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Quantum Theory in Educational Contexts: Beyond Conventional Learning Models

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Abstract

The main characteristic of modern thinking, which spanned several centuries, was mechanistic thought, epitomized by Newtonian mechanics. However, the emergence of quantum theory over a century ago fundamentally altered our understanding of the structure of matter and its interactions. Contemporary thinking is based on a new worldview and thought process shaped by quantum scientific theories, emphasizing uncertainty, discontinuity, and wholeness. Originating in physics, quantum theory has been successfully applied to other natural sciences. In humanities and social sciences, including philosophy, education, and economic management, quantum theory is profoundly influencing the in-depth development of various disciplines. This paper will review existing research on quantum theory in education, explore the application of quantum theory and thinking in education, and discuss the profound impact quantum thinking may have on educational research.

Keywords

Quantum Thinking; Education Theory; Higher Education.

1. Background

Interest in the quantum nature of education stems from the contemplation of whether human cognition possesses quantum characteristics. In his book "What is Life?," Schrödinger discussed the potential role of quantum effects in the formation and development of life[1]. Nobel laureate and British mathematical physicist, Professor Roger Penrose of Oxford University, in his book "The Emperor's New Mind," argued that the human brain cannot be simulated by a Turing machine, suggesting that quantum mechanics should be used to explain brain activity[2]. Penrose posited that despite the advancements in artificial intelligence, the complexity of human thought and consciousness cannot be fully captured by finite algorithms. He observed that humans cannot engage in numerous completely independent thought processes simultaneously, but rather focus consciousness on a specific task while vaguely dispersing it across many related pieces of information. Penrose described this characteristic as the "unity" of consciousness. Quantum parallelism allows for different choices to coexist in linear superposition; a single quantum state could theoretically comprise numerous different and concurrent activities, aligning with the characteristics of focused and dispersed consciousness, making quantum language more suitable for explaining this "unity." Penrose has called for continuous revisions in quantum mechanics to reconcile issues with relativity and time irreversibility, key to unlocking the mysteries of conscious thought.

Penrose's theory, though controversial and not widely accepted in physics, biology, or computer science, aligns with recent neuroscience and psychology findings suggesting quantum mechanics might indeed influence consciousness and cognition. As Jim Al-Khalili notes in "Life on the edge," many biological phenomena involve quantum mechanics, like

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enzymes facilitating particle tunneling in life-sustaining reactions, unique proteins in animal eyes sensitive to geomagnetic fields aiding migration, quantum beats in photosynthesis elucidating energy-efficient pathways, and inelastic electron tunneling in olfaction[3]. Al-Khalili argues that cellular quantum coherence, despite the noisy molecular environment, is a unique life trait, underscoring its role in maintaining biological order.

Al-Khalili, sharing Penrose's view on human consciousness, posits that consciousness is a product of quantum computation. He suggests that human activities, governed by consciousness, are controlled by neural signals opening ion channels on neurons, with ion exchange generating action potentials to control muscle contractions[4]. These ion channels act as logic gates, with countless such gates representing human activities. However, these activities are not independent but serve our consciousness. Thus, Al-Khalili speculates that the brain exhibits quantum coherence, integrating information from individual neurons through quantum entanglement among these logic gates (ion channels).

2. Quantum Models of Cognition and Learning

In the field of quantum cognition, Professor Jerome Busemeyer of Indiana University, a member of the American Academy of Arts and Sciences, and his team have made pioneering contributions[5]. Differing from Penrose's view, Busemeyer emphasizes that quantum cognition does not study the physical mechanisms of the brain but uses quantum theory to describe human judgment and decision-making. He points out two quantum features aligning with human cognition: (1) Quantum probability, which explains judgment and decision-making processes sometimes inconsistent with classical probability models, using vector space representations akin to neural network cognitive models. (2) The presence of conjugate variables in measurement, akin to quantum theory, where judging one matter changes the psychological state, influencing decisions on related matters, similar to how measuring one variable affects another's probability distribution in quantum mechanics[6].

In empirical studies of causal reasoning and rational decision-making, humans often violate classical models but align with quantum models[7]. Classical probability theory considers events as subsets of a single sample space, with the probability of an event being higher than its simultaneous occurrence with another event, i.e., $P(A) \geq P(A \cap B)$. However, the "conjunction fallacy" occurs when the probability of "two events happening together" is perceived as higher. Quantum cognition models suggest that the incompatibility of events causes this fallacy due to the sequential effect in quantum theory. Human cognitive state vectors projected first on event B, then on A, have greater effects than direct projection on B alone, leading to higher perceived probabilities of simultaneous events. Additionally, decision-making often defies the classical total probability formula, as shown in the Dilemma Game. This challenges educators to consider the quantum nature of education.

The integration of quantum theory and education is beginning to manifest across multiple levels. At the micro level, while the question "Is the human brain fundamentally a quantum computer?" remains unanswered, there is a growing body of research indicating that individual performance in certain cognitive tasks exhibits quantum characteristics. These findings in the field of quantum cognition are prompting researchers in learning sciences and curriculum instruction to reevaluate the patterns of student learning and reasoning.

