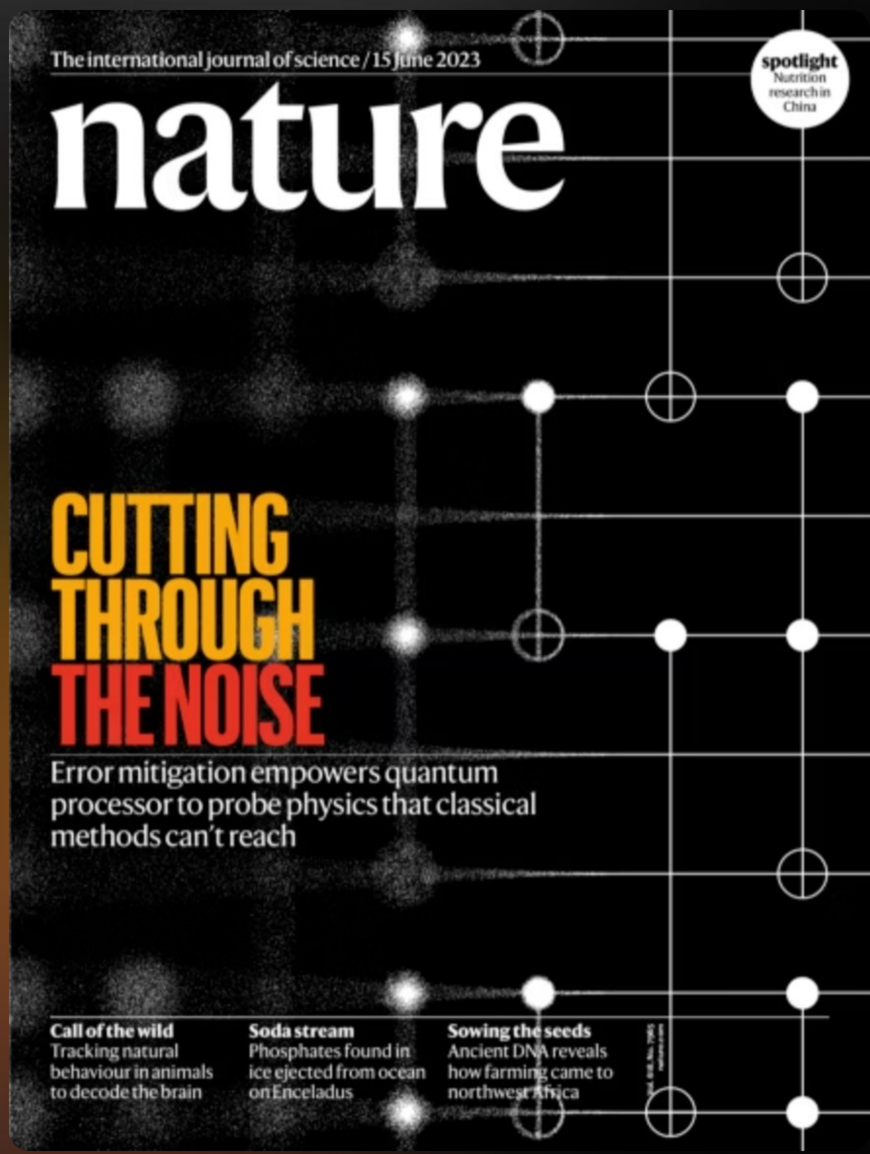

Quantum Data Management

in the NISQ Era

Rihan Hai, Shih-Han Hung, Tim Coopmans,
Tim Littau, Floris Geerts

Where it all started

s2.smu.edu/~mitch/class/5395/papers/feynman-quantum-1981.pdf
en.wikipedia.org/wiki/Richard_Feynman#/media/File:Richard_Feynman_Nobel.jpg

Simulating Physics with Computers

Richard P. Feynman

Department of Physics, California Institute of Technology, Pasadena, California 91107

Received May 7, 1981

1. INTRODUCTION

On the program it says this is a keynote speech—and I don't know what a keynote speech is. I do not intend in any way to suggest what should be in this meeting as a keynote of the subjects or anything like that. I have my own things to say and to talk about and there's no implication that anybody needs to talk about the same thing or anything like it. So what I want to talk about is what Mike Dertouzos suggested that nobody would talk about. I want to talk about the problem of simulating physics with computers and I mean that in a specific way which I am going to explain. The reason for doing this is something that I learned about from Ed Fredkin, and my entire interest in the subject has been inspired by him. It has to do with learning something about the possibilities of computers, and also something about possibilities in physics. If we suppose that we know all the physical laws perfectly, of course we don't have to pay any attention to computers. It's interesting anyway to entertain oneself with the idea that we've got something to learn about physical laws; and if I take a relaxed view here (after all I'm here and not at home) I'll admit that we don't understand everything.

The first question is, What kind of computer are we going to use to simulate physics? Computer theory has been developed to a point where it realizes that it doesn't make any difference; when you get to a *universal computer*, it doesn't matter how it's manufactured, how it's actually made. Therefore my question is, Can physics be simulated by a universal computer? I would like to have the elements of this computer *locally interconnected*, and therefore sort of think about cellular automata as an example (but I don't want to force it). But I do want something involved with the

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be understood very well in analyzing the situation. And I'm not happy with all the analyses that go with just the classical theory, because nature isn't classical, dammit, and if you want to make a simulation of nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem, because it doesn't look so easy. Thank you.

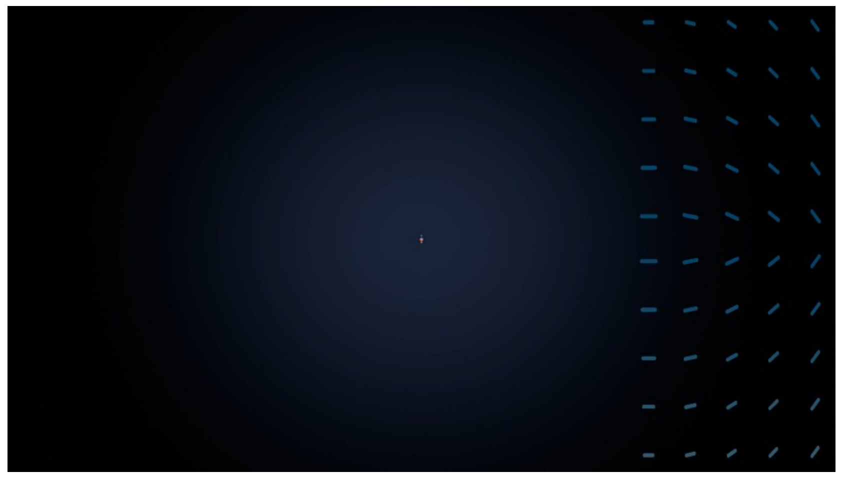
Understanding Quantum Data

Probabilistic Nature

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

$$\alpha, \beta \in \mathbb{C} \text{ with } |\alpha|^2 + |\beta|^2 = 1$$

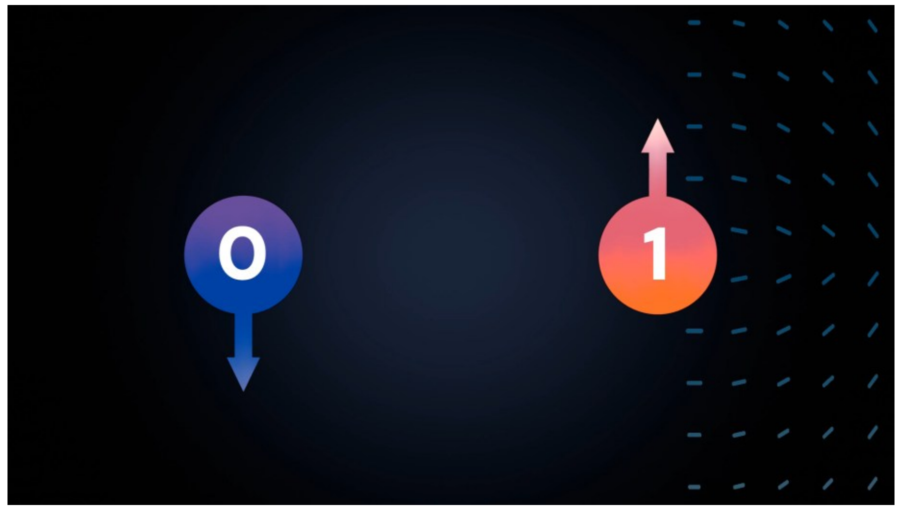
Superposition



Entanglement

Multiple qubits can be correlated such that measuring one immediately affects others. A well-known example is Bell's state:

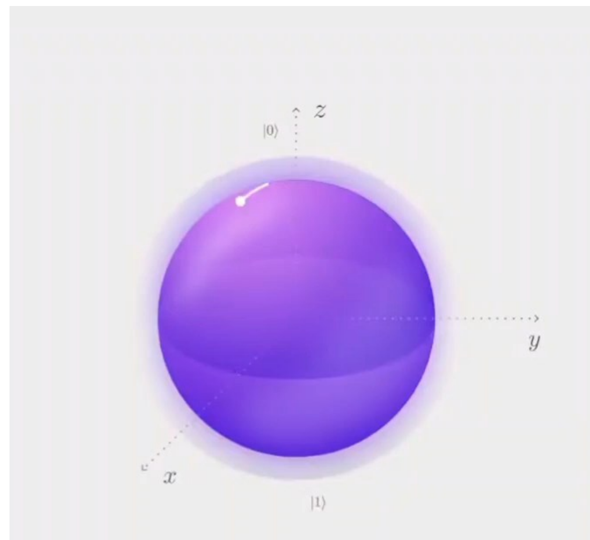
$$|\Psi\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle) = \frac{1}{\sqrt{2}}\begin{bmatrix}1\\0\\0\\1\end{bmatrix}$$



