ECE 1724 Project: Quantum Computing and Consciousness: Investigating the Relationship between Quantum Processes and Consciousness

Pouya Kananian
Electrical and Computer Engineering
University of Toronto
Toronto, Canada
pouya.kananian@mail.utoronto.ca

***Abstract*—This paper offers a concise overview of theories proposing a connection between quantum processes in the brain and consciousness. Quantum computing can open up new possibilities for studying this link, including through the use of artificial quantum neural networks. However, the feasibility of using these networks to study theories of consciousness remains uncertain. The paper highlights the potential of quantum computing to explore the relationship between quantum processes and consciousness.**

***Index Terms*—consciousness, quantum mechanics, quantum computing, quantum neural networks**

I. INTRODUCTION

Consciousness is a subjective and multifaceted phenomenon that is difficult to measure and quantify objectively. One of the biggest challenges of studying this phenomenon is defining the concept of consciousness itself [1]. David Chalmers famously described the ”easy” and ”hard” problems of consciousness. The ”hard” problem refers to the question of why and how there is subjective experience associated with certain types of information processing. Chalmers argues that even if we had a complete understanding of the brain processes underlying conscious experience, we would still not know why those processes give rise to subjective experiences [2]. The question of whether the hard problem represents a fundamental challenge to our scientific understanding of the world, or if it should be dismissed rather than solved, is up for debate. Those who dismiss the hard problem argue that it only appears to be a difficult problem because of the limitations of the concepts we use to represent our own conscious states, which they refer to as ”phenomenal concepts” [3], [4]. Similar to the debates around the reality of the hard problem, when it comes to the question of free will, researchers tend to fall into two camps: those who reject our ability to make intentional choices and act upon them and those who believe our understanding of free will is incomplete or flawed [8].

In the 17th century, Descartes posited that there are two distinct kinds of substance in the world: material substance (that makes up the physical body) and mental substance (that makes up the mind) [9]. This dualistic view of the mind and body created a problem: how can two substances that are so different interact with each other? This problem became known as the mind-body problem and set the stage for future debates on the nature of consciousness itself. Due to the principle of causal closure of classical physics, if the mind-brain system can be entirely explained by classical physics, then the current physical state of the brain is sufficient to determine its future state, with no role for the mind to play. This implies that the mind is merely an epiphenomenon and has no power to influence the physical world. Therefore, the deterministic nature of classical physics means that free will cannot exist, leading to challenges for legal reasoning about intentional acts [8]. To reconcile determinism and free will, some philosophers propose a concept called ”compatibilism” [10]. However, this paper does not delve into this concept.

Substance dualism is incompatible with classical physics' deterministic nature, leaving us with the alternatives of Idealism, Physicalism, or Dual-Aspect Monism (and its related notion, Neutral Monism) [8], [11], [12]. Idealism proposes that reality is mental or spiritual [13], Physicalism asserts that everything is ultimately physical, including consciousness [8]. Dual-Aspect Monism proposes that the mental and physical aspects of reality are two inseparable facets of a single underlying substance [14]. Unlike classical physics, in quantum mechanics, the behavior of physical systems is inherently probabilistic, meaning that there is a fundamental uncertainty in the outcome of any measurement. The inherent indeterminacy and temporal non-locality in quantum mechanics has led some philosophers and scientists to suggest that it might provide an avenue for understanding the relationship between mind and body, as well as the existence of free will [15].

This paper briefly examines the theories that establish a connection between quantum effects and consciousness, and explores the potential of quantum computing to shed light on the possible links between quantum processes and consciousness.

