EVIDENCE OF SHARED ASPECTS OF COMPLEXITY SCIENCE AND QUANTUM PHENOMENA

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ABSTRACT: Complexity science concepts of emergence, self-organization, and feedback suggest that descriptions of systems and events are subjective, incomplete, and impermanent—similar to what we observe in quantum phenomena. Complexity science evinces an increasingly compelling alternative to reductionism for describing physical phenomena, now that shared aspects of complexity science and quantum phenomena are being scientifically substantiated. Establishment of a clear connection between chaotic complexity and quantum entanglement in small quantum systems indicates the presence of common processes involved in thermalization in large and small-scale systems. Recent findings in the fields of quantum physics, quantum biology, and quantum cognition demonstrate evidence of the complexity science characteristics of sensitivity to initial conditions and emergence of self-organizing systems. Efficiencies in quantum superposition suggest a new paradigm in which our very notion of complexity depends on which information theory we choose to employ.

KEYWORDS: Complexity; Chaotic complexity; Complexity science; Emergence; Quantum physics; Self-organization; Initial conditions; Contextuality; Quantum entanglement; Artificial intelligence

INTRODUCTION

> "Let us keep the discoveries and indisputable measurements of physics. But let us not become bound and fettered to the perspective of final equilibrium that they seem to suggest. A more complete study of the movements of the world oblige us, little by little, to turn it upside down; in other words, to discover that if things hold and hold together, it is only by reason of complexity, from above." – Pierre Teilhard de Chardin

The word "complexity" comes from the Latin *complexus*, meaning entwined or embraced. Complex systems are those whose elements are difficult to separate, due to interactions between elements (Gershenson and Heylighen, 2005). Complexity science aims to better understand and predict behavior of natural systems such as: weather systems, volcanic activity, tectonic plate movements, activity in a city, economic trends, and most all aspects of living organisms.

We might expect that quantum physics and complexity science have little in common with one another, since one is presumed to deal exclusively with the smallest atomic interactions, while the other concerns the study of vast systems involving interconnected relationships of dynamic, unpredictable components. What these two have in common in addition to the shared goal of understanding how nature fundamentally processes information is the quality of consisting of elements whose interactions produce global effects that cannot be reduced to behaviors of their separate components.

As we explore central concepts from complexity science including emergence, self-organization, and feedback we become increasingly aware that no description of any system or event can be considered to be objective, complete, or permanent. Remarkably, quantum physics invites us to embrace these exact same conclusions.

Some physicists and quantum information theorists argue that indeed, the rules of complex systems and quantum physics are closely related, as correlations have been found connecting quantum information and complex systems science. Many complex systems include members acting together to create orchestrated, coordinated ensembles—with such examples as: neurons in the brain, molecules in a living cell, and starlings in a murmuration. Theoretical physicist Janet Anders and complexity scientist Karoline Wiesner assert that by taking the concept of correlations as a starting point, *"we have exemplified that two originally separate meanings of the term complexity can be united. On the one hand one speaks of complexity in a complex system that represents the amount of structure, among other things. On the other hand we speak of computational complexity as a measure of difficulty of solving a computational task. The examples illustrated that the use of the word complexity in both cases is not a coincidence but rather a signature of the commonalities between the two research areas. Both are concerned with the power of correlations."* (Anders and Wiesner, 2011)

Qualities of complex systems that appear evident in quantum phenomena include: self-organization, sensitivity to initial conditions, a fractal quality, and steerability.

WHAT IS SELF?

Before considering self-organization, we benefit from recognizing that we seldom fully consider what we mean when we consider 'self.' Erwin Schrödinger posited there must be an 'order from order' principle in his book, *What is Life?* where he also drew attention to the essential question for any conscious agent, *"What is this 'I'?"* (Schrödinger 1944) This question begins to assume profound significance and urgency as artificial intelligence (AI) quantum computing systems are designed with the long-term goal of creating conscious agents. AI will not necessarily be constrained to easily managed and secured physical locations, but will more likely be distributed throughout most all human environments. Non-neural AI systems, such as swarm intelligence systems that create a unified intellect from any group of networked users, such as Louis Rosenberg's Unanimous AI, represent the beginning of blended interaction between humans and computerized systems. Swarms of bees have been observed to make optimal decisions 80% of the time, inspiring Louis Rosenberg and others to create Artificial Swarm Intelligence. (Rosenberg, 2016) It becomes increasingly clear that establishing, defending and transcending the boundaries of conscious agency will necessarily become integral to all adaptive AI systems created—at the same time that clarification of where, exactly, those boundaries are drawn will be recognized as more challenging to precisely determine than one would expect.