Fragility

Quantum noise results from unwanted coupling with the environment

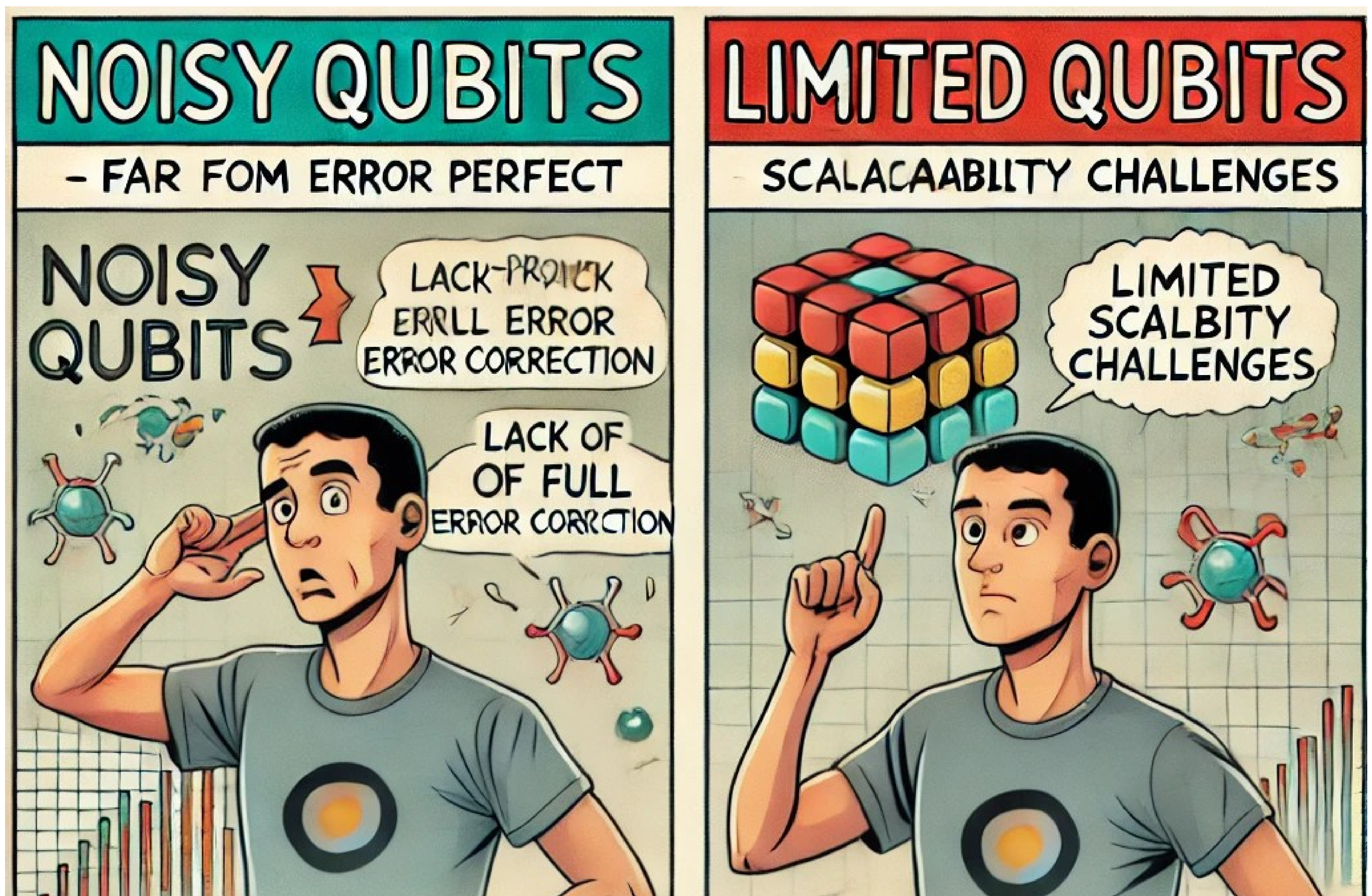
- Depolarizing
- Bit & phase flipping
- Amplitude & phase damping



Noisy Intermediate-Scale Quantum (NISQ)

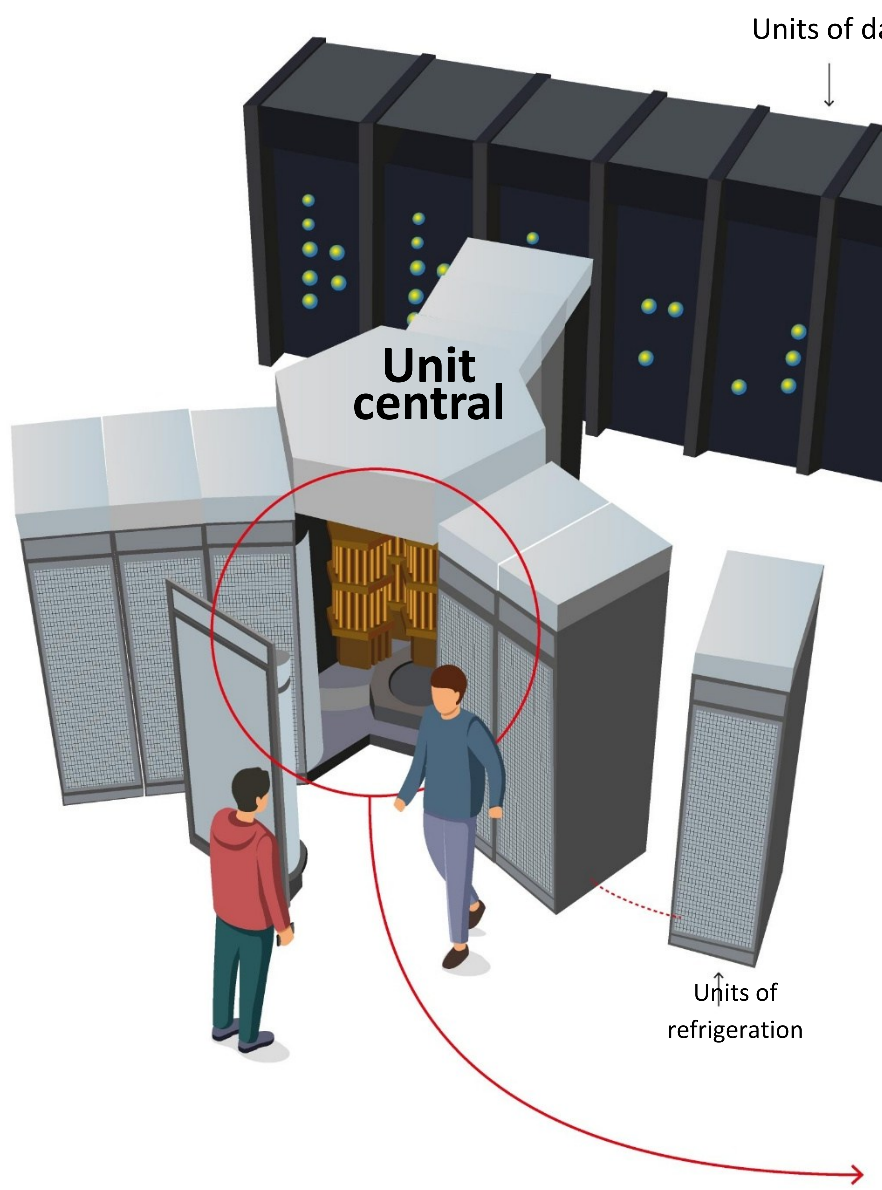
Quantum Computing in the NISQ era and beyond