At the macro level, Professor David Selby of the University of Toronto has proposed a quantum model for educational globalization[8]. This model, drawing from the uncertainty in quantum mechanics system development, examines the interplay between "Possible Future," "Preferred Future," and "Alternative Future" scenarios. Similarly, Professor Sally Kift from Australia has explored the concept of "quantum leaps" in higher education, suggesting that building bridges

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between academic, administrative, and student support roles can significantly enhance the first-year experience of university students[9].

Reimagining education from first principles reveals its essence as a human-centric learning activity characterized by randomness and variability, necessitating a shift from Newtonian-Cartesian to quantum thinking in the intelligence era. Traditional educational models emphasize certainty in teaching and assessment, assuming uniform outcomes from identical methods. However, a quantum perspective recognizes education's "quantum leap" nature, with development being non-linear and unpredictable, akin to photons diffracting through slits, demonstrating varied outcomes despite identical paths. This viewpoint reinterprets the inherent uncertainties in educational processes and outcomes, traditionally attributed to individual learner differences. Talent development in the quantum era calls for theoretical frameworks and empirical data grounded in quantum thinking.

3. Educational Model inspired by Quantum Thinking

Unlike the deterministic mindset of Newtonian mechanics, the nature of education leans more towards quantum thinking, characterized by variability and uncertainty. For instance, in a classroom where students are taught by the same teacher, each student's learning experience and test results differ. Similarly, twins raised by the same parents can exhibit significant differences in intelligence and personality traits, further illustrating the inherent variability and unpredictability in educational outcomes.

In quantum mechanics, the allowed energy levels of a system are determined by the time-independent Schrödinger equation (eq.1). This intrinsic uncertainty in quantum systems, where the exact energy level isn't known until measured, parallels the nature of education. Students, akin to energy in quantum systems, are influenced by the educational environment. However, within the same environment, students may attain different levels of intelligence and proficiency, highlighting the inherent variability and unpredictability. Quantum thinking, therefore, provides a framework to understand why students in the same educational setting can exhibit diverse outcomes.

$$(\widehat{H} + V)\psi = E\psi \tag{1}$$

From a quantum perspective, the significance of education, despite its inherent uncertainty, lies in "probability." The potential energy of an environment determines the likelihood of a system attaining different energy levels. Similarly, in education, an appropriate environment can increase the probability of students achieving certain levels of intelligence and proficiency. Conversely, an inadequate environment can hinder student development. The goal of education at all levels—national, societal, school, and family—is to create environments conducive to learning. For example, a home that fosters a culture of reading and learning can influence children to adopt similar habits. School environments, or the academic and institutional culture, also play a crucial role in student development, as seen in different educational settings and their impact on students' attitudes towards learning.

The uncertainty inherent in education suggests that educational outcomes should be viewed as a probability distribution rather than solely judged by final results. Even high-performing students may not always score well in tests, sometimes even falling below average, a discrepancy difficult to explain solely through random errors in classical educational assessment theories. This necessitates exploring quantum models in education, particularly in educational measurement, to develop assessment models that better align with the true nature of education, grounded in quantum thinking.

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The nature of educational measurement—whether classical or quantum—is a subject worthy of in-depth study. Classical educational measurement theory assumes that a student's ability at any given moment has an objective true value, which, due to measurement errors, cannot be precisely captured. This true value plus error accounts for the observed score in assessments, as illustrated in the formula (eq.2) where X represents the observed score, T the true ability score, and E the random error in testing.

$$X = T + E \tag{eq.2}$$

Classical educational measurement theory views measurement as an independent process that doesn't affect a student's true ability. However, measurements not only assess but also influence student ability development, making it an integral part of education. Measurement impacts students' self-perception and environment assessment. Allison Godwin's survey of 6772 first-year college students showed that academic performance significantly affects students' external environment perception and identity[10]. High achievers experience more positive feedback and higher self-identity, while struggling students are more sensitive to negative feedback, impacting their learning process, attitudes, choices, and even future career paths.

Quantum theory's worldview may be more aligned with the essence of educational measurement compared to classical theories, mainly differing in two fundamental assumptions: (1) Whether attributes of the measured subject (ability, knowledge, personality, etc.) have a definite true value, and (2) Whether the measurement process alters the state of the subject. These assumptions, examined under the lens of quantum theory, suggest a nuanced understanding of how educational assessment impacts and is impacted by the attributes and state of learners.

In quantum theory, the state of microscopic particles is described using wave functions. When a physical quantity of a particle is observed, its wave function collapses into a specific eigenfunction corresponding to that quantity. For instance, measuring the energy of a microscopic particle in a one-dimensional infinite potential well would result in the particle's wave function collapsing to a particular eigenstate of the energy observable (eq.3).

$$\Psi(x,t) = \sqrt{\frac{2}{a}}\sin\left(\frac{n\pi x}{\hbar}\right)e^{-iE_n t/\hbar} \tag{eq.3}$$

The n in the wave function above corresponds to a specific energy level. When a system collapses to its lowest energy level (the ground state), n equals 1, and the observed energy is E_1, placing the system in the energy eigenstate ψ_1. If the system collapses to the next higher energy level, then n equals 2, the observed energy becomes E_2, and the system is in the energy eigenstate ψ_2, and so on.

