are stronger than classical correlations. Consequently, measurements performed on one component may be interpreted as “influencing” other components entangled with it.

Because of the implication for non-local, instantaneous (therefore faster than light) influence, Einstein disliked entanglement (and quantum mechanics in general) deriding it as “spooky action at a distance”. Einstein, Podolsky and Rosen (1935) formulated the “EPR paradox”, a thought experiment intended to disprove entanglement. Imagine two members of a quantum system (e.g. two paired electrons with complementary spin: if one is spin up, the other is spin down, and vice versa – Tables 1 and 2, top). If the paired electrons (both in superposition of both spin up and spin down) are separated from each other by being sent along different wires, say to two different locations miles apart from each other, they each remain in superposition of both spin up and spin down. However when one superpositioned electron is measured by a detector at its destination and reduces/collapses to a particular spin, (say spin up), its entangled separated twin (according to entanglement) must instantaneously reduce/collapse to the complementary spin down. The experiment was actually performed in 1983 with two detectors separated by meters within a laboratory (Aspect et al., 1982) and showed, incredibly, that complementary instantaneous reduction did occur! Similar experiments have been done repeatedly with not only electron spin pairs, but polarized photons sent along fiber optic cables many miles apart and always results in instantaneous reduction to the complementary classical state (Tittel et al., 1998). The instantaneous, faster than light coupling, or "entanglement" remains unexplained, but is being implemented in quantum cryptography technology (Bennett et al., 1990). (Though information may not be transferred via entanglement, useful correlations and influence may be conveyed.)

Another form of entanglement occurs in quantum coherent systems such as Bose-Einstein condensates (proposed by Bose and Einstein decades ago but realized in the 1990's). A group of atoms or molecules are brought into a quantum coherent state such that they surrender individual identity and behave like one quantum system, marching in step and governed by one quantum wave function. If one component is perturbed all components "feel" it and react accordingly. Bose Einstein condensates (“clouds”) of cesium atoms have been shown to exhibit entanglement among a trillion or so component atoms (Vulsgaard et al., 2001).

There are apparently at least two methods to create entanglement. The first is to have components originally united, such as the EPR electron pairs, and then separated. A second method (“mediated entanglement”) is to begin with spatially separated non-entangled components and make simultaneous quantum measurements coherently, e.g. via laser pulsations which essentially condense components (Bose-Einstein condensation) into a single system though spatially separated. This technique was used in the cesium cloud entanglement

experiments and other quantum systems and holds promise for quantum information technology.

Quantum superposition, entanglement and reduction are currently being developed technologically for future use in quantum computers which promise to revolutionize information processing. First proposed in the early 1980's (Benioff, 1982), quantum computers are now being developed in a variety of technological implementations
(electron spin, photon polarization, nuclear spin, atomic location, magnetic flux in Josephson junction superconducting loops, etc.). Whereas conventional classical computers represent digital information as "bits" of either 1 *or* 0, in quantum computers, "quantum information" may be represented as quantum superpositions of both 1 *and* 0 (quantum bits, or "qubits"). While in superposition, qubits interact with other qubits (by entanglement) allowing computational interactions of enormous speed and near-infinite parallelism. After the computation is performed the qubits are reduced (e.g. by environmental interaction/decoherence) to specific classical states which constitute the solution (Milburn, 1998).

Are microtubules quantum computers?

Quantum dipole oscillations within proteins were first proposed by Fröhlich (1968; 1970; 1975) to regulate protein conformation and engage in macroscopic coherence. Conrad (1994) suggested quantum superposition of various possible protein conformations occur before one is selected. Roitberg et al (1995) showed functional protein vibrations which depend on quantum effects centered in two hydrophobic phenylalanine residues, and Tejada et al (1996) have evidence to suggest quantum coherent states exist in the protein ferritin. In protein folding, nonlocal quantum electron spin interactions among hydrophobic regions guide formation of protein tertiary conformation (Klein-Seetharaman et al., 2002), suggesting protein folding may rely on spin-mediated quantum computation.