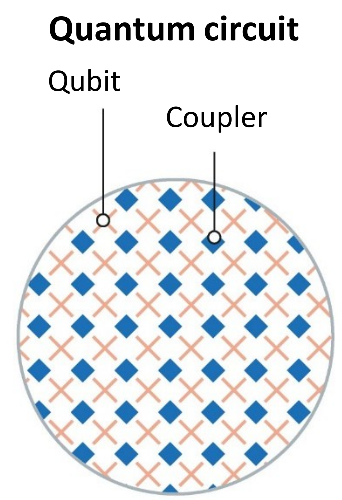
John Preskill

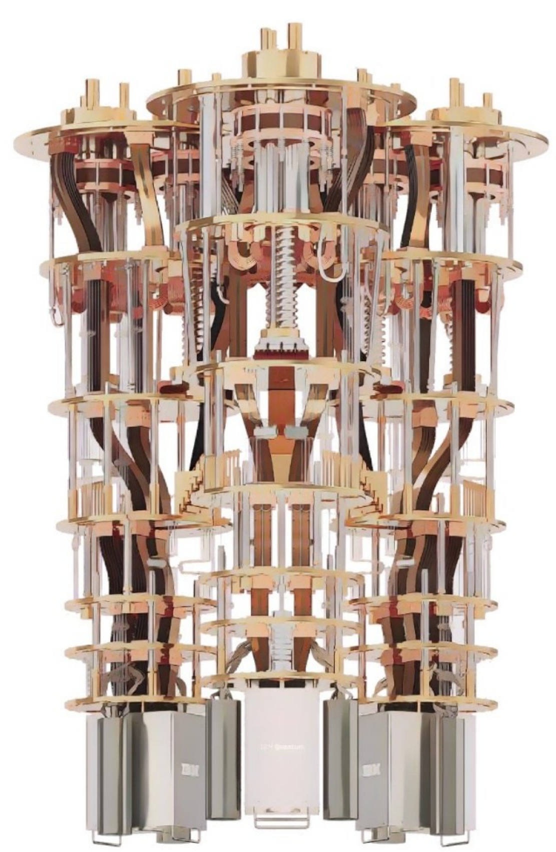


Example

The IBM System Two

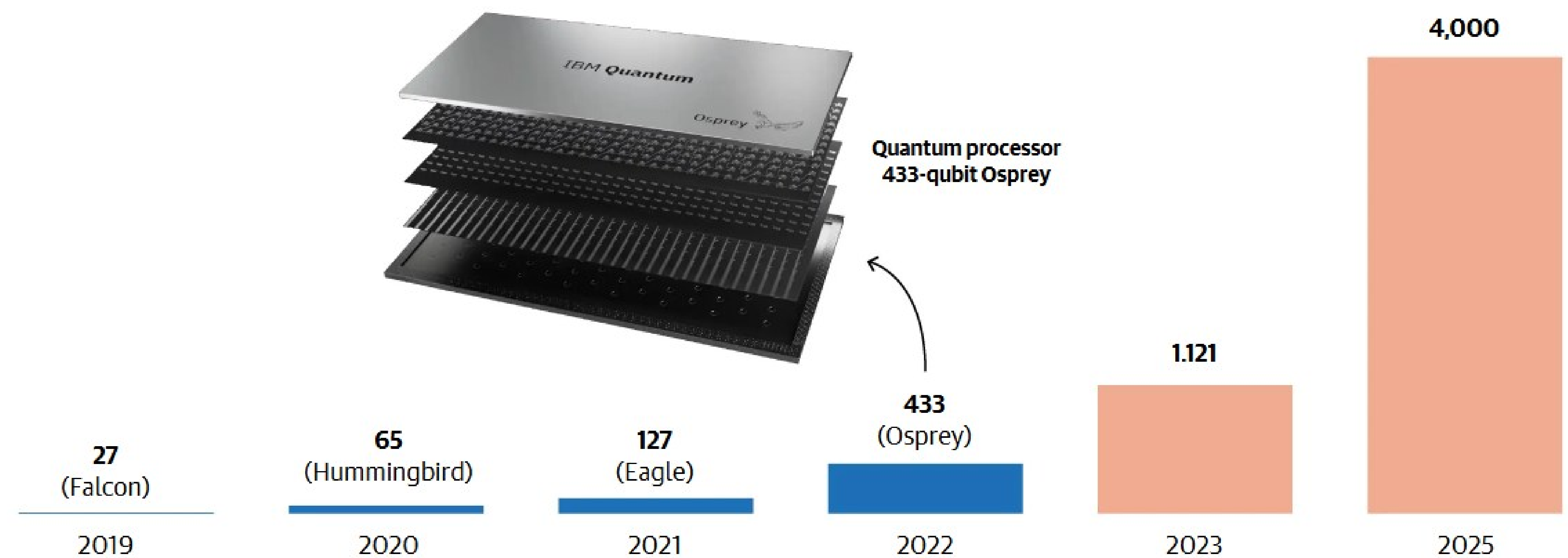




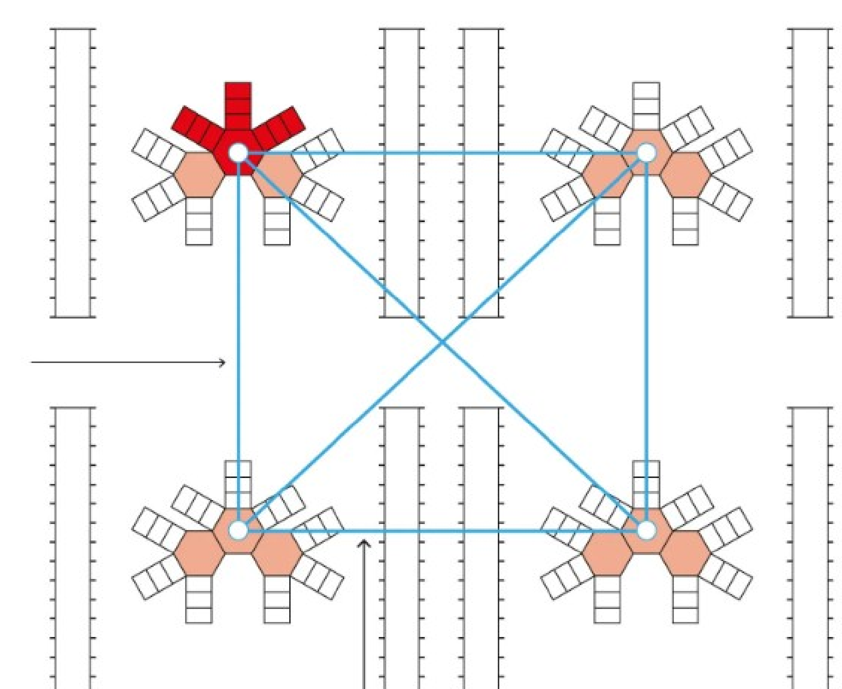


System Two processor
Quantum processor
156-qubit Heron

Evolution of the number of qubits in IBM quantum processors



Scaling system



Groups of 25, 000 qubits

This paper -- Databases to the rescue

Can DB technologies boost the development of quantum computing?

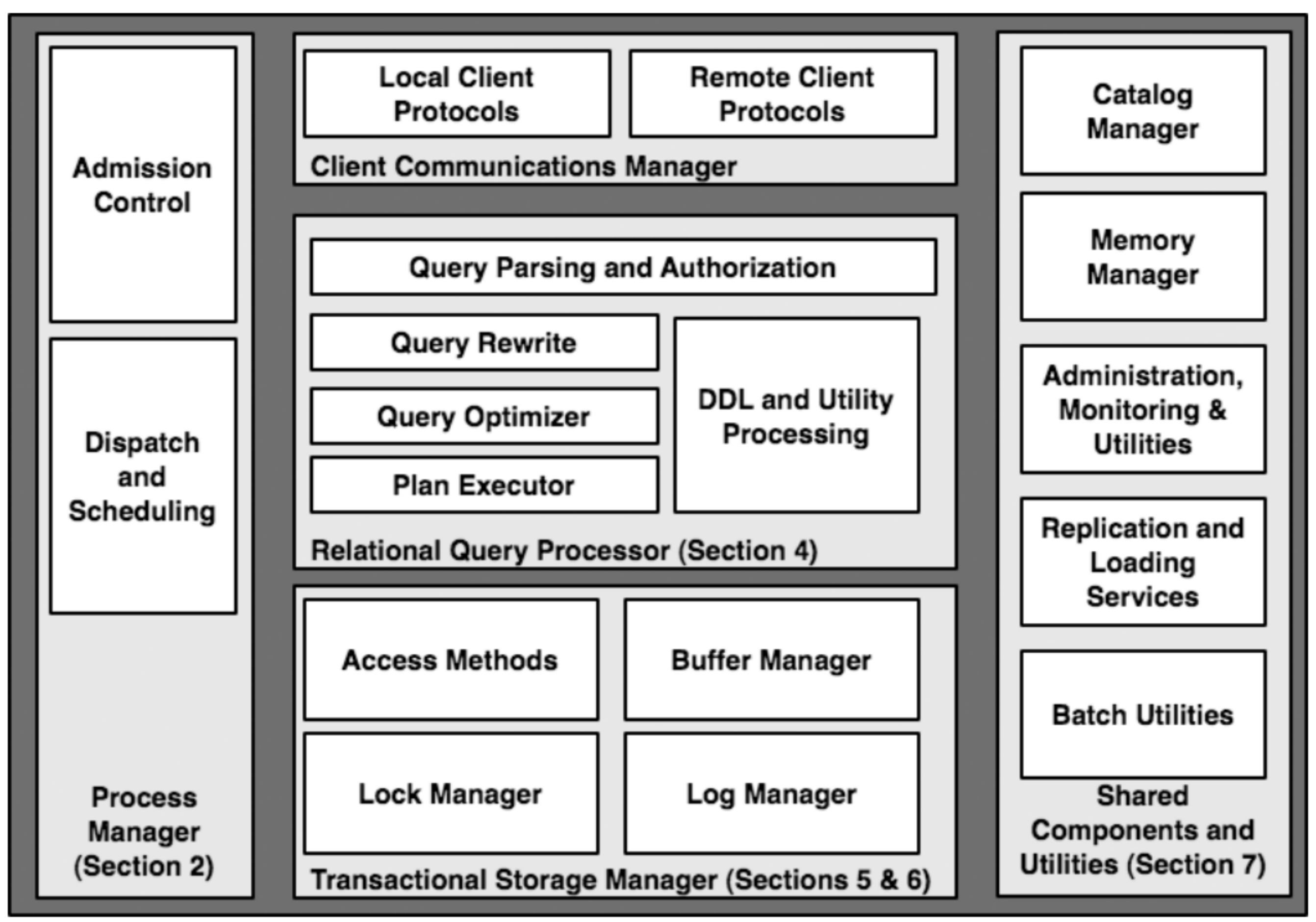
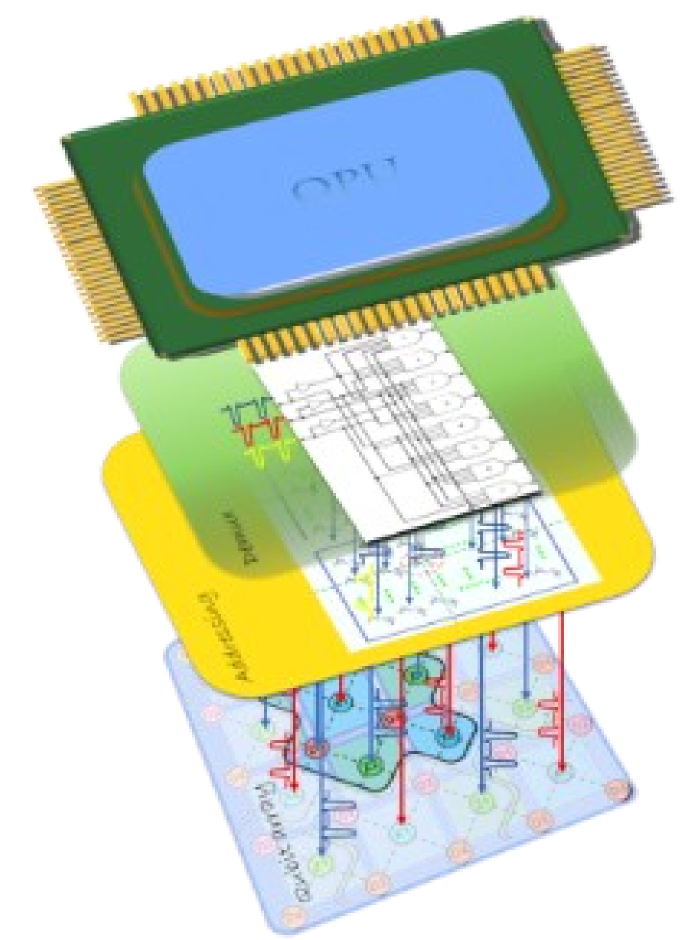
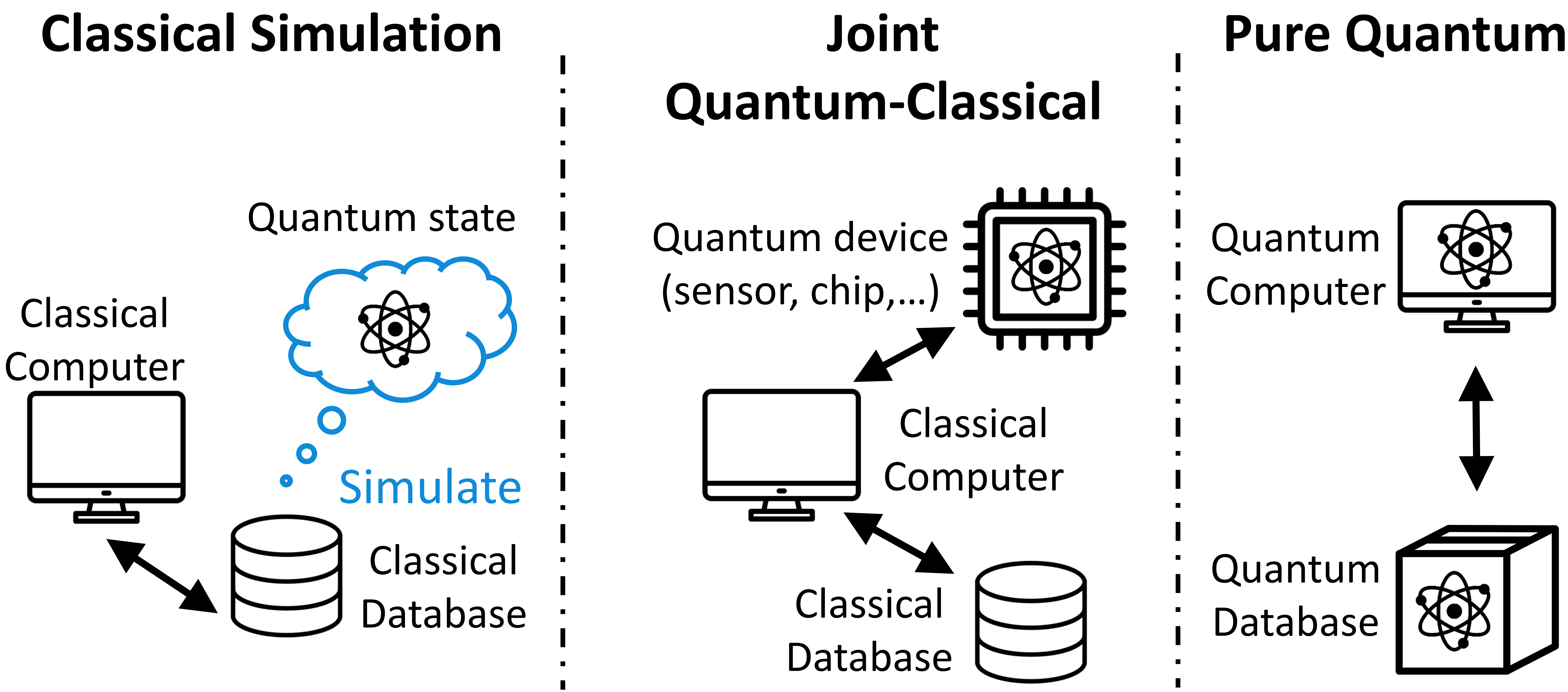


