on each of 13 protofilaments in a crosssection of the microtubule. This overlooks the negative charges borne by amino acid side groups and numerous other charges associated with tubulin, all of which attract counterions from the surrounding medium.

Tubulin has only been imaged to atomic resolution within the last two years, following twenty years of difficult work with this protein. Nogales et al. published the structure of α - and β -tubulin, co-crystallized in the heterodimeric form [42]. The work establishes that the structures of α - and β -tubulin are nearly identical and confirms the consensus speculation. A detailed examination shows that each monomer is formed by a core of two β -sheets that are surrounded by α -helices. The monomer structure is very compact, but can be divided into three functional domains: the amino-terminal domain containing the nucleotide-binding region, an intermediate domain containing the taxol-binding site, and the carboxy-terminal (C-terminus) domain, which probably constitutes the binding surface for motor proteins [42].

Recently, tubulin's electrostatic properties, including its potential energy surface, were calculated [43] with the aid of the molecular dynamics package TINKER. This computer program serves as a platform for molecular dynamics simulations and includes a facility to use protein-specific force fields. With the C-terminus tail excluded, the electrostatic properties of tubulin are summarized below, following Brown [43].

Tubulin Property		Calculated Value
Charge		$-10 \; q_e$
Dipole Moment		1714 Debye
Dipole	p_x	337 Debye
Moment	p_y	-1669 Debye
Components	p_z	198 Debye

TABLE I. Calculated values of some electrostatic properties of tubulin

Since 1 Debye = $\frac{1}{3} \times 10^{-29} \,\mathrm{C} \cdot \mathrm{m}$, we find that the total dipole moment is approximately $5.7 \times 10^{-27} \,\mathrm{C} \cdot \mathrm{m}$, but only a fifth of it is oriented along the protofilament axis.⁴

It turns out that tubulin is quite highly negatively charged at physiological pH, but that much of the charge is concentrated on the C-terminus. This is the one portion of the tubulin dimer which was not imaged by Nogales et al. [42] due to its freedom to move following formation of the tubulin sheet. This tail of the molecule extends outward away from the microtubule and into the cytoplasm and has been described by Sackett [44]. At neutral pH, the negative charge on the carboxy-terminus causes it to remain extended due to the electrostatic repulsion within the tail. Under more acidic conditions, the negative charge of the carboxy-terminal region is reduced by associated hydrogen ions. The effect is to allow the tail to acquire a more compact form by folding.

Any exposed charge in a cytoplasm will be screened by counterions forming a double layer. The screening distance provided by these counterions and water is the Debye length and, in the case of microtubules, its value is typically 0.6-1.0 nm under physiological conditions. Due to the exposure of negatively charged amino acids in the C-terminus, a Debye layer is formed, screening thermal fluctuations due to the stronger Coulomb interactions over distances within the Debye length.

Ionic forces thus tend to cancel over even relatively short distances so that the forces mediating between tubulin and its environment should instead be characterized by dipolar interactions. This suggests that Tegmark's derivation of the decoherence time in equation (1) should be replaced with one that characterizes tubulin in terms of its electric dipole moment, thus avoiding the need to make a rather arbitrary cut in selecting which charges are to be constitutive of the overall charge of the kinked microtubule and which are to be neglected. Such a modification is accomplished by replacing the Coulomb potential, $V_{\rm Coulomb} = q^2/4\pi\epsilon_0 |{\bf r}_1 - {\bf r}_0|$, describing the interaction of a quantum state of charge q at ${\bf r}_0$ and a similarly charged environmental ion at ${\bf r}_1$, in favor of a dipole

⁴The x-direction coincides with the protofilament axis. The α monomer is in the direction of increasing x values, relative to the β monomer. This is opposite to the usual identification of the β monomer as the 'plus' end of the microtubule, but all this identifies is whether the microtubule is pointed towards or away from the cell body.

