QUANTUM INFORMATION SCIENCE AND THE MIND: STRUCTURAL MODELS OF CONSCIOUSNESS

INFORMATYKA KWANTOWA I UMYSŁ: STRUKTURALNE MODELE ŚWIADOMOŚCI

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Abstract: Consciousness remains an unresolved challenge in both science and philosophy, defying conventional physicalist explanations. Classical neuroscience, despite its advances in correlating brain activity with behaviour, fails to address the "hard problem" – why and how subjective experiences arise from physical processes. This study explores the potential of quantum information science to bridge this explanatory gap. Building on Orch-OR theory, which posits that consciousness emerges from quantum coherence in neuronal microtubules, this paper evaluates its feasibility in light of critiques concerning rapid quantum decoherence. Structural and mathematical models, including set theory, topology, and Clifford algebras, are examined for their capacity to model cognitive systems. Additionally, computational approaches, such as GPU-based simulations and quantum neural networks, are considered for their relevance to cognitive modelling. Although quantum theories of consciousness remain controversial, this interdisciplinary study synthesises insights from physics, mathematics, and neuroscience to assess their plausibility. It highlights the necessity for further empirical investigation and the development of hybrid quantum-classical models that might better encapsulate the complexity of conscious processes. Ultimately, this research contributes to ongoing efforts to integrate quantum mechanics and computational neuroscience in redefining the relationship between consciousness and physical reality.

Streszczenie: Świadomość wciąż stanowi nierozwiązane wyzwanie zarówno dla nauki, jak i filozofii, wymykając się konwencjonalnym, fizykalistycznym wyjaśnieniom. Klasyczna neuronauka, mimo postępów w łączeniu aktywności mózgu z zachowaniem, nie odpowiada na „trudny problem" – dlaczego i w jaki sposób subiektywne doświadczenia wyłaniają się z procesów fizycznych. Niniejsze opracowanie bada potencjał informatyki kwantowej w przezwyciężeniu tej luki eksplanacyjnej Bazując na teorii Orch-OR, która zakłada, że świadomość powstaje dzięki kwantowej koherencji w mikrotubulach neuronów, artykuł ocenia jej realność w świetle krytyki dotyczącej szybkiej dekoherencji kwantowej. Analizowane są również modele strukturalne i matematyczne – teoria mnogości, topologia oraz algebry Clifforda – pod kątem ich przydatności do modelowania systemów poznawczych. Dodatkowo rozważane są podejścia obliczeniowe, takie jak symulacje GPU oraz kwantowe sieci neuronowe, istotne dla modelowania poznawczego. Chociaż kwantowe teorie świadomości pozostają kontrowersyjne, niniejsze interdyscyplinarne studium syntetyzuje ustalenia z fizyki, matematyki i neuronauki, aby ocenić ich wiarygodność. Podkreśla ono również konieczność dalszych badań empirycznych i rozwoju hybrydowych modeli kwantowo-klasycznych, mogących lepiej uchwycić złożoność procesów świadomości. Ostatecznie praca ta wzbogaca trwające wysiłki na rzecz integracji mechaniki kwantowej z neuronauką obliczeniową w przeformułowaniu relacji między świadomością a rzeczywistością fizyczną.

Keywords: *Quantum information science, consciousness modelling, Orch-OR theory, quantum neural networks, computational neuroscience*

Słowa kluczowe: *Informatyka kwantowa, modelowanie świadomości, teoria Orch-OR, kwantowe sieci neuronowe, neuronauka obliczeniowa.*

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1. Introduction

Consciousness remains one of the most profound challenges in contemporary science and philosophy, raising questions that traditional frameworks have yet to answer. While classical neuroscience has significantly advanced our understanding of brain functions by correlating neuronal activity with behaviours, it has not addressed the "hard problem of consciousness"[2]. This problem probes why and how subjective experiences, or qualia, emerge from physical processes and why certain neural states are accompanied by these experiences while others are not[3]. This challenge underscores a conceptual divide between objective, measurable processes, such as synaptic activity, and subjective, first-person experiences, such as the perception of colour or the sensation of pain. Physicalist frameworks describe behaviour through causal closure within the physical domain, represented as $P_1 \to P_2$, where P_1 and P_2 denote successive physical states. However, the function $f: P \to E$, which would map physical states P to experiential states E, remains not only undefined but may also be fundamentally inaccessible within the framework of physicalist explanations. This mirrors Gödel's incompleteness theorems[4], which establish that any sufficiently expressive formal system contains true statements that cannot be proven within the system itself. Analogously, the explanatory gap between physical processes and subjective experience suggests that consciousness may reside in a domain that inherently transcends the descriptive power of physicalist models.