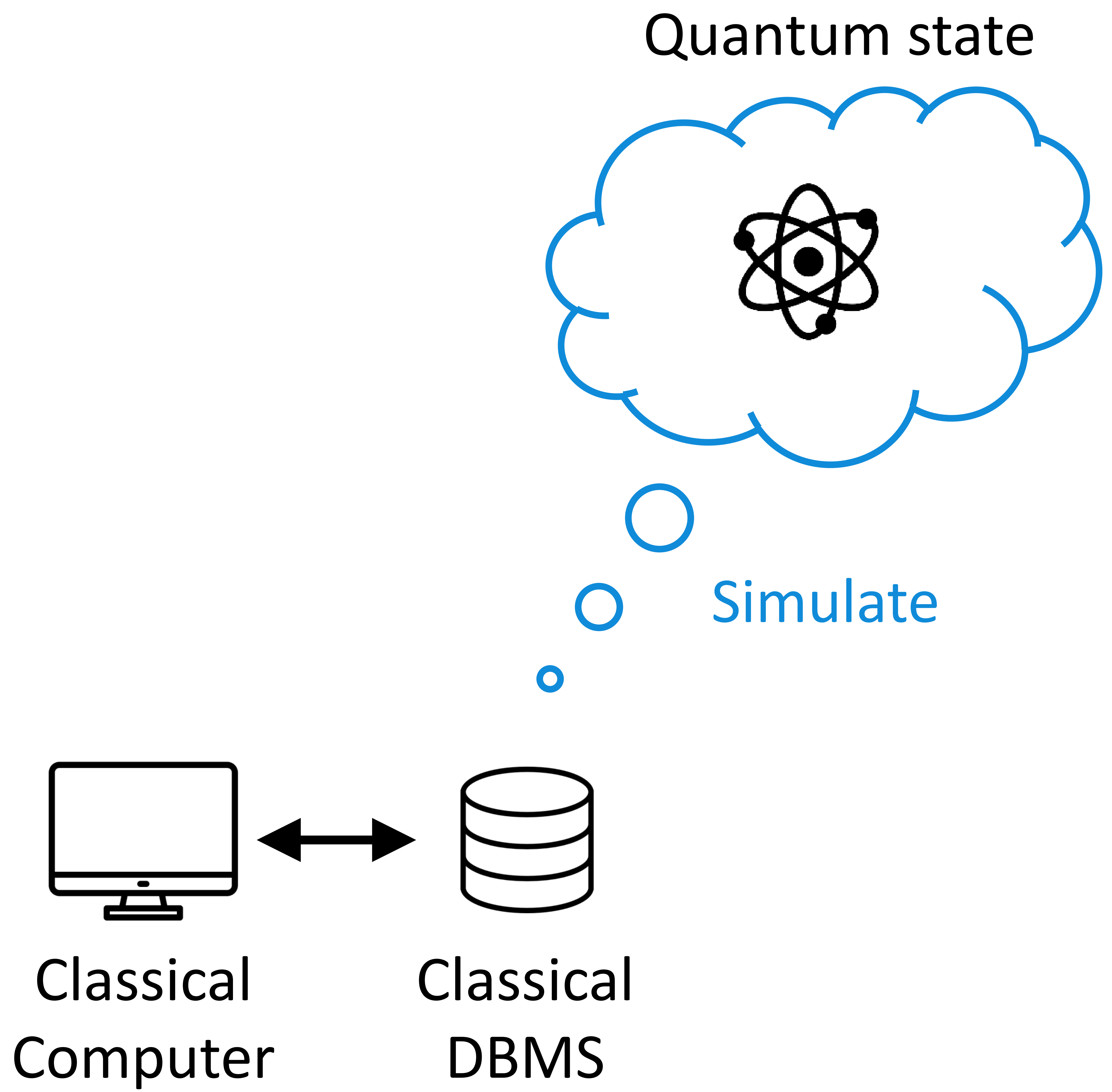
Fig. 1.1 Main components of a DBMS.



