Towards Quantum Data Structures for Enhanced Database Performance

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Quantum Data Science and Management

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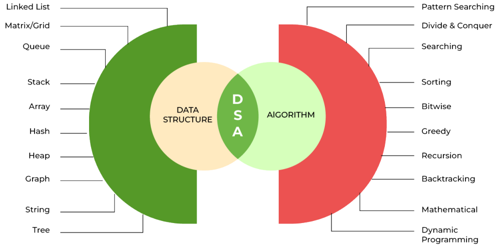
Introduction

- Highly efficient solutions in classical data management
- Some problems remain challenging:
  - unstructured search
  - optimisation under uncertainty
- Quantum Computing not a "one-size-fits-all" solution
- How can these properties be harnessed to solve problems?

Leveraging Quantum Properties

Why Quantum Data Structures?

- Implementing Quantum Algorithms
- Translate data into the quantum realm



Define Quantum Data Structures

- Utilise Structural Properties
- Optimise Data Accessibility

Data Structures

- Bits
- Sequential and Deterministic
- Robust

Quantum Data Structures

- Qubits
- Quantum Parallelism
- Prone to Error / Probabilistic

Foundations: QRAM and QRAG

- **QRAM:**
  - Quantum equivalent of classical RAM
  - Store and retrieve data efficiently in quantum states
  - Querying multiple data entries utilising superposition, crucial for the parallelism needed in Algorithms like Grover's
- **QRAG:**
  - Extends QRAM by integrating in-memory quantum operations
  - Data manipulation occurs during memory retrieval phase
- **QPD:**
  - Simple data encoding using CNOT gates (QuAM)
  - Grover's Algorithm applied to prepared registers
  - Lower qubit requirements

Quantum Partitioned Database (QPD)

QPD components

- Store database subsets
- Grover's Algorithm on $|i_j\rangle$ and $|x_{ij}\rangle$

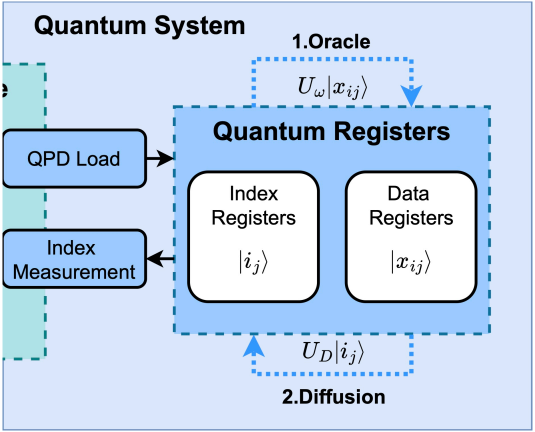


Figure: Proposed architecture of QPD

QPD Architecture

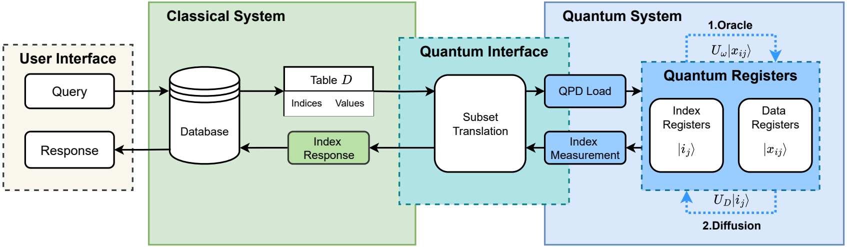


Figure: Proposed architecture of QPD based System

- Data flow from classical to quantum system and back.
- Quantum registers handle subsets of database for parallel processing.

Circuit Design of QPD

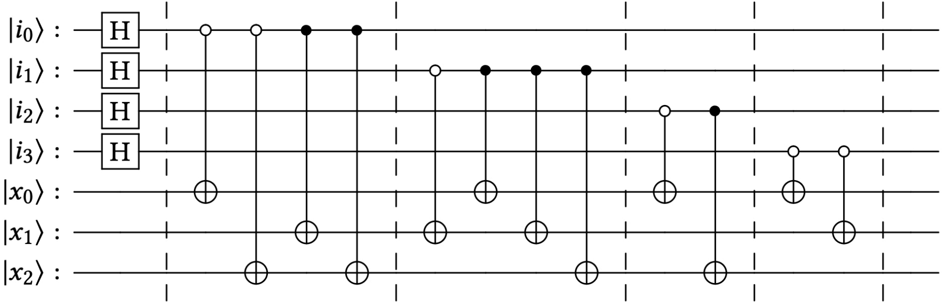


Figure: QPD circuit design of a split into four subsets, $\{(5, 6), (2, 7), (1, 4), (3, 0)\}$. The first column of Hadamard-gates superposes all index registers into $\frac{|0\rangle + |1\rangle}{\sqrt{2}}$