Quantum mechanics provides a promising avenue to bridge this explanatory gap. Penrose and Hameroff's Orchestrated Objective Reduction (Orch-OR) theory suggests that quantum coherence within neuronal microtubules underpins consciousness[5]. This model describes qua,n-tum superpositions collapsing into conscious states through gravitational thresholds: $T \sim \hbar/E_G$, where T is the superposition lifespan, $\hbar$ is the reduced Planck constant, and E_G is the gravitational self-energy. These states are expressed as $\Psi = \alpha\,|P\rangle + \beta\,|Q\rangle$, with $|P\rangle$ and $|Q\rangle$ denoting physical and experiential states, respectively. This approach situates consciousness as an intrinsic aspect of quantum processes.

Beyond physics, structural models have emerged as complementary tools. Król and Schumann employ Zermelo-Fraenkel set theory (ZFC) to model consciousness as layered structures interacting within spacetime, presenting these as dynamically shifting systems influenced by both local and global interactions within physical reality[6].

Other contributions have built on the idea of dynamic interplay between mind and matter. John Bell's advocacy for incorporating real-time events into quantum theory, particularly through his emphasis on "beables" - things that fundamentally "are" - and the necessity of explicitly describing the flow of information within quantum systems, has laid the groundwork for exploring consciousness as a physically instantiated phenomenon[7]. These ideas align with Schlichtinger's

2 D. Chalmers, *Facing up to the problem of consciousness*, "Journal of Consciousness Studies" (3), 1995, pp. 200–219.

3 It is worth noting that the so-called "hard problem of consciousness" implicitly presupposes a particular ontological stance – namely, that consciousness arises from physical processes and is intrinsically linked to specific neurobiological states. In this sense, the question may be seen as somewhat question-begging, insofar as it assumes as given what remains philosophically and empirically contested: that consciousness is an emergent property of material complexity, rather than a fundamental or irreducible aspect of reality.

4 K. Gödel, *Über formal unentscheidbare Sätze der Principia Mathematica und verwandter Systeme I*, "Monatshefte für Mathematik und Physik" 1931, pp. 173–198.

5 S. Hameroff, R. Penrose, *Orchestrated reduction of quantum coherence in brain microtubules: A model for consciousness*, "Mathematics and Computers in Simulation" 1996 (3–4), pp. 453–480.

6 J. Król, A. Schumann, *The formal layer of {brain and mind} and emerging consciousness in physical systems*, "Foundations of Science" 2023, pp. 1–30

7 J. S. Bell, *On the impossible pilot wave*, "Foundations of Physics", vol. 12, no. 10, 1982, pp. 989–999.

perspective, which interprets consciousness and time as inherently relational constructs. Schlichtinger emphasises their co-evolutionary dynamics, suggesting that consciousness cannot be understood apart from its interaction with temporal and structural properties of reality[8].

Insights from neuroscience and computational models further deepen this perspective. Studies on neural engrams highlight parallels between memory encoding in neuronal ensembles and state preservation in quantum systems[9]. Similarly, cortical neurones have been likened to deep artificial neural networks, demonstrating computational complexity akin to quantum systems[10]. Quantum computational models, such as the Quantum Relief Algorithm[11], support the potential of quantum frameworks for simulating cognitive processes.

This study aims to critically evaluate these interdisciplinary approaches to consciousness, integrating quantum mechanics, mathematical models, and neuroscience to address the limitations of reductionist paradigms. Specifically, it seeks to examine the role of quantum processes in bridging the physical and experiential domains and to explore the potential of quantum information systems as analogues for cognitive and conscious processes. By synthesising these perspectives, the study proposes alternative frameworks that redefine the relationship between consciousness and the physical universe.

The methodology integrates critical analysis of existing theories with mathematical formalism and conceptual exploration. It examines the plausibility of quantum coherence in biological systems, evaluates mathematical models for emergent phenomena, and explores the integration of quantum information science into consciousness studies. Rather than advocating for a specific position, this work aims to assess the applicability of these interdisciplinary frameworks to bridge the gap between physical and experiential domains. The study ultimately seeks to provide a comprehensive overview of current approaches to consciousness, offering insight into their relevance for both natural and artificial systems.

2. Quantum approaches to consciousness

This section examines selected approaches to modelling consciousness on the grounds of quantum mechanics.