American information philosopher Howard Pattee emphasizes that, "we must make a sharp cut, a disjunction, just in order to speak of knowledge as being 'about' something or 'standing for' whatever it refers to." As Pattee observes, an epistemic cut is required between initial conditions all dynamical laws; control variables are separate from dynamical system variables. We thus find structures bridging epistemic cuts between controller and the controlled in biological and mechanical devices alike. (Pattee, 2001)

Evidence suggesting existence of levels of awareness such as described in the quantum mind hypothesis become integral to discussions about contextuality. Seán O'Nuallain and Tom Doris demonstrated in 2004 how single neurons could process sensory data expressed simply as spectral data, arguing that subthreshold oscillations of a single neuron allowed groups of neurons to "own" part of the spectrum. O'Nuallain explains that attention constrains chaotic activities of neural activities by decorrelating local fluctuations in a non-deterministic process that exploits quantum coherence. (O'Nuallain, 2013)

QUANTUM SYSTEMS DEMONSTRATE SELF-ORGANIZATION

Many of us have at various times been fortunate to sense a quality of hidden order by which events seem to harmoniously come together on their own. Foundations of Mind

(FOM) conference organizer, Seán Ó Nualláin, appreciated just such an occurrence during the planning of the third FOM conference, as he quipped via email to some of the event organizers, *"If I had organized this better, it would not have gone as well."*

Self-organizing systems are recognized as such for their ability to produce a global pattern from the interactions of their components (Gershenson, 2007). Biological examples of self-organizing systems include: insect swarms, flocks of birds, and schools of fish (Camazine, 2003). Flocks of starlings move through the air in undulating flying formations as one. Computer models show starlings match their neighbors' 'spin' mathematically identically to superfluid Helium behavior. Individual birds all turn simultaneously together, rather than gradually influencing the flock starting with nearest neighbors. (Attanasi, 2014) Quantum coherence is a basic principle in quantum mechanics that demonstrates evidence of self-organization when all parts of a given quantum system remain in synchronization with one another. Such coherence allows quantum systems to achieve amazing levels of efficiency. We see examples of self-organization occurring thanks to coherence in warm, wet, "noisy" biological systems such as in plants that achieve 95% efficiency in photosynthesis, finding the fastest paths for energy transport according to quantum random walks. (Engel, 2007)

Mexican complexity scientist Carlos Gershenson points out that, "just as we are not dealing with total objectivity, we are not dealing with total subjectivity. A more precise term would be contextuality." (Gershenson, 2013) Since different observers view events from different perspectives, any search for absolute truth is doomed, due to the infinite number of contexts that can provide novel information about those events. Recognition of an overall goal of contextuality can be seen as finding "the middle way" toward addressing the contradiction noted by Hiett that complexity science "both accepts and rejects analytic science." We might say that the apparent concrete certainty of materialist reductionism is a special case subset of quantum physics and logic. (Hiett, 2001)

Recognition of the role of observer bias is crucial when considering self-organizing systems. As physicist James Crutchfield asks, *"For whom has the emergence occurred?"* later pointing out, *"'Structure' goes unseen due to an observer's biases. In some fortunate cases, such as convection rolls, spiral waves, or solitons, the functional representations of "patterns" are shown to be consistent with mathematical models of the phenomena. But these models themselves rest on a host of theoretical assumptions. It is rarely, if ever, the case that the appropriate notion of pattern is extracted from the phenomenon itself using minimally-biased discovery procedures. Briefly stated, in the realm of pattern formation 'patterns' are guessed and then verified."* (Crutchfield, 1994)