potential, $V_{\rm dipole} = q{\bf p}\cdot ({\bf r}_1-{\bf r}_0)/4\pi\epsilon_0|{\bf r}_1-{\bf r}_0|^3$, parameterized by ${\bf p}$, the electric dipole moment due to tubulin of the kinked microtubule. The interaction is well-approximated, for the purposes of an order-of-magnitude estimate, by this dipole potential in the case that a is greater than the separation of charges in the determination of the electric dipole moment. This separation will not generally be larger than the length of a tubulin dimer, 8 nm, whereas $a=\frac{1}{2}D+n^{-1/3}\approx 14$ nm for the same ionic density used by Tegmark, $n=\eta n_{H_2O}$ with $\eta\approx 2\times 10^{-4}$.

As in the Coulomb case of interacting charges, the force resulting from the dipole potential contributes only a phase factor in the evolution of the (reduced) density matrix, traced over the environmental degrees of freedom. It is thus tidal effects that determine the leading contribution to the rate of decoherence. In terms of the vector $\mathbf{a} \equiv \mathbf{r}_0^1 - \mathbf{r}_0^0$, between the initial average positions of the environmental ion and the polarized quantum state, these tidal effects are given by the Hessian matrix of second derivatives of the interaction potential:

$$\mathbf{M} = \frac{3qp}{4\pi\epsilon_0 a^4} \left[(5\hat{\mathbf{a}}\hat{\mathbf{a}}^T - \mathbf{I})(\hat{\mathbf{p}} \cdot \hat{\mathbf{a}}) - (\hat{\mathbf{a}}\hat{\mathbf{p}}^T + \hat{\mathbf{p}}\hat{\mathbf{a}}^T) \right]. \quad (3)$$

Under the same assumptions that give rise to equation (1), the dipole case yields a decoherence timescale of

$$\tau \sim \frac{4\pi\epsilon_0 a^4 \sqrt{mkT}}{3q_e ps} \Omega_{\text{dipole}},$$
 (4)

where

$$\Omega_{\text{dipole}} = \left(5\cos^2\theta\cos^2\varphi - 4\cos\theta\cos\varphi\cos\psi + \cos^2\theta + \cos^2\varphi + \cos^2\psi\right)^{-\frac{1}{2}},$$

is a geometric factor fixed in terms of the angles between \mathbf{p} , \mathbf{s} and \mathbf{a} :

$$\cos \theta = \hat{\mathbf{a}} \cdot \hat{\mathbf{s}},$$
$$\cos \varphi = \hat{\mathbf{p}} \cdot \hat{\mathbf{a}},$$
$$\cos \psi = \hat{\mathbf{s}} \cdot \hat{\mathbf{p}}.$$

In our calculations, Ω_{dipole} is taken to be of order one.⁵ The calculation of the decoherence timescale in equation 4 can be made more realistic by taking into account the dielectric permittivity of tubulin in cytosol, neglected in the original calculation. Since the intracellular medium is primarily water, its dielectric constant can be

quite high. The precise value of the permittivity of water is both temperature and frequency dependent but can be as high as $\epsilon \approx 80$ [45,46]. Conservatively estimating the dielectric constant of the surrounding medium by $\epsilon \approx 10$, and using the values, determined above, for the component of tubulin's electric dipole moment along the microtubule axis yields a decoherence time, $\tau \approx 10^{-5}-10^{-4}$ s, that is already eight or nine orders of magnitude longer than that suggested by Tegmark.

We also wish to point out that Mavromatos and Nanopoulos [35] estimated decoherence times for dipolar excitations in microtubules. Depending on the set of assumptions adopted, the value of τ obtained ranged from as low as 10^{-10} s using a conformal field theory method to as high as 10^{-4} s using a coherent dipole quantum state. For a kink state similar to that discussed by Tegmark, that value is on the order of $10^{-7} - 10^{-6}$ s.