2.1 The Orch-OR theory: a foundation

The Orch-OR (Orchestrated Objective Reduction) theory establishes a framework where consciousness is rooted in quantum coherence and objective self-collapse of superpositions within neuronal microtubules. These microtubules, structured as crystalline lattices composed of tubulin dimers, are posited to act as quantum processors, enabling large-scale quantum coherence across neurones.

Quantum states in tubulins are maintained in superposition, allowing simultaneous potential states. The coherence grows over pre-conscious periods (up to 500 milliseconds), with the system collapsing when mass-energy differences between states reach a gravitational threshold. This collapse, termed Objective Reduction (OR), is intrinsic and non-random, marking the

8 A. M. Schlichtinger, *O koncepcjach czasu w neoplatonizmie i chrześcijaństwie oraz ich wpływie na współczesną fizykę: analiza strukturalna i relacyjna* "Theologica Wratislaviensia" 2024, pp. 157–186.

9 S. A. Josselyn, S. Köhler, P. W. Frankland, *Finding the engram*, "Nature Reviews Neuroscience" 2015 (9), pp. 521–534.

10 D. Beniaguev, I. Segev, M. London, *Single cortical neurons as deep artificial neural networks*, "SSRN Electronic Journal" 2020 (17), pp. 2727–2739.

11 W. J. Liu, P. P. Gao, Y. Wang *et al.*, *A unitary weights based one-iteration quantum perceptron algorithm for non-ideal training sets*, "IEEE Access" 2019, pp. 36854–36865.

transition from quantum pre-conscious computation to classical conscious experience. The unique integration of gravitational self-collapse prevents spatial-temporal anomalies, linking the phenomenon to quantum gravity.

Microtubule-associated proteins (MAPs) play a critical role by tuning and orchestrating quantum oscillations. These proteins act as nodes, influencing collapse probabilities and regulating information processing. This orchestration not only ensures coherent states but also connects pre-conscious quantum computations with neural activities like synaptic regulation and intra-neuronal signalling[12].

Orch-OR situates microtubules as quantum information processors that introduce non-computable elements into consciousness, bridging the explanatory gap between the physical processes of the brain and the subjective experience. By integrating principles of quantum mechanics, this theory provides a unique foundation for understanding consciousness as a fundamental and intrinsic aspect of the universe.

2.2. Critiques of the Orch-OR theory

Physicist Max Tegmark conducted calculations indicating that quantum states in the brain would decohere extremely rapidly, on the order of seconds, far shorter than the timescales required for neural processing[13]. This rapid decoherence challenges the plausibility of sustained quantum coherence as posited by the Orch-OR model; however, recent proposals explore whether certain biological mechanisms might mitigate this effect. One such hypothesis, proposed by Fisher, suggests that nuclear spins of phosphorus atoms in biochemical environments could maintain entanglement for biologically relevant timescales, potentially enabling quantum information processing in neural systems[14].

Furthermore, some studies speculate that microtubules might possess structural properties that shield quantum states from rapid decoherence through specific geometric configurations or interactions with surrounding biomolecules. While these hypotheses remain speculative, further experimental investigations into the persistence of quantum coherence in biological systems are necessary to assess the plausibility of quantum contributions to cognitive processes.

However, despite these theoretical possibilities, there remains skepticism within the neuroscience community. Researchers such as Christof Koch and Klaus Hepp argue that quantum mechanics does not play a significant role in neurophysiology. They contend that classical processes provide a sufficient basis for explaining neural activity associated with consciousness, making quantum explanations redundant[15]. This divergence of perspectives highlights the ongoing debate between proponents of quantum theories of mind and advocates of classical computational models.

Further experimental investigations have failed to provide evidence supporting the Orch-OR model. For instance, a 2022 study by Derakhshani *et al.* tested predictions of the theory related to spontaneous radiation but found no supporting data, thereby weakening the case for a quantum basis of consciousness[16].

12 This entire description is based on: S. Hameroff, R. Penrose, *op. cit.*

13 M. Tegmark, *Importance of quantum decoherence in brain processes*, “Physical Review E” 2000 (4), pp. 4194–4206.

14 M. P. A. Fisher, *Quantum cognition: The possibility of processing with nuclear spins in the brain*, “Annals of Physics” 2015 (362), pp. 593–602.