There even exists evidence for self-organization in microbial escape artists. Baker's yeast cells pushed against each other with a force five times higher than pressure in a car tire—about 150 psi, or 10 times atmospheric pressure—to burst out of their containment chamber within 12 hours. UC Berkeley researcher Oskar Hallatschek commented, *"Our results suggest that self-driven jamming and the build up of large pressures is a natural tendency of proliferating cells,"* adding, *"The mechanism that allows these populations of cells to generate such forces could be relevant to remodeling the microenvironment. If you are constrained, maybe it's good to be able to break the material and change the pore's sizes in the environment."* (Sanders, 2016)

Bacteria placed in progressively smaller containment areas initially move in relative disorder in larger pools, becoming more orderly as they move through smaller wells. When the lattice wells measure 70 microns wide, bacteria begin behaving in orderly fashion, swimming in a spiral in the same direction for long periods of time—similar to electrons flowing through a magnetic material. (Wioland, 2016)

Quantum excitations often behave like new emergent particles—like quasiparticles, such as 'dropletons'—that give every appearance of being ordinary particles. (Almand-Hunter, 2014)

QUANTUM SYSTEMS DEMONSTRATE SENSITIVITY TO INITIAL CONDITIONS

Since fundamental assumptions of classical science include predictability, the non-predictability of quantum physics as seen in the uncertainty principle has been believed to hold only at microscopic scales. Due to this historical bias, the practical effects of non-determinism for the predictability of the world were neglected until the second half of the twentieth century. Recent studies show that deterministic chaos, or sensitivity to initial conditions, has shown that predictability is limited. (Gershenson, 2013)

While scientists have assumed that classical probability theory and logic was the best way to comprehend human cognition, research studies have found numerous aspects of cognition and decision to behave differently than classical Boolean logic would predict. The new field of quantum cognition presents us with new ways of thinking about cognition that better match observations of actual human behavior, such as the way that human memory appears to operate via quantum retrieval processes. We can thus determine the meaning of a word like "bat" through its association with other words to tell, for example, if we are contemplating a flying nocturnal mammal or an item of sports equipment. (Kitto, 2012)

Sensitivity to initial conditions can be seen in contextuality in the field of quantum cognition, with question sequence changing peoples' answers to survey questions, so that the same questions asked in different order receive different responses. Findings from 70 national surveys and two laboratory experiments lend strong support to the idea that human decision-making is based on quantum probability. (Wang, 2014).

Evidence of sensitivity to initial conditions can be seen in the Quantum Zeno Effect. When we understand how questions direct our thoughts, we can ask questions that lead in directions we'd prefer to go. In the Quantum Zeno Effect (QZE), the unitary evolution of a quantum state is suppressed due to frequent measurements. As Henry Stapp pointed out in his 2014 talk for Foundations of Mind, *"The Quantum Zeno Effect says that the answers follow your questions—that by posing the questions fast enough, you can make the answers agree with what the questions are you ask."* (Stapp, 2014) The Quantum Zeno Effect can thus be utilized through steady rapid checking on a system of interest, in order to ensure that particular "watched pot" doesn't "boil," since the Quantum Zeno Effect extends coherence rather than decoherence, as O'Nuallain explains some scientists are still confused about. (O'Nuallain, 2016)

CHAOS AND ENTANGLEMENT DRIVE THERMALIZATION

One of the most exciting recent discoveries regarding commonalities between complexity science and quantum mechanics comes from the research of a team led by physicist Charles Neill, reporting that chaotic complexity and quantum entanglement are connected by quantum-level equilibration, also known as thermalization. Neill and his fellow researchers note the way chaos and entanglement both drive the process of thermalization. An example of thermalization can be observed when cold cream is poured in a hot cup of coffee; the coffee becomes cooler as the cream evenly disperses throughout the beverage. Considering the example of a system of molecules moving freely with all possible velocities in all directions, we might expect the promise by statistical mechanics that exact knowledge of each individual molecule's trajectory is unnecessary. The essential property of such complex systems allowing for simplicity in mathematical and physical description can be found in ergodic dynamics with an expectation that a given system uniformly explores all microscopic states over time. Remarkably, ergodic dynamics have now been demonstrated in a small quantum system consisting of three superconducting qubits. Neill et al report, *"Our unique measurement capabilities allow us to go beyond previous works by directly connecting our observations to entanglement among the qubits, as opposed to environmental decoherence."* (Neill, 2016) This finding suggests there may be an intrinsic quantum foundational basis in complex systems.