In the context of an explanation for the mechanism of consciousness, Penrose and Hameroff (1995; c.f Hameroff and Penrose 1996a; 1996b; Hameroff 1998) have proposed that microtubules within brain neurons function as quantum computers. (Vander Waal's forces: momentary attraction between molecules, depending on their orientation to one another, DW added) The basic idea is that conformational states of tubulins, coupled to quantum van der Waals London forces, exist transiently in quantum superposition of two or more states (i.e. as quantum bits, or "qubits"). Tubulin qubits then interact/compute with other superpositioned tubulins by nonlocal quantum entanglement. After a period of computational entanglement tubulin qubits eventually reduce ("collapse") to particular classical states (e.g. after 25 milliseconds) yielding conscious perceptions and volitional choices which then govern neuronal actions. The specific type of reduction proposed in the Penrose-Hameroff model involves the Penrose proposal for quantum gravity mediated "objective reduction" (Penrose;

1998). Despite being testable and falsifiable, the proposal for quantum computation in neuronal microtubules has generated considerable skepticism, largely because of the apparent fragility of quantum states and sensitivity to disruption by thermal energy in the environment ("decoherence"). Quantum computing technologists work at temperatures near absolute zero to avoid thermal decoherence, so quantum computation at warm physiological temperatures in seemingly liquid media appears at first glance to be extremely unlikely. (Although entanglement experiments are done at room temperature.)

Attempting to disprove the possibility of quantum computation in brain microtubules, University of Pennsylvania physicist Max Tegmark (2000) calculated that microtubule quantum states at physiological temperature would decohere a trillion times too fast for physiological effects, with a calculated decoherence time of 10^{-13} seconds. Neurons generally function in the range of roughly 10 to 100 milliseconds, or 10^{-2} to 10^{-1} seconds.

However Tegmark didn't actually address specifics of the Penrose-Hameroff model, nor any previous theory, but rather proposed his own quantum microtubule model which he did indeed successfully disprove. For example Tegmark assumed quantum superposition of a soliton wave traveling along a microtubule, "separated from itself" by 24 nanometers. The Penrose-Hameroff model actually proposed quantum superposition of tubulin proteins separated from themselves by the diameter of their atomic nuclei. This discrepancy alone accounts for a difference of 7 orders of magnitude in the decoherence calculation. Further corrections in the use of charge versus dipoles and dielectric constant lengthens the decoherence time to 10^{-5}–10^{-4} seconds. Considering other factors included in the Penrose-Hameroff proposal such as plasma phase screening, actin gel isolation, coherent pumping and quantum error correction topology intrinsic to microtubule geometry extends the microtubule decoherence time to tens to hundreds of milliseconds, within the neurophysiological range. Topological quantum error correction may extend it significantly further. These revised calculations (Hagan et al., 2002) were published in *Physical Reviews E*, the same journal in which Tegmark's original article was published.

The basic premise that quantum states are destroyed by physiological temperature is countered by the possibility of laser-like coherent pumping ("Fröhlich mechanism") suggested to occur in biological systems with periodic structural coherence such as microtubules. Moreover Pollack (2001) has shown that water in cell interiors is largely ordered due to surface charges on cytoskeletal actin, microtubules and other structures.
Thus despite being largely water, cell interiors are not "aqueous" but rather a crystal-like structure. Perhaps most importantly, experimental evidence shows that electron quantum spin transfer between quantum dots connected by organic benzene molecules is *more* efficient at room temperature than at absolute zero (Ouyang and Awschalom, 2003). Other experiments have shown quantum wave behavior of biological porphyrin molecules (Hackermüller et al., 2003). In both

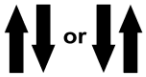
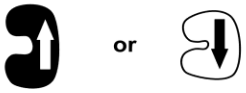
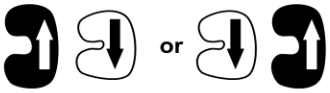
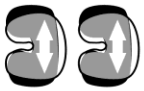
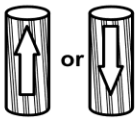
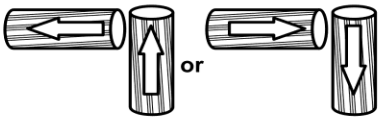
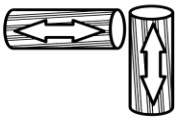
benzene and porphyrin, and in hydrophobic aromatic amino acid groups in proteins such as tubulin, delocalizable electrons may harness thermal environmental energy to promote, rather than destroy, quantum states.