15 C. Koch, K. Hepp, *Quantum mechanics in the brain*, “Nature” 2006 (440), p. 611.

16 M. Derakhshani *et al.*, *At the crossroad of the search for spontaneous radiation and the Orch OR consciousness theory*, “Physics of Life Reviews” 2022 (42), pp. 8–14.

These critiques highlight substantial challenges to the Orch-OR theory, emphasising the need for empirical validation and raising questions about the role of quantum mechanics in explaining consciousness.

2.3 Alternative quantum perspectives: insights for consciousness studies

Quantum mechanics, challenging classical determinism and locality, has inspired theories linking consciousness with quantum phenomena. Eugene Wigner's hypothesis posits that consciousness collapses the wavefunction, integrating subjective experience into physical theory, but lacks empirical support and a clear mind-matter interaction mechanism, relegating it to philosophical speculation[17].

The self-simulation hypothesis by Irwin *et al.* views the universe as a self-actualising informational loop, with consciousness both creating and emerging from recursive processes. This informational paradigm departs from materialism but faces limitations due to its lack of testable predictions[18].

Quantum information science advances computational models, applying concepts like entanglement and superposition to consciousness as emergent from formal systems, independent of biological substrates. Although innovative, these models face challenges in empirical validation and in capturing subjective experience.

3. Structural and mathematical models

Mathematics provides a rigorous framework for exploring consciousness by formalising its structural, dynamic, and informational aspects. This section discusses set-theoretic, algebraic and topological models of consciousness.

3.1. Set-theoretic modelling of conscious systems

Conscious systems can be effectively described using Zermelo-Fraenkel set theory with the axiom of choice (ZFC). A core concept of this approach is forcing extensions, which model the system's response to external stimuli. Forcing modifies a model M_i into a new model $M_i[G]$, where:

$$M_i[G] \supseteq M_i,$$

with G representing a generic ultrafilter. This extension captures how systems dynamically integrate new information from their environment[19]. Additionally, the system can be spatially distributed using regions, $U_i \subset \mathbb{R}^3$, with corresponding ZFC models:

$$S = \{(U_i, M_i) : i \in I\}.$$

Here S lescribes the global system, and M_i formalises the cognitive processes localised within each region.

17 E. P. Wigner, *Physics and the Explanation of Life*, "Foundations of Physics"1970 (1), pp. 35–45.

18 K. Irwin, M. Amaral, D. Chester, *The Self-Simulation Hypothesis Interpretation of Quantum Mechanics*, "Entropy" 2020 (22), pp. 1–26.

19 J. Król, A. Schumann, *op. cit.*

3.2. Topology and neural dynamics

Topology provides tools for understanding the structural properties of neural networks. Homology groups measure the topological features, such as loops or voids, in a space X:

$$H_k(X) = \frac{\ker(\partial_k)}{\mathrm{im}(\partial_{k+1})},$$

where ∂_k is the boundary operator acting on k-dimensional simplices. These groups are critical for identifying persistent patterns in neural dynamics. To study the evolution of these features over time, we use persistent homology, summarised in a persistence diagram:

$$D = \{(b_i, d_i) : i \in \mathbb{N}\},$$

where b_i and d_i represent the birth and death times of specific topological features. This approach enables the analysis of how neural activity changes dynamically.

3.3. Clifford algebras in microtubule modelling

Microtubules, hypothesised as computational units, can be mathematically described using Clifford algebras. Each tubulin dimer in a microtubule is modelled as a binary unit ("0" or "1"):

$$Cl(16) \cong Cl(8) \otimes Cl(8).$$

The Clifford algebra structure satisfies:

$$\{e_i, e_j\} = 2\delta_{ij},$$

where e_i and e_j are basis elements, and δ_{ij} is the Kronecker delta. This encoding allows the system to represent logical operations and computations, supporting the hypothesis of microtubules as quantum computational substrates[20].

3.4. Computational models and system dynamics

Information flow in neural networks is described by linear differential equations:

$$\frac{d\mathbf{x}}{dt} = A\mathbf{x},$$

where $\mathbf{x}$ represents the state vector, and A is the connectivity matrix. The eigenvalues of A determine the system's behaviour, such as stability or oscillations, aligning with patterns observed in conscious states. Integrated information theory (IIT), however, quantifies consciousness by measuring system integration:

$$\Phi = \sum_{S \subseteq N} I(S; N \backslash S),$$

20 T. D. Smith, *World-Line String Bohm Quantum Potential, E8, and Consciousness*, "viXra" 2015, paper no. 1512.0300, p. 1–17.

where $I(S;N\backslash S)$ is the mutual information between subsystems S and $N\backslash S$. A higher Φ value indicates greater system integration and complexity, characteristic of conscious processes[21].