II. QUANTUM COMPUTING

A. A Brief History and An Introduction to Quantum Bits

The first quantum mechanical model of a computer was proposed in 1980 by Paul Benioff [28]. Shortly after, in a notable observation, Feynman [29] pointed out that classical computers are not capable of efficiently simulating quantum mechanical phenomena. In 1985, David Deutsch gave a definition for the first universal quantum Turing machine [30]. It was in 1994 that Peter Shor came up with an algorithm for prime factorization and discrete logarithms on a quantum computer that runs in polynomial time [31]. These problems are deemed computationally hard for classical computers; however, Shor's algorithm demonstrated that quantum computers can solve some NP (non-deterministic polynomial time) problems efficiently. We still do not know how many NP problems can be solved by quantum computers in a polynomial time.

Quantum mechanics is an axiomatic theory that conceptually connects math with the physical world. Based on one of the quantum mechanics postulates, the system is defined as a complex vector space (i.e. a Hilbert space) [33]. The system's state is described by a unit vector in this complex vector space. In this formalism, a vector in a bi-dimensional complex space describes the minimum quantum state. The quantum system associated with this simple state is called a quantum bit (qubit). If we define two orthogonal states as follows, the state of a quantum bit can be represented by a vector in a two-dimensional Hilbert space spanned by these two orthogonal states.

$$|0\rangle := \begin{bmatrix}1\\0\end{bmatrix}, |1\rangle := \begin{bmatrix}0\\1\end{bmatrix}.$$

In classical computing, a classic bit can either be equal to 0 or 1. In other words, this classical bit encodes one of the two basis states of 0 or 1. A quantum bit, however, can be in a superposition of the two basis states $|0\rangle$ and $|1\rangle$ simultaneously. If we denote a quantum bit by $|\psi\rangle$, this bit can be in the following states:

$$|\psi\rangle = |0\rangle \,, \text{or: } \; |\psi\rangle = |1\rangle \,, \text{or: } \; |\psi\rangle = \alpha\,|0\rangle + \beta\,|1\rangle \,,$$

where the third state shows $|\psi\rangle$ in a superposition state. The coefficients α and β are complex numbers that satisfy $|\alpha|^2 + |\beta|^2 = 1$. While a qubit can be in a superposition of $|0\rangle$ or $|1\rangle$, measuring the quantum state collapses the state of the system into either $|0\rangle$ or $|1\rangle$. The probability that the measurement outcome is $|0\rangle$ equals $|\alpha|^2$, and $|\beta|^2$ is equal to the probability of measuring $|1\rangle$. This shows why the normalization condition $|\alpha|^2 + |\beta|^2 = 1$, which is the sum of two probabilities, must hold.

To represent the basis states of a quantum bit, $|0\rangle$ and $|1\rangle$, we used the Dirac notation. In this notation, a vector v is called ket and is shown by $|v\rangle$, while $\langle v|$ is called a bra and shows the Hermitian adjoint of v. For two vectors v and u, $\langle v|u\rangle$ represents the inner product of these vectors, and $|v\rangle\,\langle u|$ shows the outer product.

B. The No-Cloning Theorem

According to the No-Cloning Theorem [32], we cannot make a copy of an unknown quantum state. More specifically, it can be shown that no unitary operation can create an identical copy of an arbitrary quantum state. Consider an arbitrary and unknown state $|\psi\rangle$ and a blank state $|\phi\rangle$. There does not exist a unitary operation such that:

$$U\,|\psi\rangle\,|\phi\rangle = |\psi\rangle\,|\psi\rangle\,.$$

To get more information about unitary operations and their definition, please refer to [33]. Please note that in the Dirac notation, $|\psi\rangle\,|\phi\rangle$ denotes the tensor product of the two states. Let us consider Three arbitrary vectors as follows:

$$\mathbf{x} = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}, \mathbf{y} = \begin{bmatrix} y_1 \\ y_2 \end{bmatrix}, \mathbf{z} = \begin{bmatrix} z_1 \\ z_2 \end{bmatrix}.$$

The tensor product between x and y is defined as:

$$|\mathbf{x}\rangle\,|\mathbf{y}\rangle = \mathbf{x} \otimes \mathbf{y} = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \otimes \begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} x_1y_1 \\ x_1y_2 \\ x_2y_1 \\ x_2y_2 \end{bmatrix}.$$