Landscape: data management for quantum computing

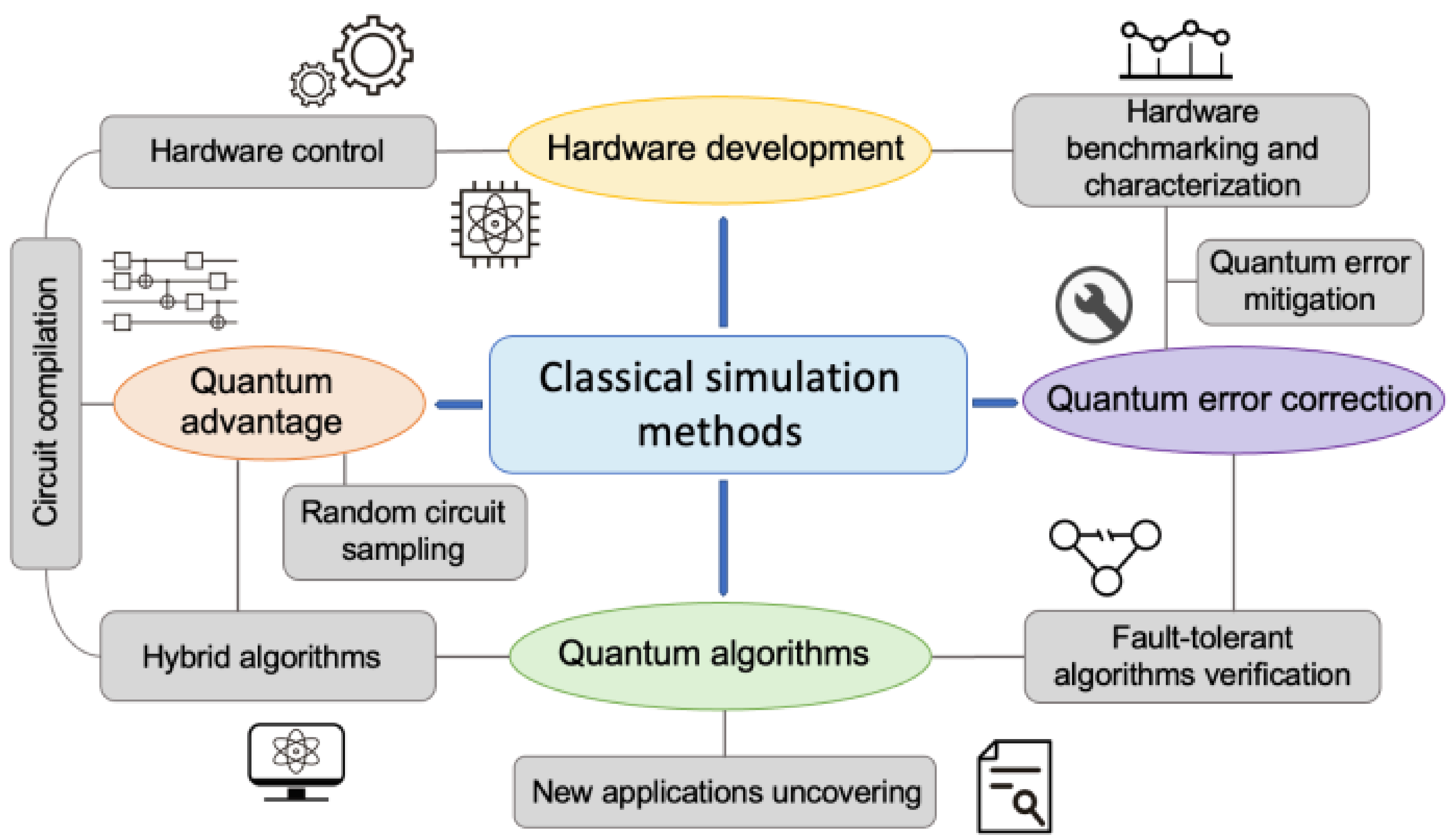


I Classical simulation of quantum computing paradigm



Classical simulation

- The process of emulating quantum computation, enabling researchers to model and analyze quantum processes as if they were operating on actual quantum hardware
- A **powerful, foundational** tool



Xiaosi Xu, Simon Benjamin, Jinzhao Sun, Xiao Yuan, and Pan Zhang. 2023. A Herculean task: Classical simulation of quantum computers. https://arxiv.org/abs/2302.08880

Simulation problem: scalability

- We can represent an **n**-qubit quantum state as a vector of size $\mathbf{2^n}$

$n = 1$

$$|0\rangle = \begin{bmatrix} 1 \\ 0 \end{bmatrix} \qquad |1\rangle = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle = \frac{1}{\sqrt{2}}|0\rangle + \frac{1}{\sqrt{2}}|1\rangle = \left.\begin{bmatrix} \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} \end{bmatrix}\right\} \text{Vector size: 2}$$

Simulation problem: scalability

- We can represent an **n**-qubit quantum state as a vector of size $\mathbf{2^n}$

$$n = 2$$

$$|00\rangle = \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix} \quad |01\rangle = \begin{bmatrix} 0 \\ 1 \\ 0 \\ 0 \end{bmatrix} \quad |10\rangle = \begin{bmatrix} 0 \\ 0 \\ 1 \\ 0 \end{bmatrix} \quad |11\rangle = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}$$

$$|\psi\rangle = \alpha_{00}|00\rangle + \alpha_{00}|00\rangle + \alpha_{00}|00\rangle + \alpha_{11}|11\rangle = \left.\begin{bmatrix} 0.5 + 0.0\mathrm{i} \\ 0.0+0.5\mathrm{i} \\ 0.5+0.0\mathrm{i} \\ 0.0+0.5\mathrm{i} \end{bmatrix}\right\} \text{Vector size: 4}$$

Simulation problem: scalability

- We can represent an **n**-qubit quantum state as a vector of size $\mathbf{2^n}$

$n = 3$

$$|\psi\rangle = \frac{1}{\sqrt{2}}|000\rangle + \frac{1}{\sqrt{2}}|111\rangle = \left.\begin{bmatrix} \frac{1}{\sqrt{2}} \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ \frac{1}{\sqrt{2}} \end{bmatrix}\right\} \text{Vector size: 8}$$

Simulation problem: scalability

- We can represent an **n**-qubit quantum state as a vector of size $\mathbf{2^n}$

$$|\psi\rangle = \alpha_{0\ldots0}|0\ldots0\rangle + \alpha_{1\ldots1}|1\ldots1\rangle = \left.\begin{bmatrix}\alpha_{0\ldots0}\\ \alpha_{0\ldots1}\\ \\ \cdots \\ \\ \alpha_{1\ldots0}\\ \alpha_{1\ldots1}\end{bmatrix}\right\} \text{Vector size: } \mathbf{2^n}$$

Simulation problem: scalability

- How much memory in GB do we need?

Number of qubits

Double-precision (16 bytes) for complex numbers

$$2^{n+4-30}$$

1 GiB = 2^{30}bytes

- Reaching the memory limits of today's supercomputers

nature physics

ARTICLES

https://doi.org/10.1038/s41567-018-0124-x

Characterizing quantum supremacy in near-term devices

Sergio Boixo[1*], Sergei V. Isakov[2], Vadim N. Smelyanskiy[1], Ryan Babbush[1], Nan Ding[1], Zhang Jiang[3,4], Michael J. Bremner[5], John M. Martinis[6,7] and Hartmut Neven[1]

2.25 petabytes for **48** qubits (single precision)

Quantum state as tensors

- Example: 3-qubit GHZ state $|\psi\rangle = \frac{1}{\sqrt{2}}|000\rangle + \frac{1}{\sqrt{2}}|111\rangle$

As a vector

$$\begin{bmatrix} \frac{1}{\sqrt{2}} \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ \frac{1}{\sqrt{2}} \end{bmatrix}$$

As tensors

Matrix product state (MPS)

$$A^0 = \begin{bmatrix} 1 & 0 \end{bmatrix} \qquad A^1 = \begin{bmatrix} 0 & 1 \end{bmatrix}$$

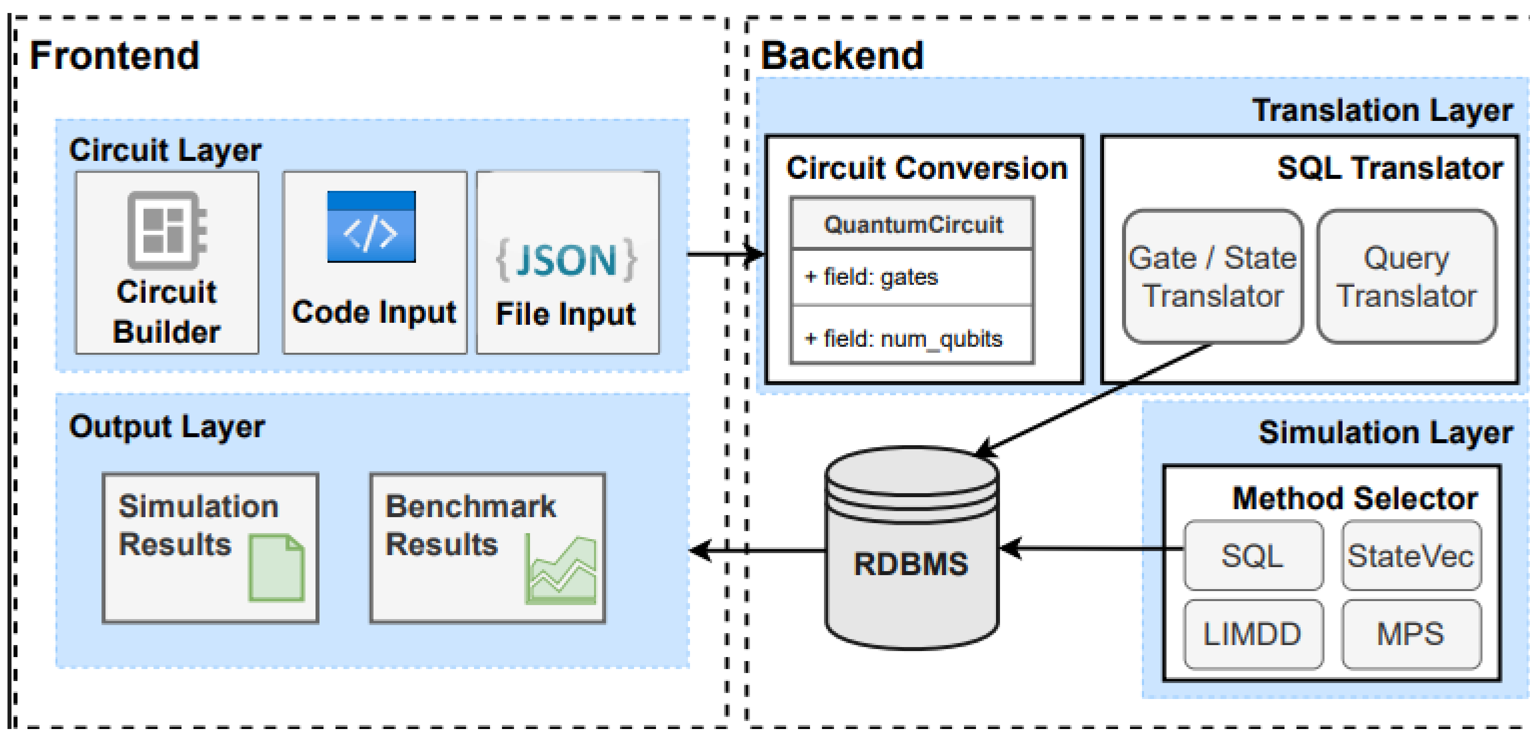
$$B^0 = \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} \qquad B^1 = \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix}$$

$$C^0 = \begin{bmatrix} \frac{1}{\sqrt{2}} \\ 0 \end{bmatrix} \qquad C^1 = \begin{bmatrix} 0 \\ \frac{1}{\sqrt{2}} \end{bmatrix}$$

Efficient tensor computation: database to the rescue

Q1: Push the simulation workload to DBMSs?