3.5. Simplifying mathematical formalisms: intuitive explanations

While mathematical models provide a rigorous formalism for studying consciousness, some sections – particularly those involving set theory, topology, and Clifford algebras – may be challenging for readers unfamiliar with these fields. To clarify their relevance, a brief and intuitive explanation is warranted.

Set-theoretic models conceptualise consciousness as a structured hierarchy of interacting subsystems, where forcing extensions simulate cognitive adaptation to new information. Intuitively, this can be compared to how neural networks update their states in response to external stimuli, dynamically reorganising cognitive structures. *Topological approaches* capture the geometry of neural dynamics. Homology groups, for example, track the emergence and disappearance of patterns in neural activity over time, akin to how stable thought patterns form and dissolve in cognition. *Clifford algebras* model microtubule-based computations by representing tubulin dimers as binary units, enabling logical operations similar to those in artificial neural networks. This perspective suggests that microtubules might function as quantum information processors, potentially linking microscopic quantum states with macroscopic cognitive processes. From the perspective of category theory, consciousness can be seen as an emergent colimit in a higher-order category, where cognitive states are objects and their transformations form morphisms. Quotient categories naturally arise in the study of equivalence relations in cognitive state spaces, where distinct but functionally identical mental representations collapse into equivalence classes under categorical adjunctions. The transition between states, modelled as functors between categories, can be interpreted as cognitive state transitions driven by neural plasticity. Although these approaches remain highly abstract, they provide a mathematically rigorous framework that could, with advances in computational technology, inform practical implementations in neuromorphic computing, quantum-enhanced AI, and biologically inspired cognitive models. The integration of category-theoretic, algebraic, and topological structures into machine learning and quantum computation might eventually allow for a formalised, computationally viable model of consciousness, bridging the gap between abstract mathematical formalism and real-world cognitive systems.

4. Computational modelling of consciousness

Quantum computing introduces superposition, entanglement, and non-classical correlations into cognitive modelling. Quantum Neural Networks (QNNs) and Variational Quantum Eigensolvers (VQE) provide new frameworks for processing and optimising cognitive states. These approaches may bridge classical computation and quantum-enhanced models of consciousness.

4.1. Structural parallelism of CUDA cores and biological neural networks

In contemporary high-performance computing (HPC), parallel architectures, particularly those based on Graphics Processing Units (GPUs), provide an effective analogue to biological neural networks. Unlike traditional Central Processing Units (CPUs), which follow a von Neumann

21 G. Tononi, *Consciousness as Integrated Information: A Provisional Manifesto*, “The Biological Bulletin” 2008 (3), pp. 216–242.

architecture[22] and execute instructions sequentially, GPUs leverage a Single Instruction, Multiple Threads (SIMT) model, enabling large-scale parallel computations across thousands of cores[23].

This parallel structure closely resembles the way cortical neurones process information, where each neuron functions as an independent computational unit, exchanging data via synapses in a massively interconnected network. Formally, a GPU-based neural model can be described using a matrix-vector formulation:

$$\boldsymbol{Y} = f(\boldsymbol{X} \cdot \boldsymbol{W} + \boldsymbol{B}),$$

where $\boldsymbol{X} \in \mathbb{R}^{N\times M}$ is the input matrix (sensory data or activation potentials), $\boldsymbol{W} \in \mathbb{R}^{M\times K}$ represents synaptic weight matrices, $\boldsymbol{B}$ is the bias vector and $f(x)$ is a nonlinear activation function, such as the ReLU (Rectified Linear Unit):

$$f(x) = max(0, x).$$

This operation is highly optimised for CUDA-based tensor cores, enabling efficient execution of deep learning models in frameworks like TensorFlow or PyTorch, which utilise cuDNN (CUDA Deep Neural Network library) to accelerate forward and backward propagation[24]

A crucial metric for assessing computational efficiency is Floating Point Operations per Second (FLOPS), which serves as a standard benchmark for comparing CPUs, GPUs and Quantum Processing Units (QPUs). CPUs, traditionally optimised for sequential processing, exhibit lower parallel throughput compared to GPUs, which leverage massively parallel architectures. Unlike CPUs, which are designed for general-purpose computing with high clock speeds and complex instruction sets, GPUs excel in highly parallel computations, making them particularly effective for matrix operations, neural network training, and large-scale data processing. GPUs efficiently model neural computations due to their ability to handle sparse matrix multiplications using block-sparse kernel decompositions, a technique that significantly enhances computational efficiency in large-scale synaptic connectivity simulations. This is particularly relevant for deep learning applications, where optimised GPU kernels exploit sparsity in weight matrices to reduce memory overhead and improve computational speed. Research on block-sparse architectures has demonstrated significant gains in efficiency, particularly in training deep neural networks with structured sparsity, which reduces the number of active parameters while maintaining performance[25].

