

Key Principles and Architectures of Hybrid Adaptive Learning Systems Using Emerging Technologies

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ABSTRACT

The hybrid quantum classical architecture is increasingly gaining popularity as a viable strategy for achieving high performance and addressing complex problems, particularly those that involve both deterministic and probabilistic elements. In such systems, QPUs (quantum processing units) and classical processors coexist, with each component being responsible for the operations it handles most effectively. This collaborative model based on the division of labor offers an optimal approach to problem solving, ensuring a balanced use of computing resources, improving performance and scalability, and also constitutes the basis of the e-learning article recommendation system in this paper. As one of the most promising emerging technologies, quantum computing brings key advantages, such as parallel processing and improved optimization capabilities, that complement classical methods in handling computationally demanding tasks. To evaluate the practical benefits of this approach, we implemented the system within a real-world adaptive learning platform, representing an early step toward the integration of quantum computing into educational technologies. This deployment enabled the assessment of the system's effectiveness in processing large volumes of unstructured textual data, while also evaluating its reliability and robustness in dynamic educational contexts.

KEYWORDS: emerging technologies, hybrid architecture, quantum computing, classical system, adaptive learning, recommendation, e-learning

1 The fundamental principles of quantum computing [1]

1.1 Qubits

Unlike the binary coding specific to traditional computers, in quantum systems the basic unit for information is called a qubit. Qubits can be used to store more information than classical bits and this makes it possible to perform

calculations faster. The quantum states $|0\rangle$ and $|1\rangle$ correspond to the classical bits "0" and "1." The $|0\rangle$ state is represented by a vector pointed towards the north pole of the Bloch sphere along the z-axis, whereas the $|1\rangle$ state corresponds to a vector pointing toward the south pole.

1.2 Superposition

Another important aspect is that all qubits respect the laws of quantum physics and can be found in a state of superposition, meaning they can encode any combination of 0 or 1. A quantum state exhibiting superposition can be viewed as a linear combination of other quantum states. This property highlights how quantum superposition differs fundamentally from classical wave superposition: while a quantum computer with n qubits can exist in a superposition of 2^n states, the classical one is limited to n states, scaling linearly rather than exponentially. Superposition enables quantum parallelism, allowing quantum computers to process multiple states simultaneously, which enhances computational efficiency and performance. Quantum superposition offers great potential but comes with challenges. Its fragile nature makes quantum systems prone to interference and decoherence, being difficult to preserve superposition for long durations.

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle \quad (1)$$

$$|\alpha|^2 + |\beta|^2 = 1 \quad (2)$$

$|0\rangle, |1\rangle$ - computational basis states

$|\psi\rangle$ - it represents the superposition and indicates the state of qubit

α - the state's waveform's probability amplitude for being in the $|0\rangle$ state

β - the state's waveform's probability amplitude for being in the $|1\rangle$ state

$|\alpha|^2$ - the probability to obtain $|0\rangle$

$|\beta|^2$ - the probability to obtain $|1\rangle$

1.3 Entanglement

Another important property of qubits is entanglement, a connection established between multiple qubits. This connection remains intact regardless of the distance between the qubits—whether they are separated by only a few centimeters or several light-years. When one qubit in an entangled pair is measured, the state of the other qubit is instantly determined, yielding a complementary result to the measurement of the first. This unique property of entanglement has proven invaluable in applications such as quantum communication and teleportation.

1.4 Quantum Gates

Quantum gates serve as the essential components of quantum computing, enabling the manipulation and alteration of qubits, the core units of quantum information. Quantum gates alter the superposition of states by performing certain transformations to qubits, including rotations, entanglement, and measurements.

2 Quantum-Classical Synergy

Although there are significant differences between the two types of systems and architectures, each comes with its own advantages and limitations, and a comparison only highlighting and emphasizing their different roles and not being conclusive on which approach is better than the other. In an alternative perspective, the role of quantum computers is not to be a replacement for traditional systems but rather to complement them because they can be useful in specific tasks. Our work is based on the hybrid quantum-classical paradigm and proposes a recommender system that uses classical text preprocessing techniques and quantum methods for calculating the semantic similarity score. This division of tasks leverages the strengths of both computational approaches, enabling scalable and efficient content recommendation in e-learning environments.

3 Developing hybrid quantum classical Recommender Systems for E-Learning

Hybrid systems that integrate both quantum and classical computing power offer an efficient solution for resource utilization in performing various tasks, with each component handling the operations it is best suited for, leveraging the strengths of each paradigm. [2,3]

Recommendation engines are widely used to guide students through relevant articles, resources and materials, tailored to their interests and learning needs. The proposed model involves the use of classical techniques for preprocessing the text of articles, followed by the application of quantum algorithms for calculating the

similarity between articles through entangled states. The purpose of this system is to generate, for each article, a top of the most similar works, based on their content. The classical component includes well-known preprocessing steps such as tokenization, lemmatization and stemming, which are used to extract and prepare features from the raw text. The most important features were first selected and then encoded into quantum states through the application of quantum gates, using a number of qubits equal to the number of selected features. This process enables the transformation of classical information into a quantum representation. On the quantum side, simulations were carried out using the PennyLane¹ framework, which facilitates the development and testing of hybrid quantum-classical algorithms. Finally, the quantum component computes the similarity between articles by estimating quantum fidelities. The experimental results obtained through this implementation demonstrated high accuracy and highlighted the potential of hybrid architectures to enhance both computational efficiency and recommendation quality in data-intensive environments. This approach can better capture the diversity and variability within the data, as it leverages the probabilistic nature of quantum processing. However, it also requires multiple runs and result averaging, given that quantum outputs are inherently non-deterministic. The hybrid model contributes to addressing this challenge by combining the strengths of classical stability with quantum variability, offering a more balanced and robust framework for adaptive learning systems.

4 Contributions

The proposed hybrid application, which integrates emerging technologies into adaptive learning systems, contributes to responsible computing and supports a valuable and efficient educational process. It plays a beneficial role by facilitating access to relevant and personalized information tailored to the user's interests. Additionally, it provides consistent and stable information, ensuring that the recommended content aligns with the user's needs.

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