C. Dynamical timescales, shielding and error correction

Given the sizeable discrepancy between these estimates and those of Tegmark, it seems reasonable to re-evaluate whether the assumptions made in his calculation of decoherence rates remain valid. In particular, the derivation requires that the decoherence timescale should fall far short of any relevant dynamical timescale for either the quantum object or the ionic environment, if the non-interacting contribution to the Hamiltonian is to be neglected relative to the interaction contribution. With the substantially modified decoherence times calculated above, this assumption is no longer justified, even by Tegmark's own estimates which place the dynamical timescale for a kink-like excitation traversing a microtubule at $\tau_{\rm dyn} \approx 5 \times 10^{-7}~\rm s.$ Indeed, the requirement may not even be met over the dynamical timescale of neurons firing, a scale that Tegmark places in the range $\tau_{\rm dyn} \approx 10^{-4}-10^{-3}~\rm s.$

Two possible avenues might be envisioned in the framework of the Orch OR theory by which to overcome the influence of decoherence due to scattering and tidal effects, such that decoherence by quantum gravitational effects might play a role. The most obvious solution is to require that the shortest decoherence times be those due to quantum gravity. An equally viable approach, however, is to require that decoherence due to other mechanisms be effectively countered by dynamical processes operating on timescales more rapid than that of the relevant form of decoherence. This is the means by which quantum systems like lasers maintain quantum coherence against thermal disruption at biologically relevant temperatures. The dynamical timescale is here determined by the rate at which the system is pumped by an incoherent source of energy. Appropriate dynamical timescales in the microtubule case might be determined, for instance, by the characteristic rate at which the incoherent energy provided by GTP hydrolysis - known to

⁵Though $\Omega_{\rm dipole}$ increases without bound as the three vectors, $\hat{\bf a}$, $\hat{\bf p}$, and $\hat{\bf s}$, approach mutual orthogonality, randomly oriented vectors rarely come close enough to satisfying this condition to make an order of magnitude difference in the decoherence time.

control the stability of microtubules [47,48] – is supplied to processes that maintain the quantum state against decoherence by scattering, such as actin gelation in sol-gel cycles and the ordering of water.

The transition between the alternating phases of solution and gelation in cytoplasm depends on the polymerization of actin, and the particular character of the actin gel in turn depends on actin cross-linking. Of the various cross-linker related types of gels, some are viscoelastic, but others (e.g. those induced by the actin cross-linker avidin) can be deformed by an applied force without response [49]. Cycles of actin gelation can be rapid, and in neurons, have been shown to correlate with the release of neurotransmitter vesicles from pre-synaptic axon terminals [50,51]. In dendritic spines, whose synaptic efficacy mediates learning, rapid actin gelation and motility mediate synaptic function, and are sensitive to anesthetics [52–54].

In the Orch OR model, actin gelation encases microtubules during their quantum computation phase. Afterwards, the gel liquifies to an aqueous form suitable for communication with the external environment. Such alternating phases can explain how input from and output to the environment can occur without disturbing quantum isolation.

The water within cells is itself not truly liquid, but has been shown to be, to a large extent, ordered [55]. Most of the ordered water in the cell in fact surrounds the cytoskeleton [56]. Neutron diffraction studies indicate several layers of ordered water on such surfaces, with several additional layers of partially ordered water. Tegmark himself allows that the dynamical process of ordering water in the vicinity of the microtubule⁶ could protect the quantum system from short-range sources of decoherence such as the scattering of nearby molecules.

In fact, there is a long history to the hypothesis that macroscopic quantum coherence might be supported biologically by maintaining a supply of energy at a rate exceeding a threshold value [57–59]. The collective effects responsible for the ordering of water arise in the context of a supply of metabolic energy [55]. Empirical evidence indicates that, in the presence of an activation energy approximating the amount required for the formation of a soliton on the microtubule ($\approx 0.3 \text{ eV}$), the surrounding water can be easily brought to an electret state [60,61]. Spontaneous breaking of the dipole rotational symmetry in the interaction of the electric dipole moment of water molecules with the quantized electro-

magnetic field would then give rise to the dipolar wave quanta that are postulated to mediate collective effects [62–64].