System



Littau, Tim, and Rihan Hai. "Qymera: Simulating Quantum Circuits using RDBMS." SIGMOD. 2025.

Theory

QC meet CQ: Quantum Conjunctive Queries

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Abstract

We explore how recent methods for evaluating conjunctive queries (CQs) can help to efficiently simulate quantum circuits (QCs), i.e., computing output amplitudes from a given input state.

ACM Reference Format:

Floris Geerts and Rihan Hai. 2025. QC meet CQ: Quantum Conjunctive Queries. In *Workshop on Quantum Computing and Quantum-Inspired Technology for Data-Intensive Systems and Applications (Q-Data '25), June 22–27, 2025, Berlin, Germany*. ACM, New York, NY, USA, 1 page. https://doi.org/10.1145/3736393.3736696

Hypertree width of quantum conjunctive queries. An initial observation is that the treewidth of a quantum CQ [4] aligns with the treewidth of the corresponding QC [6]. Treewidth is defined via the CQ's primal graph, where nodes represent variables and edges connect variables co-occurring in a relation. In QC terms, variables map to qubits and relations to gates, making the primal graph of a quantum CQ the dual of the QC's circuit graph. However, graph-based representations are not always ideal. For instance, acyclic CQs can have arbitrarily large treewidth, despite being evaluable in linear time via the Yannakakis algorithm. To address this,

State $\vert\psi\rangle$	Order-n tensor (Baseline I)	Relational representation (RDBMS solutions)	MPS (Baseline II)
General state	$O(2^n)$	$O(n \cdot \mathrm{nnz}(\vert\psi\rangle))$	$O(n\chi^2)$
W_n State	$O(2^n)$	$O(n^2)$	$O(n)$
GHZ_n State	$O(2^n)$	$O(n)$	$O(n)$
QFT_n	$O(2^n)$	$O(n \cdot 2^n)$	$O(n\chi^2)$

Table 1: Space complexity comparison of different representations of state $|\psi\rangle$. Here, n is the number of qubits, $nnz(|\psi\rangle)$ denotes the number of non-zero probability amplitudes in the state $|\psi\rangle$, and the MPS bond dimension χ is a fixed constant that one chooses oneself, potentially making the representation approximate.

Geerts, Floris, and Rihan Hai. "QC meet CQ: Quantum Conjunctive Queries." *Proceedings of the 2nd Workshop on Quantum Computing and Quantum-Inspired Technology for Data-Intensive Systems and Applications*. 2025.

[Hai, Rihan, et al. "Quantum Data Management in the NISQ Era: Extended Version." arXiv preprint arXiv:2409.14111 (2024).]

Databases to the Rescue: Classical-Quantum Simulation System

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

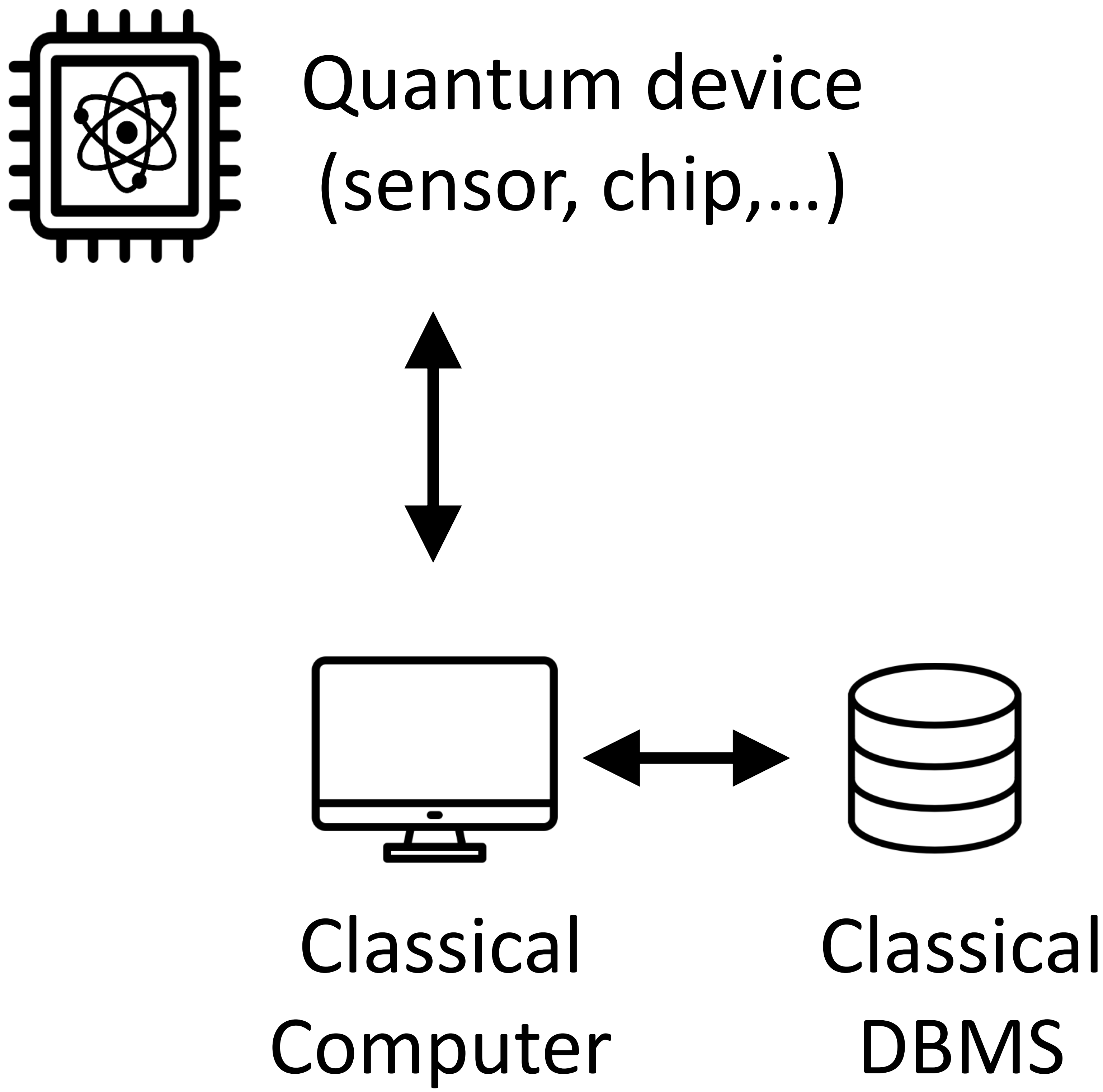
Preventing data corruption and enabling recovery in the event of large-scale simulation crashes.

Workflow Improvement

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

At its core, a CQSS must be capable of evaluating quantum circuits, primarily involving tensor network operations.

