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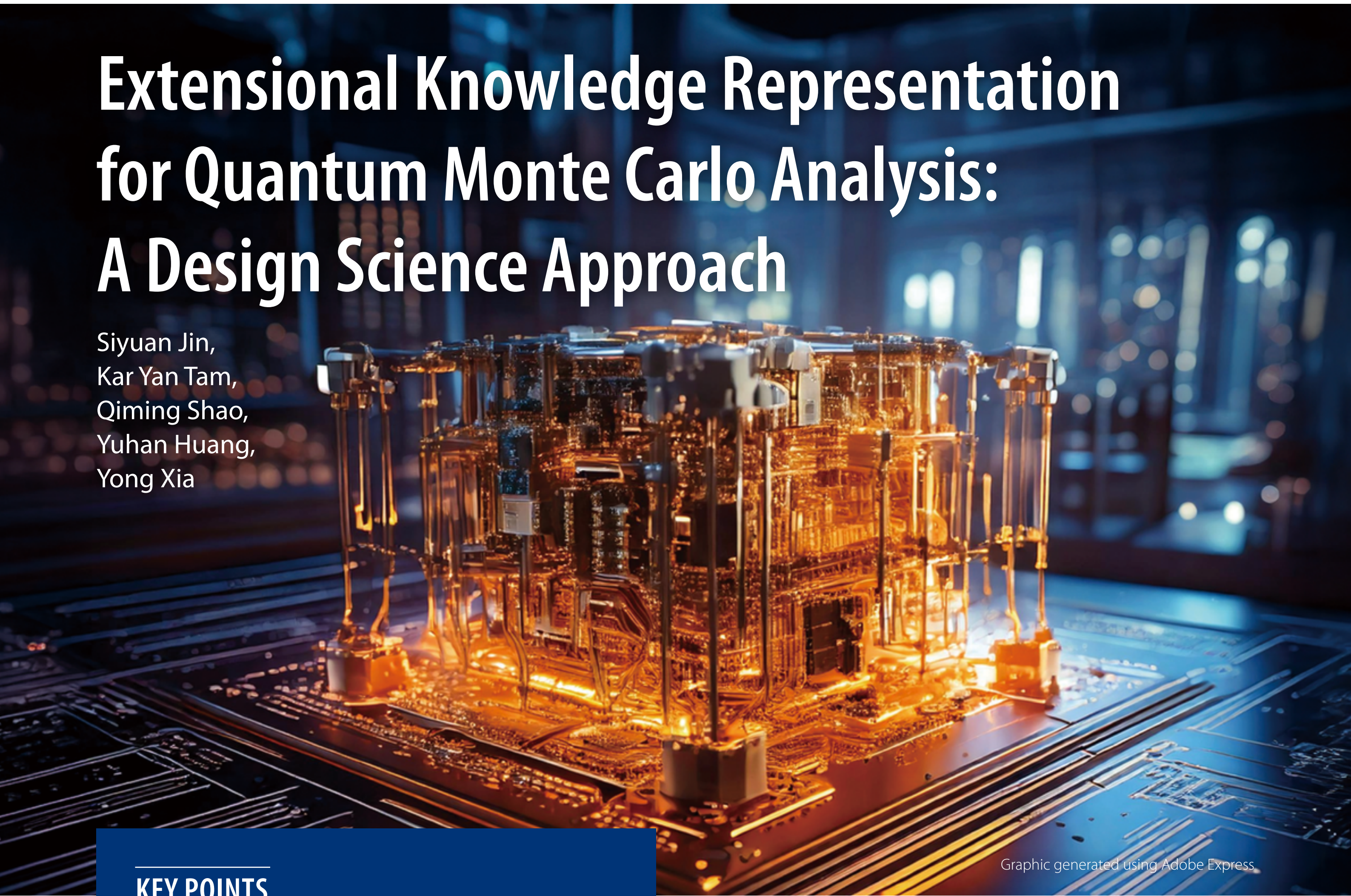
THOUGHT LEADERSHIP BRIEF

Extensional Knowledge Representation for Quantum Monte Carlo Analysis: A Design Science Approach

Siyuan Jin,
Kar Yan Tam,
Qiming Shao,
Yuhan Huang,
Yong Xia



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KEY POINTS

- Quantum computing is difficult to understand because its concepts are abstract and rely on advanced knowledge of mathematics and physics.
- We find that conversion from classical contextual knowledge toward extensional representation is the most effective for decision makers. Firms already understand classical solutions, and this knowledge can help them see the potential of quantum counterparts.
- We develop a conversion artifact that can convert contextual classical algorithms toward quantum ones. By doing so, organizations can better evaluate the potentials of quantum computing in a focused, evidence-based manner thereby improving decision-making.