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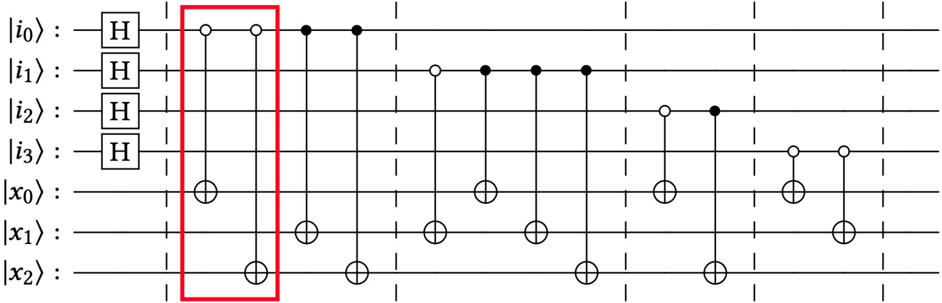

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QPD Data Encoding

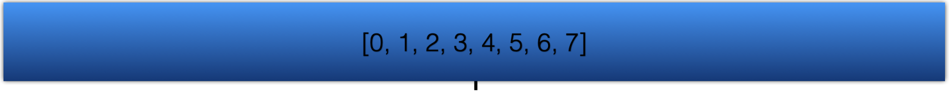

Figure: Schematic example of the QPD split into four subsets, $\{(5, 6), (2, 7), (1, 4), (3, 0)\}$ and the corresponding index-value mapping

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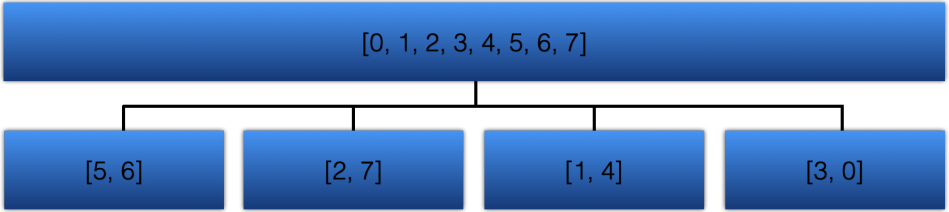

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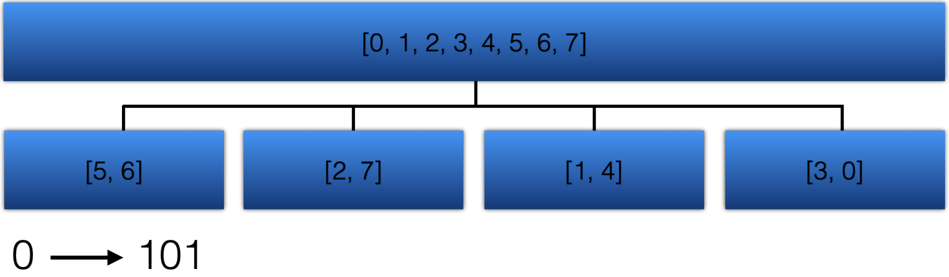

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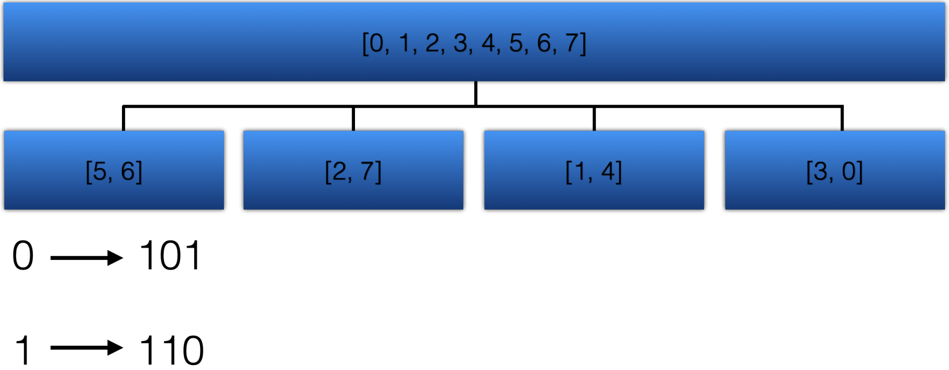

