How Quantum-like Models Illuminate Complex Systems

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Professor Andrei Khrennikov (Linnaeus University – Sweden) and Professor Emmanuel Haven (Memorial University of Newfoundland – Canada) utilise the mathematical framework of quantum theory to offer novel insights into the complexities of biological systems, cognition, decision-making, and other areas of social science, such as economics and finance. Their work showcases the potential of quantum-like models to decode the intricacies of non-physical systems, paving the way for innovative approaches to understanding the dynamics of life and thought, social processes and financial markets.

Extending the Application of Quantum Theory

Quantum-like models leverage the peculiar uncertainty and observer role inherent in quantum theory, adapting them to explain information processing and decision-making in biological, cognitive, social, and financial contexts. These models exploit the uncertainty and the role of the observer inherent in quantum theory, adapting them to explain how information is processed, and decisions are made in various contexts. This approach provides a nuanced framework for understanding phenomena that elude classical deterministic models, offering insights into the operational principles of cognition and decision processes. The book Quantum Social Science presents, in quite some detail, a formal overview of those ideas.

Moreover, the paper *Open Systems, Quantum Probability, and Logic for Quantum-like Modeling in Biology, Cognition, and Decision-Making* by Professor Andrei Khrennikov (Linnaeus University) represents a significant advancement in applying quantum theory's mathematical framework beyond physics.

Moving Beyond Quantum Physics

Based on Hermitian operators in complex Hilbert space and density operators for systems' states, the quantum probability model has proven exceptionally effective in capturing quantum phenomena's irreducible randomness. This success has prompted inquiries into extending quantum probability applications beyond physics.

Professor Khrennikov explores applying quantum theory principles to complex biosystems, cognition, and decision-making processes. His collaboration with Professor Haven led to further extending quantum-like modelling to social and political sciences, economics, and finance.

Quantum-like modelling adopts quantum probabilistic laws and contextual dependencies to simulate information processing in non-physical systems. This approach isn't about identifying quantum physical processes but applying the quantum framework to understand complex behaviours and decision-making phenomena that classical theories struggle to explain.

Key elements of quantum theory crucial in quantum-like modelling include:

a) Processing information in the form of states' superposition representing unresolved uncertainties.

b) Operating with incompatible observables. Such observables cannot be described by a single Kolmogorovian space. Mathematically, this basic quantum property is expressed via the non-commutativity of operators.

c) Entanglement: Existence of states encoding correlations of incompatible observables.

Biological Entities as Information Processors

The successful application of this approach to biological systems rests on the premise that biological systems process information in ways classical mechanics cannot fully describe. The above paper illustrates how quantum-like models can represent gene expression and cellular glucose and lactose consumption, treating biological entities as information processors making decisions akin to quantum-like interference phenomena.

Experiments on E. coli bacteria populations at Tokyo University demonstrated behaviour analogous to quantum mechanics' probabilistic outcomes under certain conditions. The paper also explores open quantum systems to explain how biosystems maintain order and stability amidst entropy increases in their subsystems, exemplified by subsystem states' entanglement.

The Human Mind and Consciousness

In cognitive science, contextuality and quantum probability offer fresh perspectives on decision-making processes. Contextuality in quantum mechanics parallels cognitive processes, where decisions and beliefs are influenced by the context in which information is received and processed. Quantum probability applied to cognitive models allows for describing decision-making processes that classical probability theory fails to capture.

Quantum logic is considerably different from classical Boolean logic, particularly through the violation of the distributivity law. This framework captures the fluid and dynamic thought process where classical logic falls short. Classical logic is realised as Boolean algebra, while quantum logic is realised as the lattice of projections in a Hilbert state space. This lattice is essentially a collection of Boolean algebras, with the overlap of a few algebras representing statements corresponding to compatible questions or problems.