Furthermore,

$$\mathbf{x} \otimes \mathbf{y} \otimes \mathbf{z} = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \otimes \begin{bmatrix} y_1z_1 \\ y_1z_2 \\ y_2z_1 \\ y_2z_2 \end{bmatrix} = \begin{bmatrix} x_1y_1z_1 \\ x_1y_1z_2 \\ x_1y_2z_1 \\ x_1y_2z_2 \\ x_2y_1z_1 \\ x_2y_1z_2 \\ x_2y_2z_1 \\ x_2y_2z_2 \end{bmatrix}.$$

C. Multi-Qubit Systems

Tensor products can be used to show the state of a two-qubit system. Let us define four basis states as follows:

$$|00\rangle := |0\rangle \otimes |0\rangle = \begin{bmatrix}1\\0\end{bmatrix} \otimes \begin{bmatrix}1\\0\end{bmatrix} = \begin{bmatrix}1\\0\\0\\0\end{bmatrix},$$

$$|01\rangle := |0\rangle \otimes |1\rangle = \begin{bmatrix}1\\0\end{bmatrix} \otimes \begin{bmatrix}0\\1\end{bmatrix} = \begin{bmatrix}0\\1\\0\\0\end{bmatrix},$$

$$|10\rangle := |1\rangle \otimes |0\rangle = \begin{bmatrix}0\\1\end{bmatrix} \otimes \begin{bmatrix}1\\0\end{bmatrix} = \begin{bmatrix}0\\0\\1\\0\end{bmatrix},$$

$$|11\rangle := |1\rangle \otimes |1\rangle = \begin{bmatrix}0\\1\end{bmatrix} \otimes \begin{bmatrix}0\\1\end{bmatrix} = \begin{bmatrix}0\\0\\0\\1\end{bmatrix}.$$

Similar to a single qubit system, a state of a two-qubit system can be in a superposition of the above basis states:

$$|\psi\rangle = \alpha_0\,|00\rangle + \alpha_1\,|01\rangle + \alpha_2\,|10\rangle + \alpha_3\,|11\rangle = \begin{bmatrix}\alpha_0\\\alpha_1\\\alpha_2\\\alpha_3\end{bmatrix},$$

where the following normalization condition must hold: $\sum_0^3 |\alpha_i|^2 = 1$.

More generally, a n-qubit system can be in a superposition of 2^n basis states:

$$|\psi\rangle = \sum_{i=0}^{2^n-1} \alpha_i |i\rangle .$$

Each α_i is a complex number and the following condition must hold:

$$\sum_{i=0}^{2^n-1} |\alpha_i|^2 = 1.$$

D. Entanglement

Entanglement can occur when two or multiple qubits interact with each other. To understand this fascinating phenomenon, consider the following quantum state:

$$|\Psi\rangle = \frac{|00\rangle + |11\rangle}{\sqrt{2}}.$$

This state is in fact equal to the following:

$$|\Psi\rangle = (\frac{1}{\sqrt{2}})|00\rangle + (0)|01\rangle + (0)|10\rangle + (\frac{1}{\sqrt{2}})|11\rangle .$$

We have a two-qubit system, in which with probability $|1/\sqrt{2}|^2 = 1/2$ the first and second bit both collapse to 0 after measurement. The probability of measuring both bits as 1 is similarly equal to $1/2$. It is impossible for the first bit to collapse to 0 when the second bit is measured as 1. The probability of a measurement outcome to be $|10\rangle$ is zero similarly. Say we give the first qubit to Alice and give the second bit to Bob. Alice and Bob grab their qubits and each go to a different continent. If Alice conducts a measurement on the qubit of $|\Psi\rangle$ available at her side independently from Bob, she gets a random output with zero and one outcomes. If Alice and Bob both independently measure their qubits, the outcome of those measurements will be similar. Quantum mechanics says that when one of the two qubits is measured, the state of the other one becomes determined instantly. This is regardless of the distance between the qubits, and there does not need to be any interactions between Alice and Bob.