Furthermore, Paul Davies (2004) has suggested that a "post-selection" feature of quantum mechanics put forth by Aharonov et al. (1996) may operate in living systems, making the decoherence issue moot.

Quantum entanglement in mitosis and differentiation?

Centriole replication and subsequent coordinated activities of the mitotic spindles appear to be key factors in forming and maintaining two identical sets of chromosomes, thus avoiding aneuploidy, genomic instability and cancer. Viewing mitosis as a dissipative, clock-like process which, once set in motion has no adaptive recourse, seems unlikely to account for the necessary precision. Some organizing communication between replicated centrioles and daughter cell spindles seems to be in play (Karsenti, 2001), and would certainly be favored in evolution if feasible. The perpendicular centriole replication scheme has long been enigmatic to biologists. Alternative mechanisms such as longitudinal extension ("budding"), or longitudinal fission with regrowth (akin to DNA

Table 1. Classical and quantum superposition states for electrons/electron pairs (top), tubulins/tubulin pairs (middle), and centriole cylinders/centrioles (bottom).

	Classical State	Quantum Superposition
Single Electron Spin	 Up *or* Down	 Up *and* Down
Paired Electrons (Complementary)	 Up, Down *or* Down, Up	 Up and Down *and* Down andUp **Entangled**
Single Tubulin State	 Open *or* Closed	 Open *and* Closed
Paired Tubulins (Complementary)	 Open, Closed *or* Closed, Open	 Open *and* Closed **Entangled**
Centriole Cylinder State		
Paired Cylinder/ Centriole (Complementary)		 **Entangled**

replication) would seem to be more straighforward. In DNA replication each component of a base pair is in direct contact so direct binding of the complementary member of the base pair is straightforward. However in centrioles replication by neither extension/budding nor fission would permit direct contact/copying of each component tubulin because of the more complex three dimensional centriole geometry. The enigmatic perpendicular centriole replication provides an opportunity for each tubulin in a mature ("mother") centriole to be transiently in contact, either directly or via filamentous proteins, with a counterpart in the immature ("daughter") centriole. Thus the state of each tubulin (genetic, post-translational, electronic, conformational) may be relayed to its daughter counterpart tubulin in the replicated centriole, resulting in an identical or complementary mosaic of tubulins, and two identical or complementary centrioles. Assuming proteins may exist in quantum superposition of states, transient contact of tubulin twins during centriole replication would enable quantum entanglement so that subsequent states and activities of originally coupled tubulins within the paired centrioles would be unified

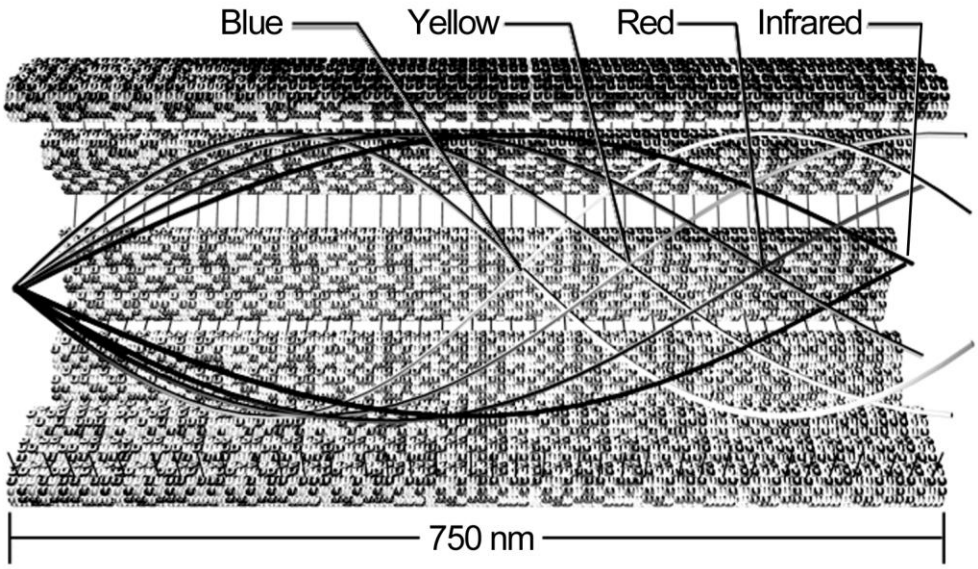


Figure 8. Cutaway view of centriole cylinder showing (to scale) wavelengths of visible and infra-red light suggesting possible waveguide behavior. By Dave Cantrell.