Before observation, a particle's wave function might be a superposition of multiple energy eigenstates. For instance, if the wave function prior to measurement is a superposition of the two lowest energy eigenstates, ψ_1 and ψ_2, this means the particle exists in a state that is a combination of these two states. It's only upon measurement that the wave function collapses to one of these definite eigenstates, thus determining the particle's energy level. However, Before an energy measurement is made, the particle's energy is neither E_1 nor E_2, nor is it any definite value between E_1 and E_2. According to quantum theory, if a particle is in a superposition state of two energy eigenstates, the system's energy doesn't have a definite value until the energy measurement is performed.

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The Quantum Educational Measurement Model posits that before measurement, a student's attributes (such as ability, knowledge, personality) exist in a superposition of states without a single definite value. For instance, in the newly published "High School Physics Curriculum Standards" in China, student competency in "scientific inquiry" is divided into five levels (Table 1). Classical theory would place a student's ability at one of these levels or between two adjacent levels. In contrast, the quantum model suggests a student's ability could be at any of these levels or in a superposition of multiple levels, which may not be adjacent.

Table 1. Scientific inquiry ability levels (in the high school physics curriculum standards)

Ability Level	Description of scientific inquiry ability level
Level 1	Basic problem awareness, simple data collection under guidance, preliminary data organization, awareness of communication and discussion.
Level 2	Observing phenomena, posing physical questions, using basic equipment for data, organizing data for initial conclusions, and simple report writing.
Level 3	Analyzing phenomena, hypothesizing, formulating inquiry plans with help, data analysis to form conclusions and attempts at explanation, writing experimental reports.
Level 4	Analyzing facts to pose and articulate investigable questions, planning and executing inquiries, discovering patterns in data, forming reasoned conclusions, and writing comprehensive reports.
Level 5	Addressing real situations, innovatively posing questions, flexible equipment use, diverse data analysis methods, forming logical conclusions, and writing complete, reflective inquiry reports.

The second assumption of Quantum Educational Measurement Theory is that measurement changes the state of the measured subject. When attributes (e.g., scientific inquiry ability) are measured, an eigenvalue is obtained, collapsing the student's state into the corresponding eigenstate. For example, a student in a superposition of Levels 2 and 4 will collapse into either Level 2 or 4 upon measurement. It's noted that while these five levels are used for convenience in teaching and assessment, student ability may not be discrete and could be a continuous distribution, akin to the superposition of infinite eigenstates in a free particle's wave function. This model highlights the unique aspects of quantum educational measurement theory.

The assumption in Quantum Educational Measurement Theory that measurement changes the state of the measured aligns with educational experiences. Professor John Bransford's efficiency-innovation model suggests balancing routine training with innovative approaches[11]. Routine experts excel in familiar problems but struggle with unfamiliar ones, while adaptive experts continuously expand their expertise despite lower efficiency. Sam Wineburg's research shows how routine experts' overreliance on assimilation can lead to ineffective conclusions. Traditional assessments, if not adapted, can revert students' innovative thinking back to conventional patterns. This mirrors the "quantum Zeno effect," where frequent measurements of an unstable quantum system can freeze its state, preventing evolution.

Determining whether a measured educational attribute stabilizes post-measurement (stationary state) or continues to evolve (non-stationary state) is a challenge in applying quantum thinking to educational assessment. In quantum mechanics, some states (like energy eigenstates in an infinite potential well) are stationary, while others, like position eigenstates, evolve over time. Similarly, certain learned skills like swimming or cycling may remain stable

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over time, while other abilities and competencies might evolve rapidly post-assessment, leading to different results in subsequent measurements.

4. Summary

In this manuscript, we integrate the principles of quantum theory into the realm of educational theory and practice. This integrative approach is predicated on the foundational aspects of quantum mechanics, such as uncertainty, discontinuity, and wholeness, and their potential applicability to understanding human cognition and learning. The manuscript posits that the quantum nature of human consciousness might provide a more accurate framework for comprehending learning processes, drawing on parallels with quantum effects observed in biological phenomena.

Central to the manuscript is the exploration of quantum-inspired models in education, which challenge traditional Newtonian methodologies. These models emphasize the diversity and unpredictability inherent in student learning outcomes, suggesting a shift towards more probabilistic and dynamic approaches in educational measurement and evaluation. The manuscript advocates for a transition from conventional educational paradigms to those that embrace the complexities and uncertainties of the modern educational landscape. Although the application of quantum theory to education presents significant challenges, the manuscript underscores its potential to revolutionize educational practices and theories, paving the way for a more nuanced and effective educational system.

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