ISSUE

"If you think you understand quantum mechanics, then you don't." – Richard Feynman Quantum computing has the potential to transform fields like finance, where solving complex problems and green computing are essential. However, its adoption is challenging because its core concepts are abstract and difficult to understand. This is largely due to quantum knowledge being presented in theoretical ways (intensional representations) that require advanced knowledge of mathematics and the need to develop entirely new ways of thinking.

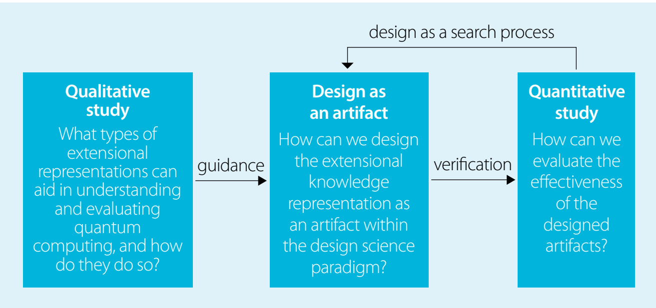
Intensional representations use abstract symbols and properties, offering flexibility but making learning difficult. Extensional representations, on the other hand, rely on concrete examples and analogies, making them easier to understand but less adaptable to different contexts. While intensional representations require significant effort to grasp, extensional representations simplify learning by using relatable, real-world examples.

Extensional encoding, such as the use of analogies, converts intensional representations toward extensional representations. However, research into effective approaches for achieving extensional encoding remains limited. This study examines four types of intensional knowledge and evaluates how well they can be communicated through extensional encoding. Based on these findings, we design an artifact for decision makers to evaluate the potentials of quantum computing in their local firms.

ASSESSMENT

We adopt a mixed-methods approach, combining qualitative and quantitative research to explore the transition from intentional to extensional knowledge. Insights from this study guide the design of extensional knowledge representations as artifacts within the design science framework. We then conduct a quantitative study to evaluate these artifacts, allowing us to validate their effectiveness (Figure 1).

Figure 1. Study Design



We carried out a qualitative study to explore four types of knowledge encoding: common/contextual and classical/quantum knowledge. The research was done in partnership with a venture capital (VC) group interested in investing in quantum technology during 2021 and 2022. Our study included five senior managers and decision-makers, supported by over 200 engineers who provided feedback. However, the VC group did not have enough expertise to evaluate quantum technologies or identify promising firms for investment. To fill this gap, three researchers worked with the group to test different extensional encoding methods to help them evaluate.

We categorized knowledge into common and contextual types to understand how they fit into the encoding process. By further dividing knowledge into classical and quantum domains, we identified four distinct types (Figure 2).

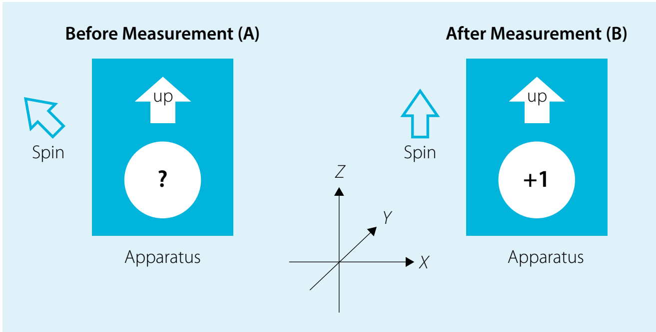
Figure 2. Knowledge Differentiation

Intensional Representation	Classical Knowledge	Quantum Knowledge
Common Knowledge	Classical Common Knowledge	Quantum Common Knowledge
Contextual Knowledge	Classical Contextual Knowledge	Quantum Contextual Knowledge

We designed three qualitative studies. The first study focused on common quantum knowledge. Researchers translated quantum physics knowledge into relatable examples (extensional representations). The second study dealt with classical common knowledge. Researchers worked with external vendors from top quantum computing companies to run proof-of-concept demonstrations. The third study focused on classical contextual knowledge. Researchers collaborated with business teams to turn domain-specific classical knowledge into relatable, easy-to-understand examples. We do not cover quantum contextual knowledge as most firms lack quantum implementations and their corresponding knowledge.