Formally, a state $|\Psi\rangle$ is said to be entangled if it cannot be written as the tensor product of two individual subsystems: $|\Psi\rangle \neq |\phi_1\rangle \otimes |\phi_2\rangle$. The following states are some examples of entangled states:

$$|GHZ\rangle = \frac{1}{\sqrt{2}}(|0000\rangle + |1111\rangle),$$
$$|W\rangle = \frac{1}{\sqrt{3}}(|100\rangle + |010\rangle + |001\rangle).$$

E. Quantum Neural Networks

Quantum machine learning (QML) is capable of learning from both classical and quantum data. Classical data can be efficiently encoded in qubit systems, where a classical bitstring of length n can be encoded onto n qubits without much difficulty. However, the opposite is not true - quantum data cannot be efficiently encoded into classical bitstrings. Quantum neural networks (QNNs) consist of parameterized gate operations and are a subset of variational quantum algorithms [34]. When classical data needs to be input into a quantum neural network (QNN), a quantum feature map is utilized to encode the information into a quantum state [35]. This state-preparation routine is necessary to enable the QNN to process classical data. Following the encoding of data into a quantum state, a variational model is applied that has parameterized gate operations optimized for a particular task, similar to classical machine learning techniques [36]–[39]. By measuring the quantum circuit after the variational model is applied, the final output of the quantum neural network is obtained [40].

III. QUANTUM THEORIES OF CONSCIOUSNESS

During the early years of the renewed interest in studying consciousness, scientists were primarily focused on the quest to find the ”neural correlates of consciousness” (NCCs) [5]. This entailed identifying the minimum set of neural events that are jointly sufficient for a particular state of consciousness [16]–[18]. Due to the limitations of the neural correlates of consciousness (NCCs) framework, there has been a shift in focus towards developing theories of consciousness (ToCs). Rather than being gradually disproven as more empirical data accumulates, ToCs are increasing in number [5].

Several theories of consciousness have explored possible connections between quantum processes and consciousness [19]. Among these theories, the ideas of Roger Penrose and Stuart Hameroff that link consciousness to quantum computations within brain microtubules have received significant attention and criticism [20]. One of the criticisms toward this theory is based on the observation that the coherence time of ions involved in the propagation of action potentials is much shorter than the relevant time scales of neural dynamics. This means that the quantum coherence of the ions would be destroyed before it could have any macroscopic effect on the neural dynamics of the brain [21], [22]. To explain how the large-scale functioning of biological neural networks can stem from coherent dynamics on a smaller scale, Fisher [23] suggested that phosphorus can act as a neural qubit inside brain. Generally, the idea of quantum effects occurring in living cells was not taken seriously until about two decades ago because it was believed that the warm and wet environment of living cells would quickly destroy any quantum coherence due to environmental decoherence [8]. However, recent years have seen a growing body of evidence supporting the presence of quantum effects in various biological systems, ranging from bird navigation, olfaction, photosynthesis, and more recently, in the human brain [24]–[27].

IV. QUANTUM COMPUTING AND CONSCIOUSNESS

Quantum computing utilizes the principles of quantum mechanics to process information. Thanks to the principles of superposition, entanglement, and interference, quantum computers can perform certain types of calculations much faster than classical computers, potentially revolutionizing fields such as cryptography, materials science, and drug discovery. Quantum neural networks (QNNs) are a recently developed set of machine learning models that utilize quantum effects and are run on quantum computers. The full range of applications for QNNs is not yet known. While achieving quantum speedup for data science remains uncertain even in theory, it is one of the primary objectives of quantum machine learning [41].