In the gel phase, the water-ordering surfaces of a microtubule are within a few nanometers of actin surfaces which also order water. Thus bundles of microtubules encased in actin gel may be effectively isolated with the decoherence-free zone, a, extending over the radius of the bundle, on the order of hundreds of nanometers. Applied to the previously corrected version of Tegmark's equation, an order of magnitude increase in the the decoherence-free zone results in a revised decoherence time for the microtubule bundle of $10^{-2} - 10^{-1}$ s.

Technological quantum computing is, in general, feasible because of the use of quantum error correction codes. It has been suggested that error correction may be facilitated by topologies – for instance, toroidal surfaces [65,66]– that allow computation and error correction to run along different axes, repeatedly intersecting. Similarly, quantum computation in the medium of microtubules may proceed longitudinally along protofilaments, with error correction codes running around the microtubule circumference in helical pathways. Interpenetration of the left- and right-handed pathways occurs such that the numbers of rows in the two pathways are successive Fibonacci numbers. Penrose [67] has suggested that this might be optimal for quantum error correction.

D. Low temperature limit

An examination of limiting cases casts further doubt on the validity of the reasoning that led Tegmark to claim such a rapid decoherence rate due to long-range forces. If the adoption of equation (1), even in the modified form, (4), is justified and definitively forecasts the climate for coherence, then it would appear that no quantum coherent states are likely to exist at any temperature. Both equations require that, as the temperature approaches absolute zero, decoherence times should tend to zero as the square root of temperature. The apparent implication is that low temperatures, at which decohering environmental interactions should presumably have minimal impact, are deemed most inhospitable to the formation and preservation of quantum coherence, contrary to experience.

Yet the low temperature regime is precisely the context in which the assumptions on which Tegmark premises his argument should be most clearly valid. Both object and environment should be well-localized near their initial average positions in this limit and, unless it is imagined that the dynamical timescale goes to zero in the low temperature limit even more rapidly than the decoherence scale – entailing a dynamical rate that increases without bound as absolute zero is approached – the requirement that the decoherence scale lie well below the dynamical timescale is also met. Accounting for the tem-

⁶Curiously, while the point is conceded with respect to the water *inside* the microtubule, Tegmark finds it more contentious as regards the water *outside* the microtubule, which "fills the entire cell volume." The mechanism of ordering is independent of whether the water is inside or outside the microtubule, and is only contended for the water closely approaching the microtubule.

perature dependence implicit in a, which must decrease to a minimum in the absence of thermal agitation, only exacerbates the counter-intuitive trend.

As quantum coherent states do, in fact, exist, and the predictions of equation (1) run contrary to observation, Tegmark's conclusions appear unfounded.

III. SYSTEMS AND SUBSYSTEMS

A. Subject vs. object

Tegmark devotes some introductory remarks in his article to an exposition of the philosophy in terms of which he means to account for cognition and, more specifically, its subjectivity. This discussion rests on an extension of the usual decomposition of physical systems in terms of object and environment to include a third subsystem, the subject, consisting of the "degrees of freedom associated with the subjective perceptions of the observer," where the term 'perception' is to include "thoughts, emotions and any other attributes of the subjectively perceived state of the observer."