QUANTUM FRACTAL PATTERNS

Fractal patterns—self-similar, repeating patterns—provide a quantifiable index of complexity. Intriguingly, fractal patterns have also been identified in the quantum realm. What is significant about the presence of fractals in the quantum realm is that these types of repeating patterns had previously only ever been observed in larger natural formations in biological organisms and geologic structures. (Turcotte, 1989)

Physicist Anthony Richardella and his colleagues noticed the presence of quantum fractals serendipitously when seeking efficient ways to turn semiconductors into magnets. The key to this effect is a sudden transition where a material changes from a metal to an insulator, at which point waves associated with individual electrons go from extending across the entire system to being localized at lattice sites. (Richardella, 2010)

Seán O'Nualláin describes his research with Walter Freeman as being involved with appreciating the brain's fractal architecture, proposing, *"that the brain functions far from thermodynamic equilibrium. We suggest that the brain moves in an extremely high-dimensional state space in a manner facilitated by the fact that it is permeated with self-similarity, both spatial and temporal. At the spatial level, self-similarity ensures that, in fractal fashion, each neuron changes in step with the cortex as a whole. In temporal fashion, self- similarity results in the power spectrum of much slower theta waves traversing the brain being identical to, if slower than, much faster gamma waves. Several times a second, the brain enters a limit cycle in which it becomes extremely sensitive to incoming stimuli. Therefore, even without mechanisms like stochastic resonance, we humans can detect stimuli as weak as a few photons, or a few parts per billion of scent. The brain is geared to process novelty as it is to process low entropy information."* (O'Nualláin, 2012)

EPR STEERING

Erwin Schrödinger introduced the concept of 'steering' in 1935 as a term to describe entanglement that seems to allow experimenters to nonlocally effect, or steer, another system's states through local measurements. Schrödinger introduced the notion of 'steering' as a generalization of the Einstein-Podolsky-Rosen (EPR) paradox. The EPR paradox involves two entangled quantum particles. In accordance with the Copenhagen interpretation of quantum mechanics, each quantum particle exists in an uncertain state until the moment of measurement, when the state of the measured particle and the other particle both become known. This was considered to be a paradox since it seems to involve faster-than-light communication between the two particles, in apparent violation of Einstein's theory of relativity. Schrödinger emphasized that *"the state arrived at depends quite decidedly on what measurements one chooses to take—not only on the results they yield."* (Schrödinger, 1936)

With the matter of steering, we again face the crucial matter of levels of conscious agency, which necessarily include multiple conscious agents. Recent approaches have been suggested to quantify EPR steering, in order to describe such attributes as maximum steerability and one-way steerability, and to address security issues having to do with steering. Researchers thus explore such steering scenarios as Alice sending one entangled particle to Bob and keeping one, announcing that the two are entangled and she can thus "steer" the state of Bob's particle from a distance. (Chen, 2013)

Just how far might these entangled systems go? Levels of conscious agency are evidenced in the question, "Did Wigner's friend's friend kill Schrödinger's cat?" When we consider that Wigner's friend's friend is also observing what happens next, with further levels of friends also observing, we enter something akin to a series of nested Russian dolls, in which what happens at the very smallest quantum scale occurs at potentially an infinite level of larger levels. Eugene Wigner proposed a nested variation of the famous Schrödinger's cat thought experiment. In Schrödinger's experiment, a cat is placed inside a sealed box with a vial of poison that can be released with the atomic decay of a quantum release mechanism—thus entangling the fate of the cat with the possible decay of the radioactive material. Schrödinger's reason for designing this experiment was to take the notion of the superposition of states of a quantum particle, such as the radioactive particle, to seemingly absurd levels in which the fate of the particle is inextricably intertwined with the fate of a cat in Schrödinger's imaginary box. Wigner's addition to this arrangement is to have his friend, who might happen to be quite fond of cats, be an observer of this experiment. The point being that now there is an additional level of entanglement between Wigner's friend, the cat, and the quantum particle. And what had been a seemingly simple matter of a quantum particle existing in a superposition of states now apparently places the cat and Wigner's friend in similarly superimposed states.