The study of QNNs can be seen as a pragmatic exploration of the concept of the ”quantum brain” [22]. However, It remains to be seen whether this line of study can help in explaining the properties emerged from biologic neural networks (BNNs) and the brain, such as consciousness. The biological basis of classical artificial neural networks is questionable, despite their neuroscience-inspired origins. There is limited evidence to support the idea that synaptic connections between neurons are modified via backpropagation of error, although recent theories have suggested that an approximation of this process may exist in the brain [42]–[45]. While we can raise questions on the biological basis of QNNs in a similar manner, it would be exciting to see if research around QNNs can facilitate new discussions around the connections between quantum mechanics and consciousness.

One of the challenges that we might face while studying the connection between quantum processes and consciousness using artificial quantum neural networks is small networks' potential lack of ability to generate consciousness. The Orch OR theorem [20], [46] claims that small networks lack the necessary complexity and coherence for consciousness, as they rapidly lose quantum coherence and behave classically due to their size.

REFERENCES

[1] Seth, Anil K., Bernard J. Baars, and David B. Edelman. ”Criteria for consciousness in humans and other mammals.” Consciousness and cognition 14.1 (2005): 119-139.

[2] Chalmers, David J. ”Facing up to the problem of consciousness.” Journal of consciousness studies 2.3 (1995): 200-219.

[3] McLaughlin, Brian, Ansgar Beckermann, and Sven Walter, eds. The Oxford handbook of philosophy of mind. Oxford University Press, 2009.

[4] Perry, John. Knowledge, possibility, and consciousness. mit Press, 2001.

[5] Seth, Anil K., and Tim Bayne. ”Theories of consciousness.” Nature Reviews Neuroscience 23.7 (2022): 439-452.

[6] Kauffman, Stuart A., and Dean Radin. ”Quantum aspects of the brain-mind relationship: A hypothesis with supporting evidence.” Biosystems 223 (2023): 104820.

[7] Descartes, R. ”Discourse on method and meditations on first philosophy.” New York: Hackett.(Original work published 1633) (1999).

[8] McKenna, Michael, and D. Justin Coates. ”Compatibilism.” (2004).

[9] Goodman, R. William James. *The Stanford Encyclopedia Of Philosophy*. (2022), https://plato.stanford.edu/archives/spr2022/entries/james/

[10] Russell, Bertrand. The analysis of mind. Taylor & Francis, 2022.

[11] Downing, L. George Berkeley. *The Stanford Encyclopedia Of Philosophy*. (2021), https://plato.stanford.edu/archives/fall2021/entries/berkeley/

[12] Stubenberg, L. & Wishon, D. Neutral Monism. *The Stanford Encyclopedia Of Philosophy*. (2023), https://plato.stanford.edu/archives/spr2023/entries/neutral-monism/

[13] Hameroff, Stuart. ”How quantum brain biology can rescue conscious free will.” Frontiers in integrative neuroscience 6 (2012): 93.

[14] Crick, Francis, and Christof Koch. ”Towards a neurobiological theory of consciousness.” Seminars in the Neurosciences. Vol. 2. Saunders Scientific Publications, 1990.

[15] Metzinger, Thomas, ed. Neural correlates of consciousness: Empirical and conceptual questions. MIT press, 2000.

[16] Koch, Christof, et al. ”Neural correlates of consciousness: progress and problems.” Nature Reviews Neuroscience 17.5 (2016): 307-321.

[17] Sattin, Davide, et al. ”Theoretical models of consciousness: a scoping review.” Brain Sciences 11.5 (2021): 535.

[18] Hameroff, Stuart, and Roger Penrose. ”Consciousness in the universe: A review of the 'Orch OR'theory.” Physics of life reviews 11.1 (2014): 39-78.

[19] Tegmark, Max. ”Importance of quantum decoherence in brain processes.” Physical review E 61.4 (2000): 4194.

[20] Marais, Adriana, et al. ”The future of quantum biology.” Journal of the Royal Society Interface 15.148 (2018): 20180640.

[21] Fisher, Matthew PA. ”Quantum cognition: The possibility of processing with nuclear spins in the brain.” Annals of Physics 362 (2015): 593-602.