By introducing the term 'subject' in this context, Tegmark fails to remark an important conceptual distinction between subject and object. In effect, he treats the subject as merely a special name for that object one studies when, for one reason or another, one wants to impute subjectivity to that collection of degrees of freedom, without explanation as to why these degrees of freedom in particular should have subjective implications or how they come to be associated with one another in a manner that does not depend on the arbitrary assignment of an observer. It is not sufficient, in accounting for the fact that an observer subjectively perceives, to simply identify certain degrees of freedom as "subjective." Whereas the object is simply the name assigned to an arbitrarily delineated subsystem of the whole, the subject is not an arbitrary product of the way one happens to choose to analyze a system. If it were, then it should be possible to associate a subject with any given subset of the available degrees of freedom. Arbitrary collections of degrees of freedom are not, however, generally credited with subjective perception. While it is a matter of the observer's choice what degrees of freedom to associate with an object, the subject must be determined as a matter of fact prior to any observer-orchestrated carving up of the problem. The existence of an object of study is a relative fact, an artifact of analysis, whereas the existence of a subject is absolute, and its determination is a fact that is itself in need of explanation.

Tegmark demonstrates his conception of the subject at work with a simple example involving two degrees of freedom, one an object, the other a subject. If the object is in the state $|\uparrow\rangle$, the system involving both degrees of freedom evolves such that $U|:\uparrow\rangle = |:\downarrow\uparrow\rangle$ and likewise, if the object is in the state $|\downarrow\rangle$, the system evolves such

that $U|:\downarrow\rangle = |:\downarrow\downarrow\rangle$. The joint subject/object density matrix, ρ_{so} , then evolves as:

$$\rho_{so} = \frac{1}{2} U(| \ddot{-} \rangle \langle \ddot{-} |) \otimes (| \uparrow \rangle \langle \uparrow | + | \downarrow \rangle \langle \downarrow |) U^{\dagger},$$

$$= \frac{1}{2} (| \ddot{\cup} \uparrow \rangle \langle \ddot{\cup} \uparrow | + | \ddot{\cap} \downarrow \rangle \langle \ddot{\cap} \downarrow |), \tag{5}$$

Tegmark's interpretation of the final state as containing two definite but opposite subjective states correlated with the object state has no basis in the formalism. Had he not illustrated the states in question with happy and sad faces, there would be nothing to necessitate, or even suggest, reading them as subjective perceptions. In a less leading notation,

$$\rho_{so} = \frac{1}{2} \Big(|\uparrow\uparrow\rangle\langle\uparrow\uparrow| + |\downarrow\downarrow\rangle\langle\downarrow\downarrow| \Big), \tag{6}$$

the same final state might be interpreted as a system in which there are simply two correlated object degrees of freedom. The ambiguity of interpretation, and the fact that there need be no subjective implications whatsoever here, is indicative of the fact that the 'subject' is simply a covert 'object'.

In exploring the thesis that "consciousness is synonymous with certain brain processes," Tegmark appears to mitigate this approach with the explicit recognition that consciousness is not arbitrarily allotted, but he gives us little help in understanding the particularity of these processes, or even why they should occur in brains. His discussion in this context, of the mutual information, I_{12} , between the subject and its environment, might be construed as the tendering of a proposal to qualitatively distinguish, at least correlatively if not causally, the subject degrees of freedom that "are our perceptions." Yet his illustrations of a mutual information criterion involve only learning and information correlation of the kind seen above in the example of equation (6). These concepts have no necessary connection to or implications for the subjective. As Tegmark himself notes, his criterion would suggest that "books and diskettes" should have a subjective aspect to them, as would maps and road signs.

B. The binding problem

The conceptual confusion, in which the subject is treated as merely another kind of object, resurfaces in Tegmark's discussion of the binding problem. The problem, as set out by James [16,36], refers to the fact that "the only realities are the separate molecules, or at most cells. Their aggregation into a 'brain' is a fiction of popular speech." The brain is, in any physical description,

⁷Of course, cells are as much physical aggregates as is the entire brain, and are just as aptly viewed as fictions. James

merely an 'object', in the sense discussed above, and is treated in this role as a unit merely by convention and not out of necessity. While this has implications for most of the standard models in cognitive science, it is particularly damaging to an identity thesis, such as the one to which Tegmark explicitly subscribes. If consciousness is synonymous with the brain, and the brain is merely a fiction of convenience, the inevitable conclusion is that consciousness is itself at best a fiction, a conclusion that we are all presumably in possession of enough personal evidence to reject. To be sure, Tegmark speaks not of the brain per se, but of "certain brain processes" or of the "subject degrees of freedom," taken collectively. But processes and units comprised of degrees of freedom are as susceptible to James' complaint as is the physical substance of the brain - none of these constitute, in a thoroughly classical understanding of cognition, more than a convenience. Each disappears in a sufficiently fine analysis, replaced by a complex of purely local activities that, while perhaps more difficult to understand, are entirely adequate to the description of the physical goings-on.