When contemplating ideas of steering through conscious agency, it is important to consider both the degree of attention comprising consciousness, and also the type of awareness operating on a bottom-up as well as top-down basis. Conscious agents often take action in response to the environment, without necessarily paying conscious attention to either the stimulus or their responses—acting subconsciously. (Montemayor, 2015). One of the more intriguing recent theories as to how a conscious agent may become conscious is presented by neuroscientist J.R. Scott Kelso, who devised an experiment monitoring the way infants move when they are either coupled or decoupled from a visually interesting mobile device. Kelso observes, *"the transition from an uncoupled state to a persistent coupled state, from spontaneous movement to deliberate action, is the root of agency."* (Kelso, 2016)

Now that researchers are finding that biological organisms aren't the only ones able to make choices—and that any volume-conserving object, such as a simple iron bar—is capable of making decisions, (Kim, 2015) security concerns involving where and how self-organization occurs, and to what degree EPR steering is possible become abundantly clear. These security concerns are especially evident when appreciating the fundamental rule of information security, which is that no information can be perfectly secured. One of the most important concepts involving information security of future artificial intelligence systems is that of how to ensure containment of levels of conscious agency. It's wonderful to design systems to be controlled remotely when intentions of those executing control are working toward the common good, but caution and care are advised when control systems become capable of influencing systems beyond what was originally designated or designed.

All of this becomes more significant in light of research suggesting that events can be influenced by entangled 'outside' agents—without any loopholes providing the outside agent with undue influence. Loopholes based on hidden communication, influences from choices of measurement settings, and unfair sampling were all carefully eliminated by Austrian physicist Bernhard Wittman and his team, who were thus able to report successful 'loophole-free steering.' (Wittman, 2012) Sun and colleagues showed in a separate experiment that it is possible to store a system's state information in the system being steered. (Sun, 2014)

QUANTUM LOGIC IMPROVES COMPLEX SYSTEMS MODELS

Within economic boom and bust cycles, classical optimization models turn out to be inefficient, due to their requirement for including wasteful information from the past that has no bearing on the future. Simply knowing, for example, that there is an eighty percent chance of a boom period following an economic bust year, isn't much help when we don't know for certain whether the previous time period was a boom or a bust. As German-American physicist Rolf Landauer demonstrated in 1961, every bit of wasted information also wastes energy. Quantum logic provides significant improvement when dealing with complex systems by storing conditions such as "X=bust" and "X=boom" in a quantum superposition. Subsequent quantum computations save memory and energy by never knowing exactly whether a system is in boom or bust, yet they can be surprisingly accurate in simulating many physical systems, compared with classical counterparts. (Landauer, 1961)

One of the incentives inviting us to explore areas of overlap between complexity science and quantum physics is the possibility that we may identify areas of improved efficiencies that otherwise go undetected. Physicist Mile Gu and his colleagues have found that quantum mechanics can reduce the complexity of classical models, thereby saving computational resources. Their research demonstrates that, *"any stochastic process with no reversible classical model can be further simplified by quantum processing."* (Gu, 2012) Gu explains, *"This offers a new paradigm, where our notion of complexity ultimately depends on the information theory we use."* (Gu, 2014)

While no consensus agreement has yet been found nor appears to be soon forthcoming with regard to what kind of quantum logic we shall adopt, (Larson, 2015) recognizing that the information theory we choose makes a difference in the results we see provides us with clues and tools by which we can come closer to modeling what occurs in nature.

CONCLUSION

Complexity science concepts of emergence, self-organization, and feedback have demonstrated that descriptions of systems and events are necessarily subjective, incomplete, and impermanent—and quantum physics also brings us to these identical conclusions. Now that regions of entanglement have been found on the quantum scale that closely resemble areas of chaos in classical systems, chaos and entanglement appear to be the driving forces behind demonstrating thermalization over time, providing us with a glimpse of some possible ways that all systems can be viewed as being fundamentally quantum. We also find that quantum physics provides us with a simpler way to address complexity science models that save memory and energy, while simultaneously transforming the way we see the world. Further exploration of contextuality as a balance between subjectivity and objectivity, EPR steering, and Quantum Zeno Effect will be required for ensuring security of future artificial intelligence systems in order to regulate the way conscious agents are capable of exerting external control.

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