II Joint Qantum-Classical Computing paradigm



Example

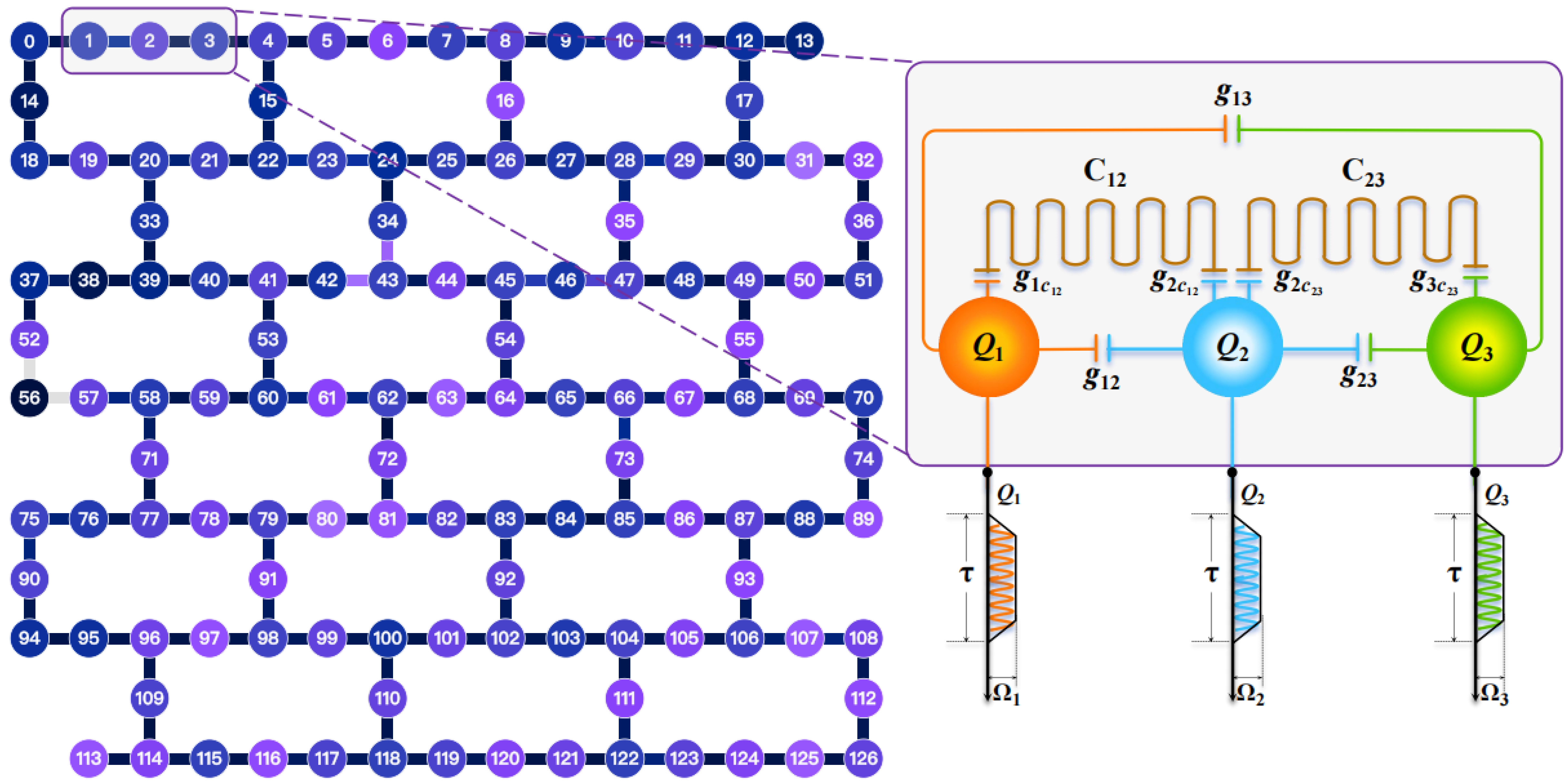


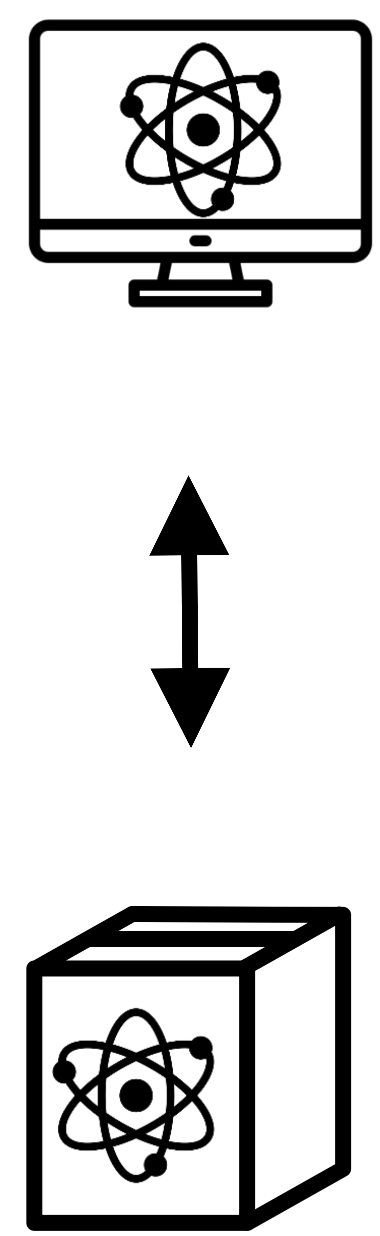
FIG. 1. **Left**: Physical layout of IBM's 127-qubit Eagle quantum processor, *ibm_ sherbrooke*. **Right**: Circuit-level representation of a selected three-qubit segment (Q_1, Q_2, Q_3) from the Sherbrooke device.

Xu, Xuexin, Siyu Wang, Radhika Joshi, Rihan Hai, and Mohammad H. Ansari. "Parity Cross-Resonance: A Multiqubit Gate." arXiv preprint arXiv:2508.10807 (2025).

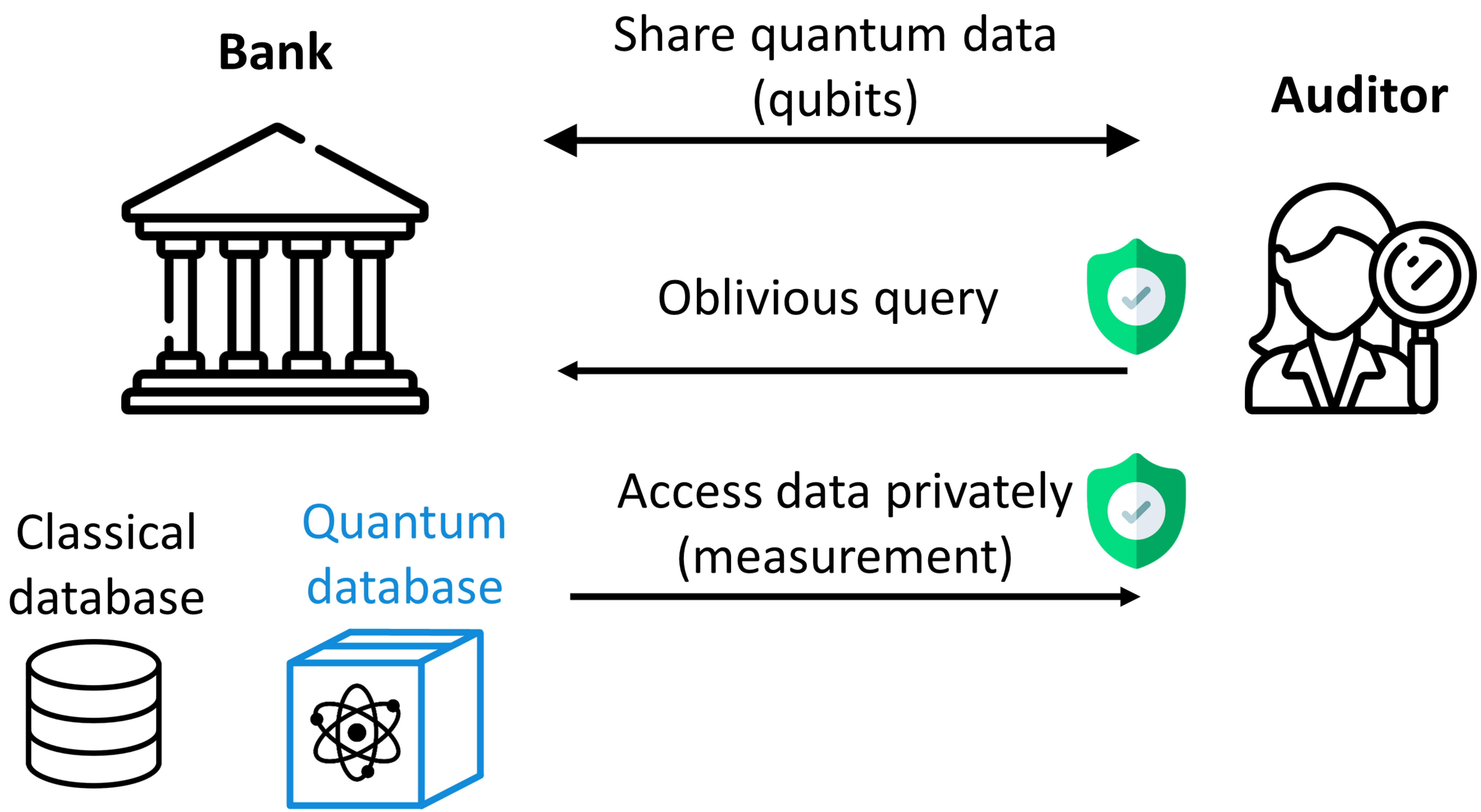
III Pure quantum computing paradigm

Quantum
Computer

Quantum
Database



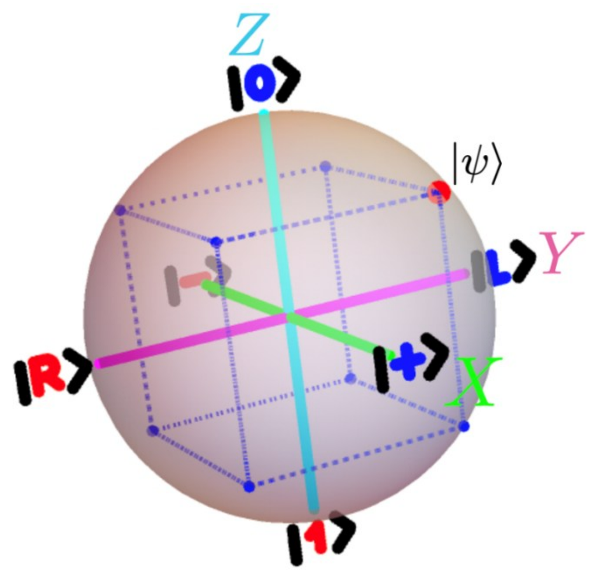
Private Quantum Database



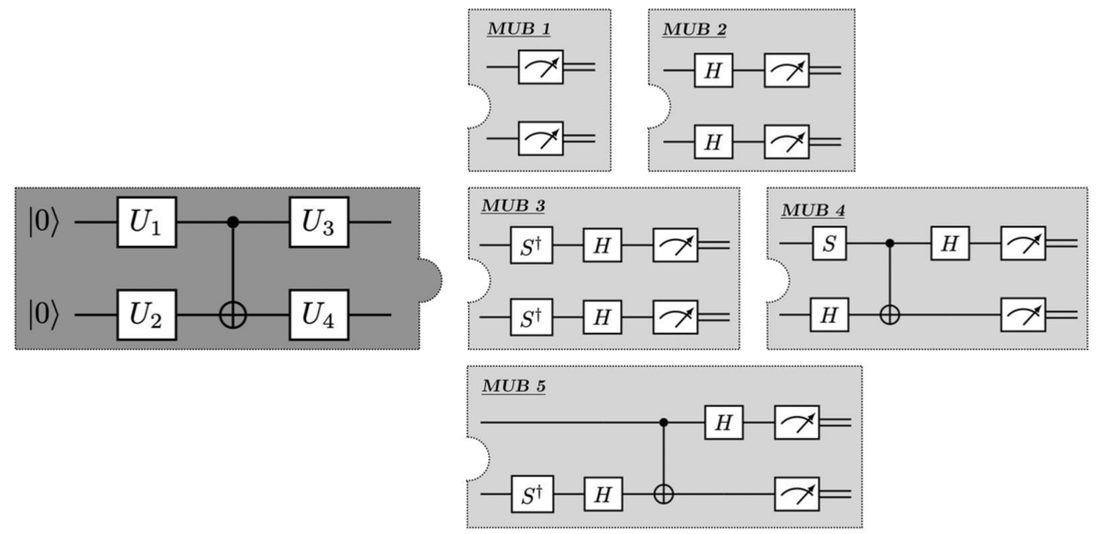
Gatti, Giancarlo, and Rihan Hai. **Private Quantum Database**. arXiv:2508.19055. 2025.
https://arxiv.org/abs/2508.19055.