22 The von Neumann architecture is still the foundation of most modern computers, including multicore and multiprocessor systems. However, its limitations are leading to the search for alternative models, such as Harvard architecture, GPU or quantum computing. Ultimately, it is the way in which memory is organised and instructions are processed that determines whether a system can be considered compatible with the von Neumann model or whether it should be classified as a separate computing paradigm.

23 E. Lindholm, J. Nickolls, S. Oberman, J. Montrym, *NVIDIA Tesla: A Unified Graphics and Computing Architecture*, “IEEE Micro”2008 (2), pp. 39–55.

24 CUDA remains the foundational framework for GPU-accelerated computing, though its implementation has evolved with successive NVIDIA architectures. From Fermi and Kepler to Ampere, Ada Lovelace, and Blackwell, each generation has enhanced CUDA’s capabilities while preserving its core conceptual foundation. Though newer architectures refine and extend CUDA’s functionality, the term itself continues to define the overarching paradigm for parallel computing on GPUs.

25 A. Narang, G. Diamos, S. Sengupta, *Block-Sparse Recurrent Neural Networks*, “arXiv” 2017, pre-print, paper no.1711.02782, pp. 1–12.

Further, NVIDIA has pioneered the use of block-sparse formats in matrix multiplications, utilising Tensor Cores to accelerate deep learning workloads by efficiently computing structured sparse multiplications[26]. These techniques allow deep learning models to be trained with significantly reduced computational complexity, which is particularly relevant for high-performance computing (HPC) and artificial intelligence (AI) applications.

In contrast, QPUs provide an entirely different computational paradigm, leveraging quantum superposition and entanglement to perform certain types of computations exponentially faster than classical architectures. While still in the early stages of practical application, QPUs have demonstrated quantum supremacy in highly specialised tasks, such as simulating quantum mechanical systems and solving complex combinatorial optimisation problems[27]

As computational hardware evolves, the integration of GPU-accelerated deep learning with quantum-enhanced computation may unlock new capabilities for neuromorphic computing and large-scale cognitive simulations, bridging the gap between classical and quantum machine learning paradigms.

4.2. Extended explanation of CUDA, abstraction classes, and quotient categories in the context of consciousness

Let $C(i,j)$ represent the CUDA kernel computation executed on the thread (i,j). The computation given by:

$$C(i,j) = \sum_{k=1}^{M} X_{ik} \cdot W_{kj} + B_i.$$

represents a generalised matrix-vector computation, a fundamental operation in scientific computing, deep learning, and numerical simulations. The efficient execution of this operation in CUDA relies significantly on its structured memory hierarchy and the deployment of warps, where 32 threads function in unison. Within this execution paradigm, warp-level primitives, such as __shfl_sync and __ballot_sync, play a crucial role in facilitating seamless intra-warp communication, minimising the need for costly global memory accesses.

This can be interpreted categorically using the concept of quotient categories, where we treat each warp as an equivalence class of threads that behave as a single computational unit modulo synchronisation constraints. More formally, given a category C (representing all threads), we can define an equivalence relation ~ over morphisms (representing computation paths) such that $C/{\sim}$ denotes the quotient category, where individual threads collapse into equivalence classes defined by their warp-level synchronisations.

This quotient structure abstracts away individual thread interactions and allows us to study the computation at a higher level of abstraction, focusing on the warp as a whole rather than its individual components.

From the perspective of topos theory, we can view CUDA computations as objects in a categorical topos, where:

- Objects represent computational states,
- Morphisms model kernel transformations,

26 T. Yamaguchi, F. Busato, *Accelerating Matrix Multiplication with Block-Sparse Format and NVIDIA Tensor Cores*, https://developer.nvidia.com/blog/accelerating-matrix-multiplication-with-block-sparse-format-and-nvidia-tensor-cores/ (on-line 24.04.2025).

27 F. Arute *et al.*, *Quantum Supremacy Using a Programmable Superconducting Processor*, “Nature” 2019 (574), pp. 505–510.

- Sheaves can encode distributed memory states.

