

Quantum Data Management in the NISQ Era

Background

- Quantum data \neq classical data: Quantum data is **probabilistic**, **fragile**, and can be **entangled**. Quantum computing promises computational potential beyond what traditional computers can achieve.
- The **noisy intermediate-scale quantum (NISQ)** era is characterized by quantum computers that are constrained by **noise** and **limited numbers of qubits**. NISQ computer are paired with **classical** computer to increase computational power.

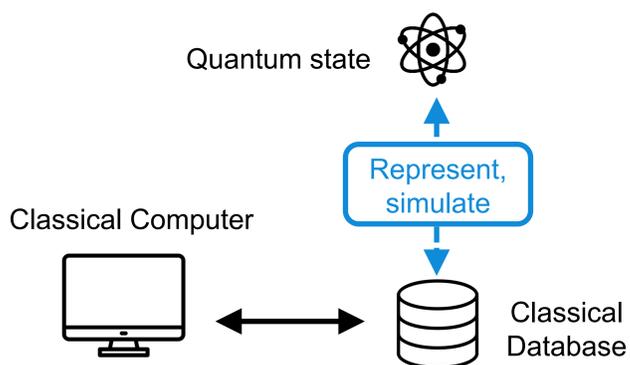
Quantum Computing & Databases

QC for DB: Existing works have explored leveraging quantum computers as new hardware to address classical database challenges.

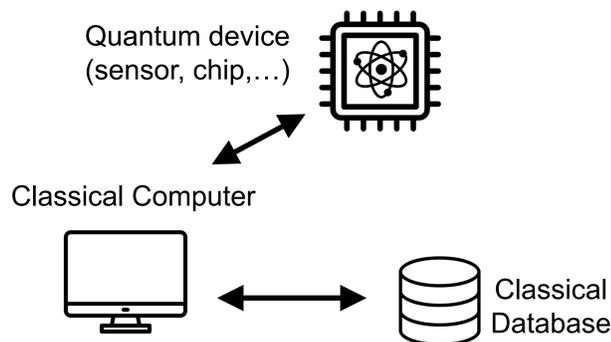
DB for QC: We shift focus to an underexplored direction: **data management for quantum computing**, where fundamental concepts, research directions, and problem definitions remain obscure in the database community.

Landscape

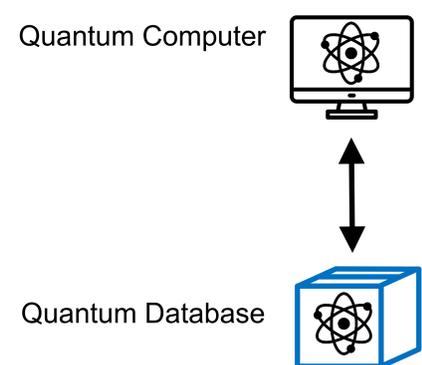
I Classical Simulation of Quantum Computing Paradigm



II Joint Quantum-Classical Computing Paradigm



III Pure Quantum Computing Paradigm



Classical-Quantum Simulation System

CQSS must be capable of **evaluating quantum circuits**, primarily involving tensor network operations.

Automatic Optimization

Providing the most efficient simulation by **selecting optimal data structures and operations** based on available resources and circuit properties.

Out-of-Core Operation

Supporting simulation of large circuits that **exceed main memory capacity** through efficient memory management.

Consistency & Recovery

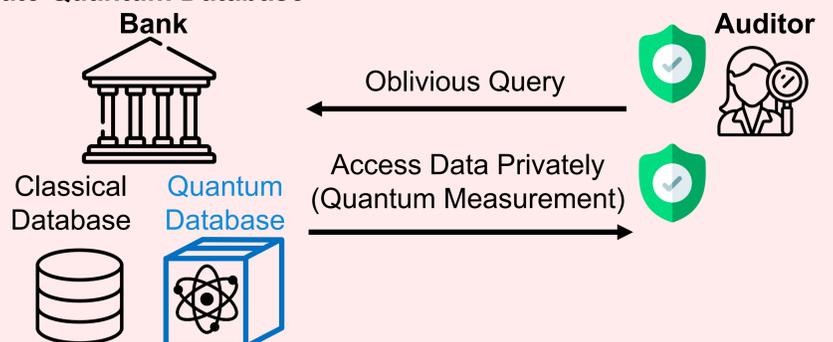
Preventing data corruption and enabling **recovery** in the event of large-scale simulation crashes.

Workflow Improvement

Enhancing the entire simulation process, including parameter tuning, data collection, querying, exploration, and visualization.

More Directions (Long-term)

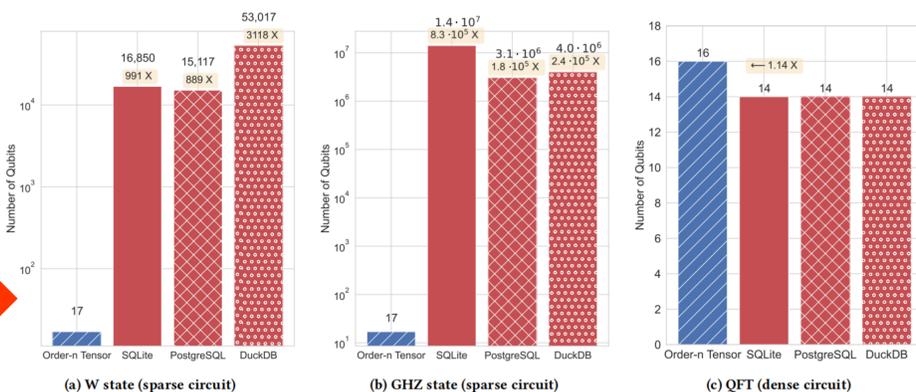
- Quantum Error Correction (QEC) & Graph Analytics
- Quantum Experiment Data & **Quantum Data Lakes**
- Private Quantum Database**



Five Research Questions

- Push the simulation into **existing DBMSs**?
 - Map states/gates to tables/SQL; exploit portability and I/O control.
- Leverage **tensor-aware DB technology** for simulation?
 - Compilation and Runtime.
- Build a **cost-based optimizer** for simulation?
 - Contraction-order \leftrightarrow join-order analogy.
- Innovate **quantum data representations**?
 - Balancing expressiveness, closure, and succinctness.
- System benefits from DB tech?
 - Out-of-core, transactions & recovery, parallel scheduling** for large circuits.

Preliminary Findings (Theory and Practice)



Quantum State $ \psi\rangle$	CQSS (RDBMs solution)	Order n-tensor (baseline 1)	MPS (baseline 2)
General state	$O(2^n)$	$O(n \cdot \text{nnz}(\psi\rangle))$	$O(n\chi^2)$
W_n state	$O(2^n)$	$O(n^2)$	$O(n)$
GHZ_n state	$O(2^n)$	$O(n)$	$O(n)$
QFT_n state	$O(2^n)$	$O(n^2)$	$O(n\chi^2)$

Takeaways:

- RDBMSs scale **efficiently** for **sparse** quantum circuits using relational representations.
- Theoretical space savings** compared to dense tensor and matrix product state baselines.
- Optimization opportunities** abound to tailor RDBMSs for simulation workloads.

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