The research contributes significantly to consciousness discussions by suggesting that conscious and unconscious processes' interaction can be modelled within open quantum systems theory. This approach posits consciousness as a measurement apparatus acting upon the unconscious mind, processing and integrating information analogously to the quantum measurement process. Such a model aligns well with higher-order theories of consciousness, which propose that consciousness arises from the brain's ability to represent and integrate its own states. This approach promises to illuminate the complex dance of consciousness and unconsciousness, offering a promising avenue for unravelling the mysteries of human cognition and emotion.

Psychology and Decision-making

Quantum-like models in psychology and decision-making incorporate superposition and entanglement concepts, providing a more nuanced understanding of information processing and decision-making, especially in complex or ambiguous situations. These models offer a framework for understanding how people can hold conflicting beliefs or change preferences based on new information, reflecting quantum mechanics' probabilistic nature.

In psychology, the adoption of quantum-like models enables the exploration of cognitive processes that classical theories struggle to explain, such as the occurrence of paradoxical decision-making patterns and the impact of context on cognitive outcomes. For decision-making strategies, these models allow for the representation of processes not easily explained by classical probability, such as violations of the sure-thing principle or the presence of preference reversals.

However, adopting quantum-like models in psychology and decision-making presents challenges, including the complexity of quantum mathematics and the need to complement rather than supplant classical models.

First Steps Towards Quantum Finance

The book *Quantum Social Science* by Haven and Khrennikov was the first monograph on quantum social science, shaping this new field and establishing its basics. It formally applies quantum theory to large human ensembles, modelling their interaction and quantum-like information processing leading to informationally non-local interactions (social entanglement) within quantum information theory's framework.

The upcoming wide implementation of quantum computers, corresponding AI systems, and quantum machine learning algorithms will stimulate the implementation of quantum and quantum-like decision-making models. Banks and financial markets are expected to become the first powerful consumers of such models, including quantum cryptography as a new instrument for improving bank transactions and financial trade security.

Opening New Realms

The work of Professor Khrennikov and Professor Haven opens doors to new research realms, merging quantum theory with complex system sciences. The future promises further empirical validation, interdisciplinary collaboration, and exploration of quantum-like models' potential to revolutionise our understanding of cognition, biology, and decision-making. Their work demonstrates the potential of quantum-like modelling to provide novel insights into complex systems across multiple disciplines, from biology to finance, opening up new avenues for understanding and predicting complex phenomena in the natural and social sciences.

MEET THE RESEARCHERS

Professor Andrei Khrennikov
Linnaeus University, Växjö, Sweden

Professor Andrei Khrennikov has been a towering figure in the intersection of quantum mechanics, mathematical physics, and the application of quantum theory to areas beyond traditional physics. His pioneering work has extended the formalism of quantum mechanics to fields such as biology, neuroscience, psychology, economics, and even political science. As a PhD holder in physics, Professor Khrennikov's contributions span both the foundational aspects of quantum mechanics and its quantum-like modelling applications. Professor Khrennikov is also director of the research group International Center for Mathematical Modeling (ICMM). His work challenges the boundaries of quantum mechanics, exploring its implications for understanding complex systems and decision-making processes.

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Professor Emmanuel Haven
Memorial University of Newfoundland, St. John's, Canada

Professor Emmanuel Haven, renowned for his interdisciplinary research, brings the principles of physics into economics, psychology, finance, and biology. Holding the prestigious Dr Alex Faseruk Chair in Financial Management at Memorial University, Professor Haven's work spans the application of quantum mechanical concepts to social sciences. Professor Haven's career commenced at the University of Essex, and he continued to progress through the academic ranks, including the appointment as a personal Chair at the University of Leicester. He is currently the co-director of the newly established Centre for Quantum Social and Cognitive Science (CQSCS; https://www.mun.ca/business/centres-and-engagement/centre-for-quantum-social-and-cognitive-science/cqscs-organizational-structure/) and also the co-founder of the newly established journal (published by SAGE) *Quantum Economics and Finance* (https://us.sagepub.com/en-us/nam/quantum-economics-and-finance/journal203837). His research, notably in quantum social science and financial non-arbitrage theorems, demonstrates the versatility of quantum formalism in reinterpreting economic and financial theories.

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FURTHER READING

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