[22] Pauls, James A., et al. ”Quantum coherence and entanglement in the avian compass.” Physical review E 87.6 (2013): 062704.

[23] Brookes, Jennifer C. ”Quantum effects in biology: golden rule in enzymes, olfaction, photosynthesis and magnetodetection.” Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences 473.2201 (2017): 20160822.

[24] Ritz, Thorsten, Ana Damjanović, and Klaus Schulten. ”The quantum physics of photosynthesis.” ChemPhysChem 3.3 (2002): 243-248.

[25] Kerskens, Christian Matthias, and David López Pérez. ”Experimental indications of non-classical brain functions.” Journal of Physics Communications 6.10 (2022): 105001.

[26] Benioff, Paul. ”The computer as a physical system: A microscopic quantum mechanical Hamiltonian model of computers as represented by Turing machines.” Journal of statistical physics 22.5 (1980): 563-591.

[27] Richard P. Feynman. ”Simulating physics with computers. ” International Journal of Theoretical Physics, 21 (1982):467–488.

[28] Deutsch, David. ”Quantum theory, the Church–Turing principle and the universal quantum computer.” Proceedings of the Royal Society of London. A. Mathematical and Physical Sciences 400.1818 (1985): 97-117.

[29] Peter W. Shor. ”Polynomial-time algorithms for prime factorization and discrete logarithms on a quantum computer. ” SIAM J. Comput., 26 (1994):1484–1509.

[30] Wootters, William K., and Wojciech H. Zurek. ”A single quantum cannot be cloned.” Nature 299.5886 (1982): 802-803.

[31] Nielsen, Michael A., and Isaac Chuang. ”Quantum computation and quantum information.” (2002): 558-559.

[32] Schuld, Maria, et al. ”Circuit-centric quantum classifiers.” Physical Review A 101.3 (2020): 032308.

[33] Schuld, Maria, Ryan Sweke, and Johannes Jakob Meyer. ”Effect of data encoding on the expressive power of variational quantum-machine-learning models.” Physical Review A 103.3 (2021): 032430.

[34] Zoufal, Christa, Aurélien Lucchi, and Stefan Woerner. ”Quantum generative adversarial networks for learning and loading random distributions.” npj Quantum Information 5.1 (2019): 103.

[35] Romero, Jonathan, Jonathan P. Olson, and Alan Aspuru-Guzik. ”Quantum autoencoders for efficient compression of quantum data.” Quantum Science and Technology 2.4 (2017): 045001.

[36] Dunjko, Vedran, and Hans J. Briegel. ”Machine learning & artificial intelligence in the quantum domain: a review of recent progress.” Reports on Progress in Physics 81.7 (2018): 074001.

[37] Cong, Iris, Soonwon Choi, and Mikhail D. Lukin. ”Quantum convolutional neural networks.” Nature Physics 15.12 (2019): 1273-1278.

[38] Abbas, Amira, et al. ”The power of quantum neural networks.” Nature Computational Science 1.6 (2021): 403-409.

[39] Cerezo, M., et al. ”Challenges and opportunities in quantum machine learning.” Nature Computational Science 2.9 (2022): 567-576.

[40] Crick, Francis. ”The recent excitement about neural networks.” Nature 337 (1989): 129-132.

[41] Grossberg, Stephen. ”Competitive learning: From interactive activation to adaptive resonance.” Cognitive science 11.1 (1987): 23-63.

[42] Lillicrap, Timothy P., et al. ”Backpropagation and the brain.” Nature Reviews Neuroscience 21.6 (2020): 335-346.

[43] Richards, Blake A., et al. ”A deep learning framework for neuroscience.” Nature neuroscience 22.11 (2019): 1761-1770.

[44] Hameroff, Stuart. ”'Orch OR'is the most complete, and most easily falsifiable theory of consciousness.” Cognitive Neuroscience 12.2 (2021): 74-76.