(Tables 1 and 2, middle). Then if a particular tubulin in one centriole cylinder is perturbed ("measured"), or its course or activities altered, its twin tubulin in the paired centriole would "feel" the effect and respond accordingly in a fashion analogous to quantum entangled EPR pairs. Thus activities of replicated centrioles would be mirror-like, precisely what is needed for normal mitosis. In Tables 1 and 2 the state of each centriole is euphemistically represented as either spin up or down (right or left). In actuality the states of each centriole would be far more complex, since each tubulin could be in one particular binary state. There are approximately 30,000 tubulins per centriole cylinder. If each tubulin can be in one of two possible states, each centriole could be in one of $2^{30,000}$ possible states. Considering variations in isozymes and post-translational modifications, each tubulin may exist in many more than two possible states (e.g. 10), and centrioles may therefore exist in up to $10^{30,000}$ possible states—easily sufficient to represent each and every possible phenotype. But regardless of their specific complexity, replicated centrioles would be in identical (or complementary, i.e. precisely opposite) entangled states.

How could entanglement actually occur? Centrioles are embedded in an electron dense protein matrix ("pericentrin") to which mitotic spindle microtubules attach; the opposite ends of the spindles bind specific chromatids via centromere/kinetochores. The centriole/pericentrin ("centrosome") and spindle complex are embedded in protein gel and ordered water so that the entire mitotic complex may (at least transiently) be considered a pumped quantum system (e.g. a Fröhlich Bose Einstein condensate) unified by quantum coherence.

As described previously, quantum optical coherence (laser coupling) can induce entanglement. Although photons generally propagate at the speed of light, recent developments in quantum optics have shown that photons may be slowed, or trapped in "phase coherent materials", or "phaseonium" (Scully, 2003). In these situations photons are resonant with the materials (which may be at warm temperatures) but not absorbed. Quantum properties of the light can be mapped onto spin states of the material, and later retrieved ("read") by a laser pulse (or Fröhlich coherence). The dimensions of centrioles are close to the wavelengths of light in the infrared and visible spectrum (Figure 8) such that they may act as phase coherent, resonant waveguides (Albrecht-Buehler, 1992). Fröhlich coherence may then play the role of laser retrieval, coupling/entangling pairs of centrioles. As described previously, experimental evidence shows an association between centriole replication and photon emission (Liu et al., 2000; Van Wijk et al., 1999; Popp et al., 2002).

How would quantum entanglement work in normal mitosis? Binding of a particular chromatid centromere/kinetochore by a spindle connected at its opposite end to a centriole may be considered a quantum measurement of the anchoring centriole, causing reduction/collapse and complementary action in its entangled twin (thus binding the complementary chromatid centromere/kinetochore). Although the action is complementary, and thus in some sense opposite, the operations are identical from an information standpoint (and because centriole orientations are opposite, the actions may be considered equivalent). Consequently, precise complementary mirror-like activities of tubulins in the two entangled centrioles would ensue, and each member of a sister chromatid pair would be captured for each daughter cell. Two precisely equal genomes would result following mitosis.

How would failed quantum entanglement lead to aneuploidy and malignancy? Defects during mitosis can occur in two ways. As shown in Figure 2 spindle attachment to chromatids during metaphase (reflecting entangled information in the centrioles) may go awry, resulting in abnormal separation of chromosomes. This may result from improper communication between the two centrioles (the "right handed centriole doesn't know what the left-handed centriole is doing"). Another type of defect may occur in the replication and entanglement as shown in Figure 3, resulting in 3 (or more) centrioles which separate chromosomes into 3 portions rather than 2 precisely equal portions.