Private Quantum Database

Core quantum technology

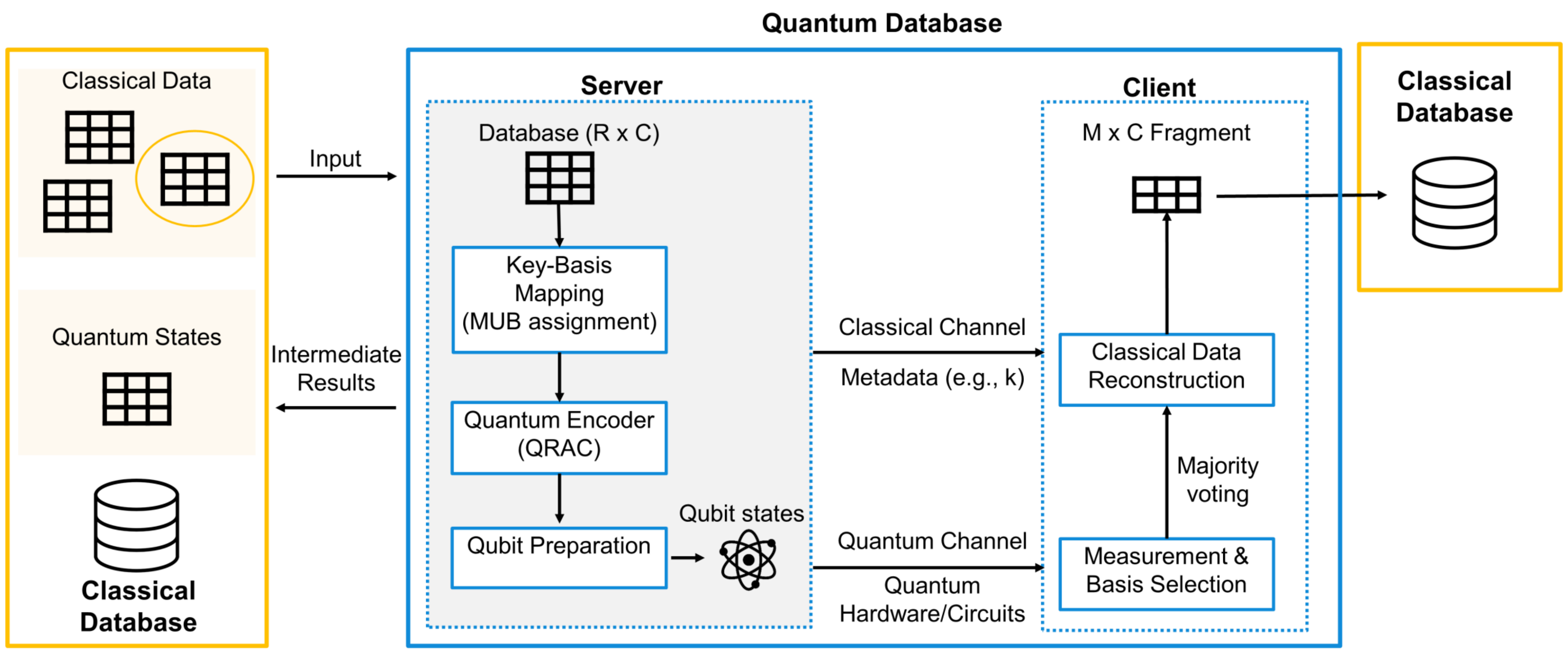


Quantum Random Access Coding



Mutually unbiased bases

Hybrid architecture



Summary: Quantum data management in NISQ era

A privileged time in data management,
with many research problems awaiting exploration.

Summary: Quantum data management in NISQ era

QC for DB

Reference	DB problem	Subproblem	Formulation	Intermediate quantum algorithm	Quantum computer
I. Trummer et al., VLDB'16	Query optimization	Multiple query optimization	QUBO	–	Annealing-based
T. Fankhauser et al., IEEE Access, 2023				QAOA	Gate-based
M. Schonberger et al., SIGMOD23, VLDB24		Join ordering		QAOA	Gate-based & annealing-based
N. Nayak et al., BiDEDE '23				QAOA, VQE	Gate-based & annealing-based
T. Winker et al., BiDEDE '23			–	VQC	Gate-based
K. Fritsch et al., VLDB'23 Demo, L. Gerlach PODS25	Data integration	Schema matching	QUBO	QAOA	Gate-based & annealing-based
T. Bittner et al., IDEAS'20, OJCC S. Groppe et al., IDEAS'21	Transaction management	Two-phase locking	QUBO	–	Annealing-based
M. Kesarwani et al., VLDB24	Index selection	Index configuration recommendation given budget	QUBO	QAOA	Gate-based & annealing-based

ICDE'24 Tutorial

DB for QC

In-DB Tensor Computation → Classical simulation

Graph analytics → Error correction

Distributed databases → Quantum network

Quantum data lakes → Quantum experiments

This paper

Q&A

Can DB technologies boost the development of quantum computing?

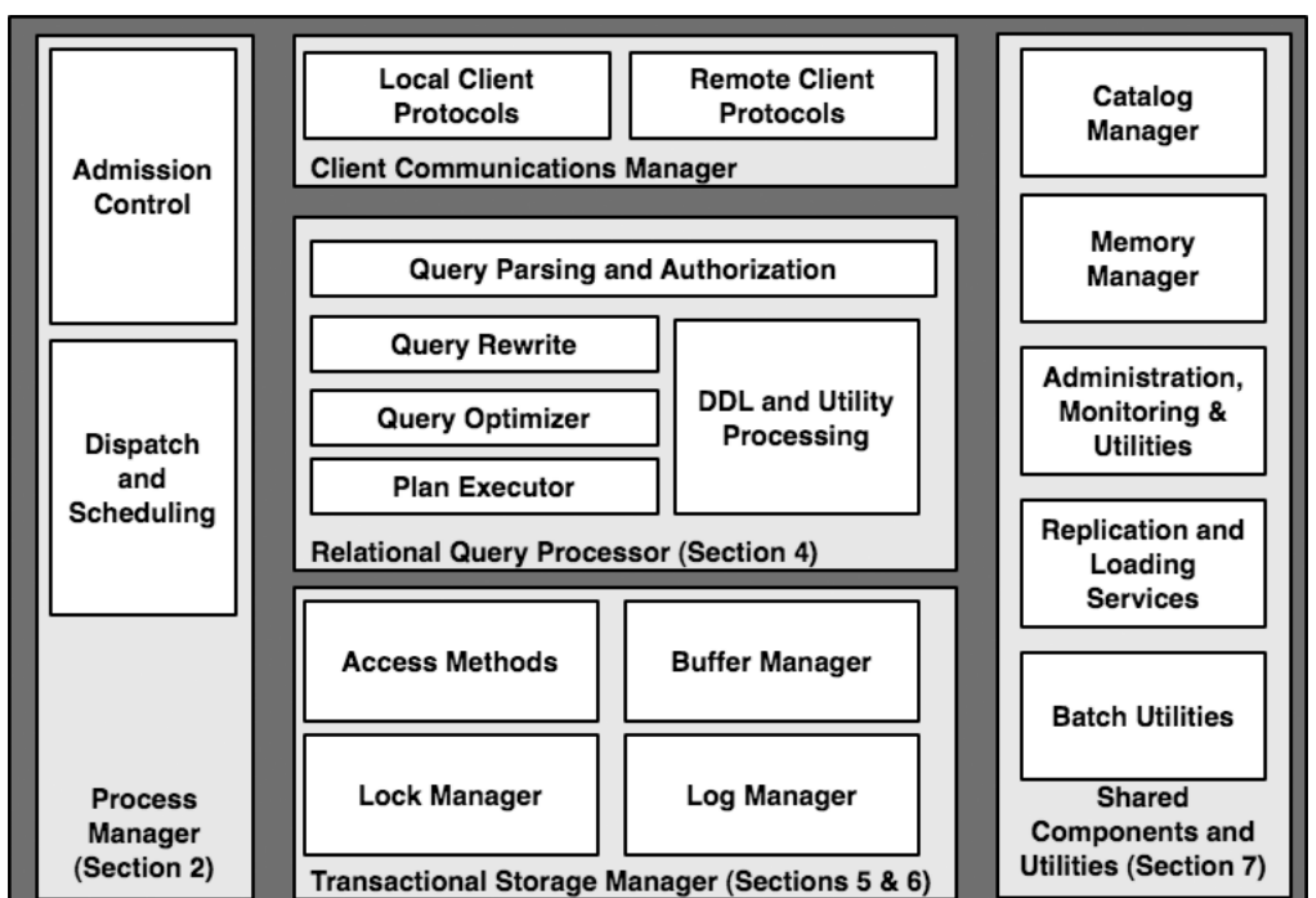


Fig. 1.1 Main components of a DBMS.