What has been suggested by several commentators on the problem [68–70] is that quantum coherence might account for holistic effects that thwart a purely local analysis, by introducing fundamentally non-local degrees of freedom. While Tegmark apparently concedes the necessity for non-local binding in the determination of fundamental wholes, he finds non-local degrees of freedom aplenty in classical physics. Crucially however, the degrees of freedom to which he points are merely artifacts of an approximate treatment. Oscillations of a guitar string, to borrow his example, can be treated as effectively non-local on timescales long compared to the timescale at which the forces that hold the string together propagate along the string. Such accounts are sufficient to an 'as if' account of the dynamics on the long timescales of an observer who lacks sufficient time resolution. Nevertheless, we do not believe that such a treatment can give a causal description because it is not relativistic.⁸ Tegmark fails to distinguish a fundamental non-locality from an effective non-locality in classical dynamics that arises only due to the presence of an insufficiently fine timescale, one that is associated with the shortcomings of an observer's knowledge of the system rather than with facts fundamental to an account of the ontology, aspects like causal propagation or the determination of a subject. Thus, the conclusion that "thoughts are presumably highly non-local excitation patterns in the neural network of our brain" is a statement made from the perspective of an outside observer making con-

presumably concedes the existence of aggregates at a cellular level only to make contact with the fundamental units of biology and an audience of biologists.

venient shorthand of the entirely local – at the classical level of interest to Tegmark – processes occurring in the extended space of the brain. The introduction into classical description, of entities and levels of analysis that supersede the local level, is superfluous.

Tegmark attempts to make room for such levels of analysis by designating a 'hyperclassical' class to distinguish the semiautonomous degrees of freedom associated with the subject. These are identified with non-equilibrium. pumped and highly dissipative systems that do not conserve energy. None of these criteria, however, constitute a qualitative distinction sufficient to remove hyperclassical degrees of freedom from the larger class of classical degrees in which they are contained, so that they appear equally subject to the criticisms above. Moreover, Tegmark's characterization of these hyperclassical systems as those with $\tau_{\rm dec} \ll \tau_{\rm dyn}$ and a dissipation time $\tau_{\rm diss} \approx \tau_{\rm dyn}$, suggests that almost any open, classical system that is not adequately treated as independent can be hyper-classical. Naturally, non-local degrees of freedom can be found, even in classical systems, at higher levels of complexity. But these are not generally taken to be fundamental in a classical ontology, as they are inevitably tied to an observer's shortcomings in terms of resolution.

IV. OUTLOOK

As discussed in detail in this paper, none of the reasons that motivated a quantum approach to the problems peculiar to subjective states have been satisfactorily addressed within a classical framework in Tegmark's critique. Neither do the mechanisms of decoherence discussed provide any clear evidence against the possibility of biologically instantiated quantum coherence of the sort envisioned in the Orch OR hypothesis. Revisions to Tegmark's numerical estimates place the decoherence times of interest in a range that invalidates the assumptions from which the calculations proceeded and the low temperature limit suggests that the theoretical foundation is flawed. When appropriately revised, both theoretically and numerically, decoherence times appear to be in line with appropriate dynamical times, an indication that there is cause for optimism that some of the fundamentally enigmatic features of the cognitive processes occurring in consciousness might yet be understood in the framework of a quantum theoretical solution.

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⁸To put it another way, such a treatment is based on a 'fictional' aggregate: the string.

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