Measurement of standard EPR pairs apparently destroys entanglement. Once complementary actions occur, members of separated pairs behave independently. In centrioles, one measurement/operation per tubulin would be useful in mitosis and differentiation, allowing approximately 30,000 measurements/operations per centriole cylinder and ensuring precise division of daughter chromosomes and subsequent differentiation. However an ongoing series of measurement operations (chromatid interactions, movements and binding of other cytoskeletal structures, differentiation etc.) persisting after completion of mitosis could be even more useful.

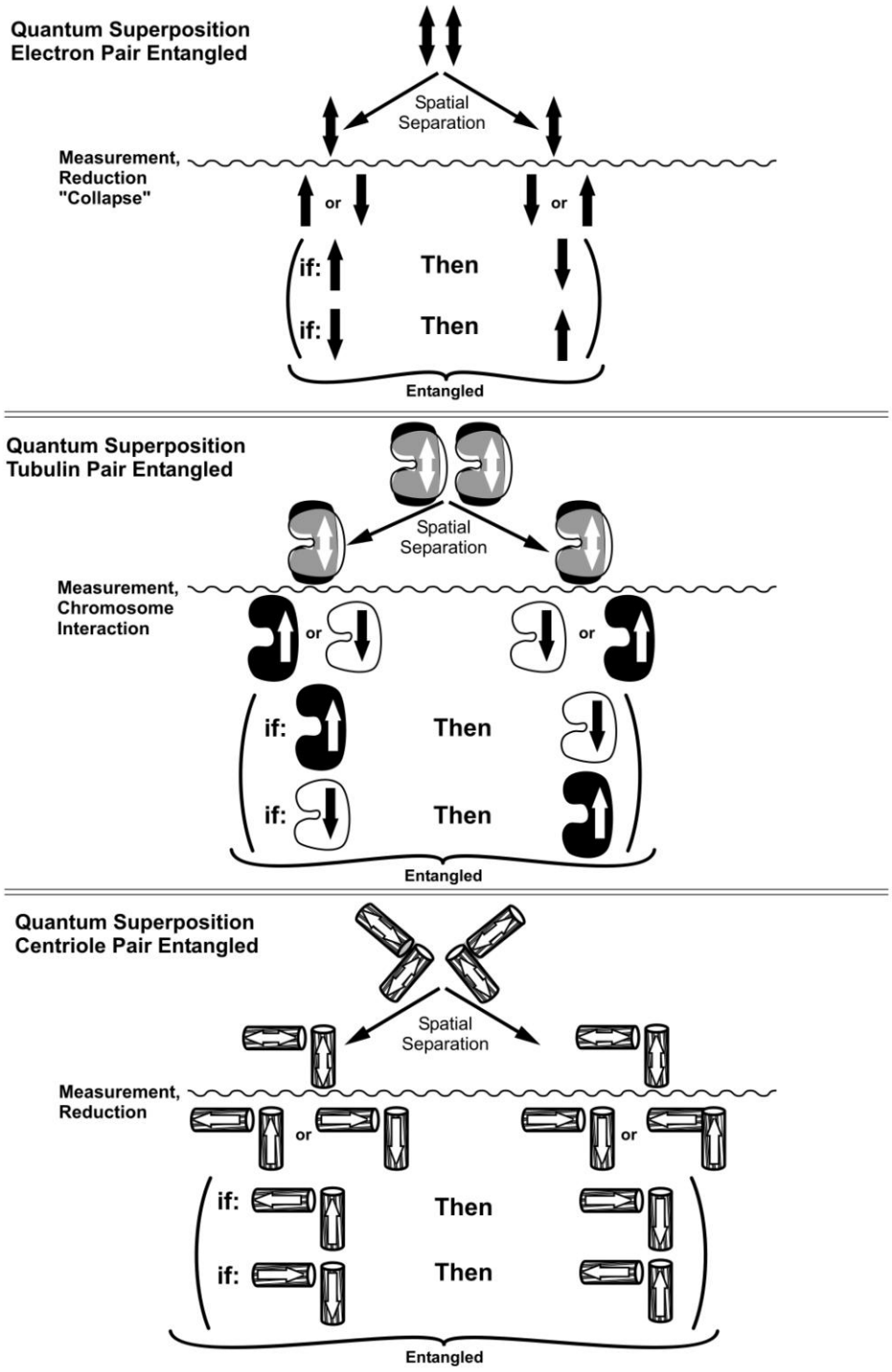
Could persistent entanglement ("re-entanglement") occur in biological systems? Unlike standard EPR pairs (e.g. electron spin) whose underlying states are random, the conformational state of each member of paired tubulin twins has identical specific tendencies due to genetic and post-translational structure. In the same fashion that laser pulsing mediates entanglement among cesium clouds and other quantum systems, quantum optical (and/or Fröhlich) coherence could mediate ongoing entanglement ("re-entanglement") among tubulin twins in separated centrioles. Because dynamic conformational states are transient, the quantum state may be transduced to, and stored as, a spin state or other more sustainable parameter. Thus centrioles throughout a tissue or entire organism may remain in a state of quantum entanglement. Impairment or loss of such communicative entanglement may correlate with malignancy.