In this setting, intra-warp communication corresponds to colimits (i.e., gluing of local computational structures), ensuring coherence in distributed execution.

The use of topos-theoretic models allows us to extend CUDA computation beyond classical von Neumann architectures into the realm of higher-order logic, intuitionistic mathematics, and even categorical formulations of consciousness.

By leveraging quotient categories, CUDA computation can be studied as a model of emergent behaviour, where threads form higher-order abstractions, much like neurones forming functional clusters in the brain. In this way, CUDA's execution model provides a concrete computational analogy to consciousness, where:

- Threads (neurones) synchronise via shared memory (synaptic transmission),
- Warps (functional clusters) act as emergent computational entities,
- Quotient categories model the abstraction process in cognition.

By extending this analogy to topos theory, we can explore consciousness as a logical structure emerging from distributed computational processes, drawing deeper connections between GPU architectures, categorical logic and emergent cognition.

4.3. Quantum information processing and its relevance to cognitive modelling

In contrast to classical parallel architectures, quantum computing leverages qubits, which exist in superposition states:

$$|\psi\rangle = \alpha \, |0\rangle + \beta \, |1\rangle,$$

where the probability amplitudes α, β satisfy:

$$|\alpha|^2 + |\beta|^2 = 1$$

Computation in a quantum processor is governed by unitary transformations:

$$|\psi'\rangle = U \, |\psi\rangle,$$

where U is a unitary matrix satisfying $U^\dagger U = I$. Unlike classical logic gates, quantum computation is represented via quantum circuits, using gates such as[28]:

- **Hadamard Gate (H)**:

$$H = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix},$$

  which enables superposition.

- **CNOT Gate (Controlled-NOT)**:

$$CNOT = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix},$$

  which entangles qubits.

28 M. A. Nielsen, I. L. Chuang, *Quantum Computation and Quantum Information*, Cambridge 2010.

4.4. Quantum algorithmic models for consciousness

Quantum-enhanced cognitive models can leverage several quantum algorithms:

- Grover's algorithm – associative memory search

Grover's search reduces search complexity from $O(N)$ to $O(\sqrt{N})$. It employs an oracle-based iteration:

$$G = (2|\psi\rangle\langle\psi| - I)O,$$

which amplifies the probability of correct solutions. This can be adapted to model associative memory retrieval in neural networks[29].

- **Quantum neural networks (QNN)**

A Quantum onvolutional Neural Network (QCNN) is defined as:

$$|\psi_{out}\rangle = U_{QCNN}|\psi_{in}\rangle,$$

where U_{QCNN} is a trainable quantum gate sequence analogous to weight matrices in classical deep learning[30].

- **Variational Quantum Eigensolver (VQE) for energy-based neural networks**

The VQE algorithm minimises quantum states to approximate eigenvalues, a mechanism suitable for energy-based consciousness models[31].

4.5. Hierarchical computation and quantum mechanics: toward a unified theory of cognition

The discussion of CUDA-based computation highlights how hierarchical parallelism and quotient categories enable efficient data processing, drawing parallels between GPU execution models and neural architectures. By interpreting warp-level synchronisation as a form of categorical abstraction, we gain insight into how complex systems, including biological cognition, can emerge from structured computational interactions. Furthermore, the application of topos theory suggests that CUDA execution can be framed within higher-order logical structures, providing a formal foundation for reasoning about distributed computation and its relevance to emergent cognitive processes.

Extending these principles into quantum computing, we recognise the potential of superposition, entanglement, and quantum parallelism in modelling cognitive states beyond classical architectures. Quantum associative memory, variational eigensolvers, and quantum neural networks (QNNs) offer novel frameworks for capturing probabilistic and non-local features of cognition. As computational paradigms evolve, the integration of GPU-accelerated deep learning with

29 L. K. Grover, *A Fast Quantum Mechanical Algorithm for Database Search*, "Proceedings of the 28th Annual ACM Symposium on Theory of Computing (STOC)", 1996, pp. 212–219.

30 S. Oh, C. Jaeho, K. Joongheon, *A Tutorial on Quantum Convolutional Neural Networks (QCNN)*, "IEEE Access", 2020 (8), pp. 188922–188940.

31 A. Peruzzo, J. McClean, P. Shadbolt *et al.*, *A variational eigenvalue solver on a photonic quantum processor*, "Nature Communications" 2014 (5), pp. 1–7.

quantum information processing may bridge the gap between classical and quantum machine learning, potentially unlocking new insights into the mathematical modelling of consciousness.