The first representation covers basic quantum knowledge. Researchers explain the fundamental physics behind quantum computing, emphasizing its business potential. They use a two-hour presentation featuring an analogy. The analogy involves an experiment where a system and a device (apparatus) measure results (Figure 3).

Figure 3. Extensional Representation Encoding from Quantum Common Knowledge (Susskind and Friedman 2014)



In a simple two-state system, this device interacts with the system (the spin) and records a value. The device acts like a black box, showing either +1 or -1 after measurement, indicating the spin's state. Despite efforts to simplify quantum concepts, some participants still found it hard to understand how they could be applied in practice. One participant said:

"I understand the analogy aims to simplify the concept, but I am struggling with the leap from a physical black box to quantum measurements. Understanding this is interesting, but I cannot imagine how it helps us use it."

The second approach involved proof-of-concept demonstrations from external vendors. Five global quantum companies, including large corporations and startups, showcased financial applications of quantum computing in three key areas: quantum Monte Carlo simulation, quantum machine learning, and quantum asset pricing. One participant raised this concern:

"I believe quantum computing holds potential for the finance industry. However, most of these demonstrations are conducted by physics scholars who may not fully understand our business processes. A crucial concern is how we can effectively integrate it within our firm."

To address this, the third approach involved internal teams to run demonstration based on existing contextual and classical examples. The presentations, which lasted an hour, showed how quantum computing could improve efficiency. One senior manager commented:

> *"The analog used in the demonstration effectively highlighted the advantages of quantum computing with practical, real-world examples. We should consider applying this approach to larger-scale use cases. This will not only show our commitment to innovation but also provide a clear path for integrating quantum solutions into our core operations. "*

Translating classical contextual knowledge into a quantum equivalent is more effective than general methods but requires greater effort and resources. To address this, we developed a novel artifact to facilitate such conversions. The core idea is to treat superposition states as distribution variables.

In finance, variables like stock prices inherently involve uncertainty. Traditional simulations handle this by sampling from predefined distributions. In contrast, quantum simulations leverage superposition states to represent multiple possibilities simultaneously. Our approach shifts from classical single-value variables to distribution variables. For instance, an asset return fixed at 1% represents just one possible outcome within a broader distribution of potential returns. Quantum mechanics enables discrete representation of the entire distribution, significantly enhancing computational modeling. This transition from a "point estimate" to a "distribution estimate" allows for capturing the full range of potential outcomes.

To test the accuracy of this process, we developed a software framework called FinQMC to generate quantum circuits. We conducted two case studies to evaluate the framework:

- **Derivative Pricing:**
  A well-known application of quantum MC methods. FinQMC successfully replicated this case, producing results consistent with previous studies.

- **Portfolio Selection:**
  A new application of quantum MC methods that had not been studied before. We use it to demonstrate the external validity.

Figure 4. Summary of Qualitative Studies

Knowledge Type	Case	Description	Participant Feedback
Quantum Common Knowledge	MasterClass Technical Introduction	A physics presentation featuring Susskind's analogy of a quantum measurement apparatus.	Participants found the analogy interesting but struggled to connect it to real-world applications.
Classical Common Knowledge	Vendor Proof-of-Concept	Demonstrations by five leading quantum companies, focusing on financial applications.	Participants perceived the techniques were too complex to adopt internally and worried about how quantum solutions would fit with existing processes.
Classical Contextual Knowledge	Internal Contextual Demonstrations	Internal teams conducted comparative demos showcasing quantum computing's efficiency against classical methods.	Senior management thought the models were too basic, but the demonstrations helped them better evaluate potential investments and partnerships.

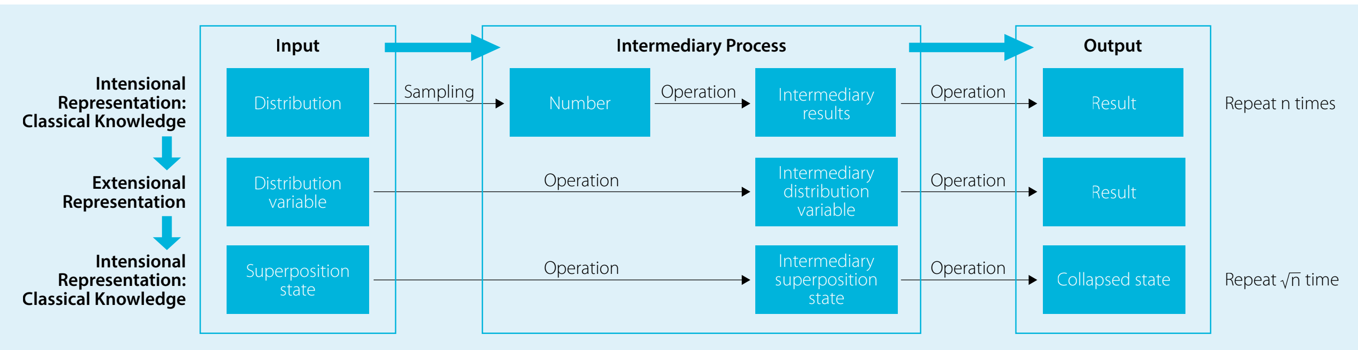
IMPLICATIONS:

Organizations need a structured framework to evaluate quantum computing before adoption. This study introduces extensional encoding as a practical approach to bridge abstract quantum concepts with actionable insights. We propose a three-type framework for extensional encoding, with a focus on converting classical and contextual knowledge into extensional representations — identified as the most effective method. Using this framework, we developed an artifact to facilitate such conversions.

For practitioners, especially in domains like finance, this framework provides a systematic way to align quantum algorithms with specific business problems, such as portfolio optimization or risk management. This ensures organizations can evaluate quantum computing's potential in a focused, evidence-based manner, reducing uncertainty and improving decision-making.

Policymakers can adopt this framework to guide funding and tool development, enabling industries to systematically evaluate and adopt quantum technologies. By integrating extensional encoding into research and practice, the framework ensures quantum computing adoption is grounded in measurable value and clear outcomes.

Figure 5. Theoretical Model for Classical and Contextual Knowledge Encoding



Siyuan (Bruce) Jin is a PhD Candidate in HKUST Information Systems (IS) Department, supervised by Prof. Kar Yan Tam. He received the China National Scholarship in 2020, the Hong Kong PhD Fellowship (HKPFS) award in 2024. He mainly focuses on blockchain, quantum computing and their business implications. His papers have been accepted by top IS conferences, including the International Conference on Information Systems (ICIS) and the Conference on Information Systems and Technology (CIST).

Kar Yan Tam is Vice-President for Administration and Business and Chair Professor of Information Systems, Business Statistics and Operations Management at the Hong Kong University of Science and Technology (HKUST). Prof Tam is known for his contributions in information systems and the diffusion of innovations in organizations. According to Google Scholar, his publications have received over 23,000 citations. Prof Tam is currently serving on the editorial board of a number of academic journals. Prof Tam also plays an active role in public services. He is a member of the Hong Kong Exchange Fund Advisory Committee of the Hong Kong Monetary Authority and the Chairperson of the Hong Kong Committee for the Pacific Economic Collaboration.

Qiming Shao, Assistant Professor at HKUST's Department of Electronic & Computer Engineering, specializes in spintronics, MRAM, quantum devices, and efficient AI systems. His research focuses on energy-efficient hardware using spintronic and quantum materials, with publications in top journals including Nature Nanotechnology, Nature Electronics, Nature Communications, Nano Letters, and International Electron Device Meeting (IEDM). He has received prestigious awards, including the IEEE Magnetics Society Early Career Award, and actively contributes to IEEE leadership and international conferences.

Yuhan Huang is a PhD student in Electronic and Computer Engineering at the Hong Kong University of Science and Technology. Yuhan's research interests include quantum computing, quantum simulation, and quantum finance. She is particularly focused on advancing the applications of quantum algorithms in finance and exploring novel quantum computing techniques. Yuhan has published her work in quantum journals, such as Physical Review A (PRA), Physical Review Research (PRR), Science China Physics, Mechanics & Astronomy, and Science China Information Sciences.

Dr. Yong Xia is currently Chief Architect for Wealth and Personal Banking at HSBC. He is also one of the five Council Members at International Requirements Engineering Board. Before that, he was Global Head of HSBC Lab, Chief Architect for Asia Pacific and Chief Architect for China at HSBC, a member of IBM Academy of Technology and a Senior Certified Consultant (at the Thought Leader level) at IBM, a Visiting Professor at Fudan University and South China University of Technology, an Enterprise Ph.D. Supervisor at Shanghai Jiao Tong University, a Board Director of Corda Network Foundation and a Lead Architect at Credit Suisse.

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HKUST IEMS
INSTITUTE FOR EMERGING MARKET STUDIES

T: (852) 3469 2215
E: iems@ust.hk
W: http://iems.ust.hk
A: Lo Ka Chung Building, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon

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