Implications for cancer therapy

Current therapies for cancer are generally aimed at impairing mitosis and are thus severely toxic. Many cancer drugs (vincristine, taxol etc.) bind to microtubules and prevent their disassembly/assembly required for formation and activities of the mitotic spindles. In addition to generalized toxicity due to impairment of non-mitotic microtubule function, partial disruption of mitosis can cause further aneuploidy (Kitano, 2003). Radiation is also a toxic process with the goal of impairing/destroying highly active malignant cells more than normal cells. Recognizing centrosomes as the key organizing factor in mitosis, Kong et al (2002) proposed disabling centrosomes by cooling/freezing as a cancer therapy.

Low level laser illumination apparently enhances mitosis. Barbosa et al (2002) using 635 and 670 nanometer lasers, and Carnevali et al (2003) using an 830 nanometer laser both showed increased cell division in laser illuminated cell cultures. Using laser interference Rubinov (2003) showed enhanced occurrence of "micronuclei" (aberrant multipolar mitoses) although specific interference modes decreased the number of micronuclei. It may be concluded that nonspecific, low intensity laser illumination enhances centriole replication and promotes cell division (the opposite of a desired cancer therapy). On the other hand if centrioles are sensitive to coherent light, then higher intensity laser

Table 2. Quantum superposition, reduction and entanglement for electron pairs (top, tubulin pairs (middle), and centrioles (bottom).



illumination (still below heating threshold) may selectively target centrioles, impair mitosis and be a beneficial therapy against malignancy.

However laser illumination may also be used in a more elegant mode.
If centrioles utilize quantum photons for entanglement, properties of centrosomes/centrioles approached more specifically could be useful for therapy. Healthy centrioles for a given organism or tissue differentiation should then have specific quantum optical properties detectable through some type of readout technology. An afflicted patient's normal cells could be examined to determine the required centriole properties which may then be used to generate identical quantum coherent photons administered to the malignancy. In this mode the idea would *not* be to destroy the tumor (relatively low energy lasers would be used) but to "reprogram" or redifferentiate the centrioles and transform the tumor back to healthy well differentiated tissue.

Stem cells are totipotential (or pluripotential) undifferentiated cells with a wide variety of potential applications in medicine. Zygotes, or fertilized eggs are totipotential stem cells, and embryonic cells in general are relatively undifferentiated. Thus fetal embryos have been a source for stem cells though serious ethical considerations have limited availability. Perhaps normally differentiated cells could be undifferentiated ("retrodifferentiated") by laser therapy as described above, providing an abundant and ethical source of stem cells for various medical applications.

Conclusion: Quantum entanglement and cancer

It is suggested here that normal mitosis is organized by quantum entanglement and quantum coherence among centrioles. In particular, quantum optical properties of centrioles enable entanglement in normal mitosis which ensures precise mirror-like activities of mitotic spindles and daughter chromatids, and proper differentiation, communication and boundary recognition between daughter cells.

Defects in the proposed mitotic quantum entanglement/coherence can explain all aspects of malignancy. Analysis and duplication of quantum optical properties of normal cell centrioles could possibly lead to laser-mediated therapeutic disruption and/or reprogramming of cancerous tumors as well as abundant, ethical production of stem cells.

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