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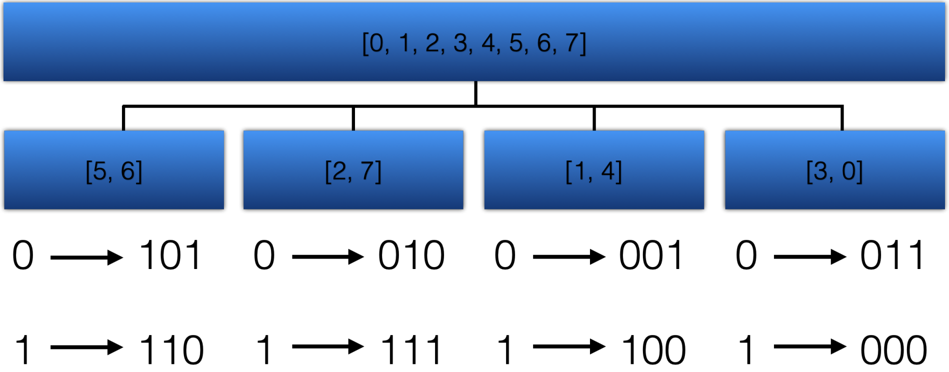

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Quantum Circuit Overview

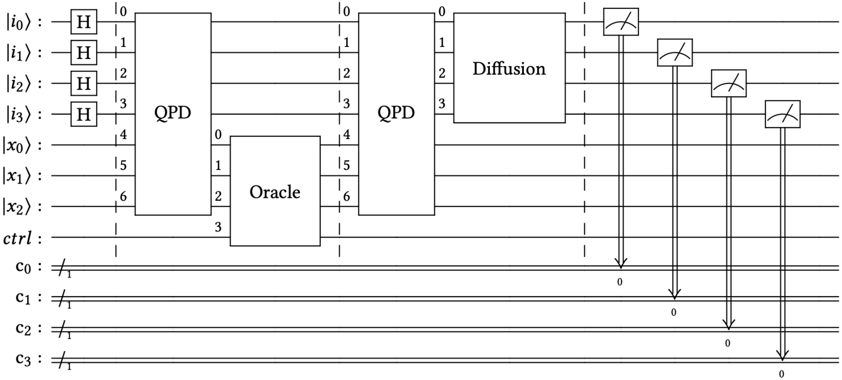

Figure: Algorithm circuit design as implemented in Qiskit. The columns with custom gates *QPD*, *Oracle* and *Diffusion* represent one iteration and are repeated $\sqrt{\frac{N}{d}}$ times.

- Index registers are initialized in superposition.
- Entanglement of Index and Data registers to create correct mapping
- Grover’s Algorithm is applied to search the database.
- Results are measured and translated back to classical indices.

Vision for Quantum Data Management

- **Short-Term:**
  - Quantum-classical hybrid systems
  - Development / optimisation of middleware layers
  - Quantum data structure prototyping
- **Long-Term:**
  - Fully quantum-based data management systems
  - Include quantum networks and distributed quantum systems
  - Collaboration with hardware developers for tight integration
- **Future Applications:**
  - Quantum Databases
  - Distributed Quantum Computing
  - Specific data management applications

Summary

- Quantum Data Structures as an approach to tackle data management tasks
- QPD: possible solution and framework for other data structures
- Performance improvements only scratching the surface
- Challenging for real applications in NISQ era

Future Research Directions

- **Current Pursues:**
  - Quantum Internet for distributed resources
  - Existing work on Middlewares like Q-CTRL [1]
  - First practical applications in finance and logistics
- **Outlook:**
  - Optimising quantum-classical interfaces.
  - Quantum data structures for other applications
  - Conceptual work on fully quantum databases

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[1] I. Faro, I. Sitdikov, D. G. Valiñas, F. J. M. Fernandez, C. Codella, and J. Glick (2023). "Middleware for Quantum: An orchestration of hybrid quantum-classical systems". In: *2023 IEEE International Conference on Quantum Software (QSW)*, pp. 1–8. DOI: 10.1109/QSW59989.2023.00011

Acknowledgments

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Questions?

- Thank you for your attention!
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