5. Conclusions

This study has examined the intersection of quantum information science, mathematical modelling, and neuroscience in addressing the limitations of reductionist approaches to consciousness. By integrating these perspectives, we have explored the potential for quantum processes to bridge the explanatory gap between the physical and experiential domains, evaluating whether quantum information systems could serve as computational analogues for cognitive and conscious processes. The findings suggest that consciousness may not be merely an emergent property of classical computation but could be deeply interwoven with quantum principles, challenging traditional assumptions in cognitive science.

A major insight of this research is the fundamental difference between classical and quantum computation in their ability to model cognitive processes. GPUs have been shown to effectively implement classical parallelism, facilitating large-scale artificial neural network computations, particularly in models of perception and memory encoding[32]. However, these architectures remain fundamentally deterministic and bitwise, which limits their capacity to capture non-local, probabilistic, and indeterminate aspects of cognition. In contrast, Quantum Processing Units (QPUs) introduce a paradigm shift by utilising superposition and entanglement, enabling exponentially parallel processing that classical systems cannot replicate efficiently. This computational advantage aligns with theoretical frameworks suggesting that cognitive states may operate as complex quantum systems, dynamically collapsing into classical experience through mechanisms akin to Orchestrated Objective Reduction (Orch-OR).

The consequences of this quantum paradigm for computational neuroscience extend beyond theoretical considerations. The integration of GPU-QPU hybrid architectures presents a promising approach for modelling large-scale cognitive systems, where classical processors handle deterministic, large-scale computations akin to synaptic weight adjustments, while quantum processors simulate probabilistic decision-making, non-local information integration, and high-level abstraction. This framework finds computational support in the development of Quantum Boltzmann Machines (QBMs) and Variational Quantum Neural Networks (VQNNs), which allow for adaptive learning in quantum-inspired cognitive models. Moreover, advancements in quantum programming frameworks, such as Qiskit, Pennylane and TensorFlow Quantum, facilitate the development of hybrid classical-quantum machine learning models, bridging the divide between traditional deep learning and quantum-enhanced cognition[33].

A crucial question remains regarding the physical realisation of quantum effects in biological systems, particularly whether quantum coherence can persist in the warm, noisy environment of the brain. While empirical studies have yet to definitively confirm the presence of sustained quantum states in microtubules or neural processes, models based on quantum brain dynamics and non-classical signal propagation continue to gain theoretical support. This suggests that future research must prioritise experimental validation of quantum effects in cognition, alongside the continued refinement of quantum-classical hybrid computational models.

32 N. P. Jouppi, C. Young, N. Patil *et al.*, *In-datacenter performance analysis of a tensor processing unit*, "Proceedings of the 44th International Symposium on Computer Architecture (ISCA'17)", 2017, pp. 1–12.

33 K. Mitarai, M. Negoro, M. Kitagawa, K. Fujii, *Quantum circuit learning*, "Physical Review A" 2018 (3), pp. 032309-1–032309-6.

Ultimately, this study highlights the emerging role of quantum information science in redefining consciousness as a computational phenomenon, moving beyond classical reductionist models towards a framework that integrates quantum principles into theories of cognition. While many challenges remain, particularly in empirical verification and computational scalability, the fusion of quantum mechanics, mathematical formalism, and computational neuroscience offers a non-reductionist yet rigorous approach to studying consciousness. The synthesis of quantum and classical models may represent a crucial step towards understanding consciousness as an emergent, self-organising system, leveraging the computational power of quantum mechanics to simulate the complexity of conscious experience.

While this study explores various quantum approaches to consciousness, a definitive conclusion on their validity remains elusive. The Orch-OR theory presents an intriguing framework linking quantum mechanics with cognitive processes, yet it faces significant challenges, particularly regarding the feasibility of sustained quantum coherence in biological environments. The critiques by Tegmark and others highlight the rapid decoherence timescales, which undermine the model's viability unless compensatory mechanisms exist. On the contrary, emerging quantum information models and hybrid quantum-classical architectures offer promising directions for computational simulations of cognitive processes.

Future research should focus on empirically testing the presence of quantum effects in neural processes, as well as refining mathematical and computational frameworks to determine whether quantum information can genuinely bridge the explanatory gap between physical processes and subjective experience. A more rigorous integration of classical and quantum paradigms may ultimately provide a more comprehensive model of consciousness, one that neither discards quantum principles outright nor assumes their necessity without experimental validation.

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