Tutorial Webpage

Quantum Data Management

From Theory to Opportunities

Rihan Hai

TU Delft Delft University of Technology

Team introduction

InfiniData Team

What we focus on

Empowering the Future of Data, Today

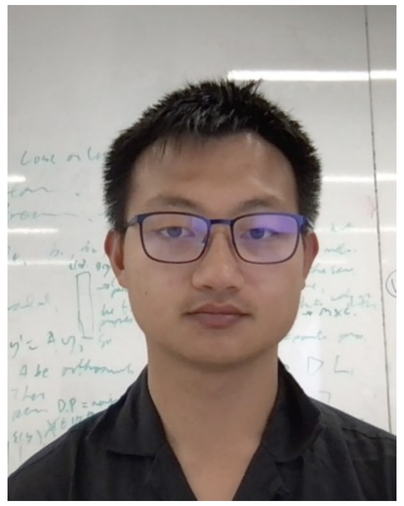
AI in data lakes
Multimodal data & GPU acceleration

Federated Learning
Data privacy and security

Quantum Data Management
Data Management for Quantum Computing and Quantum Internet

Wenbo Sun

Ziyu Li (postdoc)



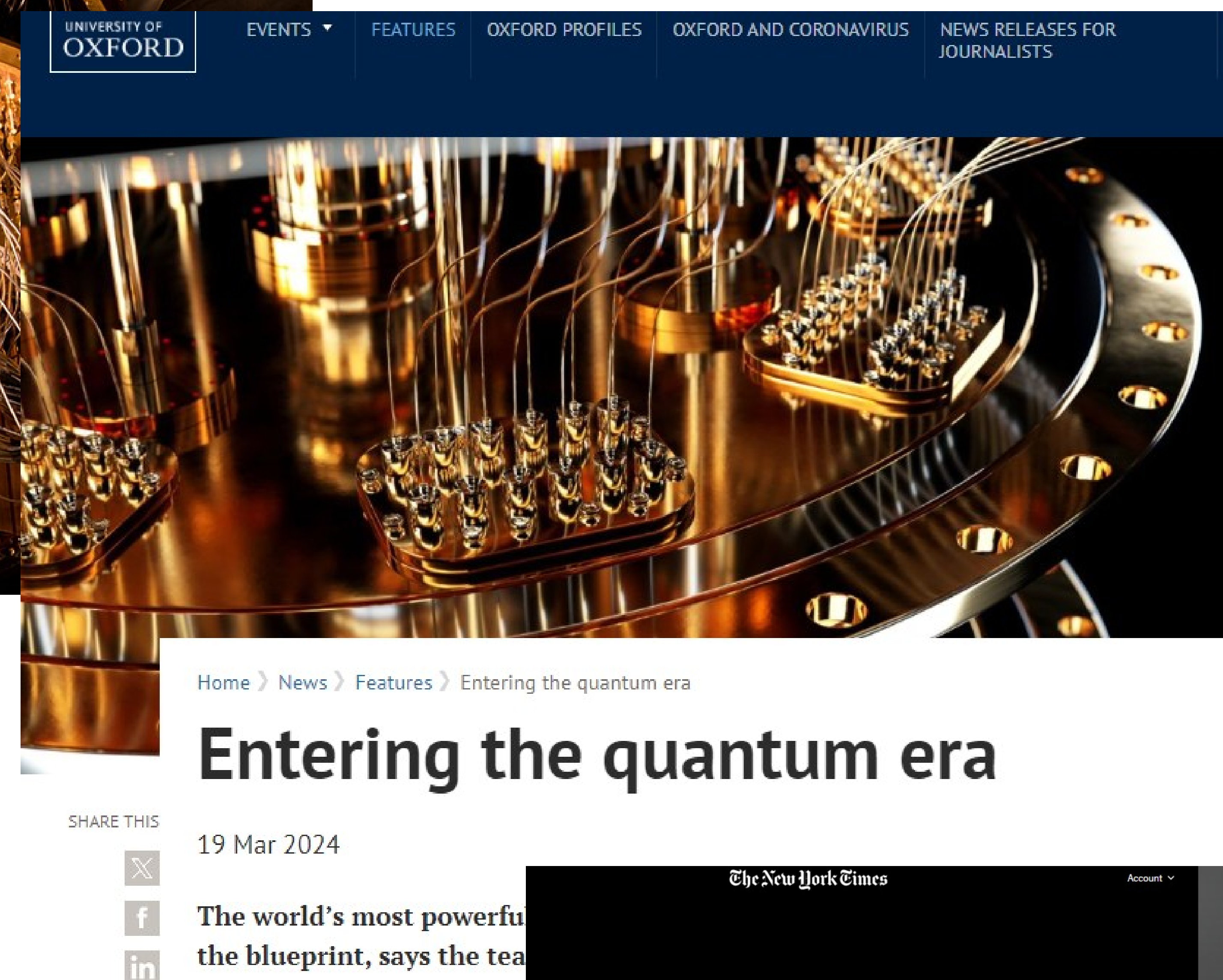
Danning Zhan

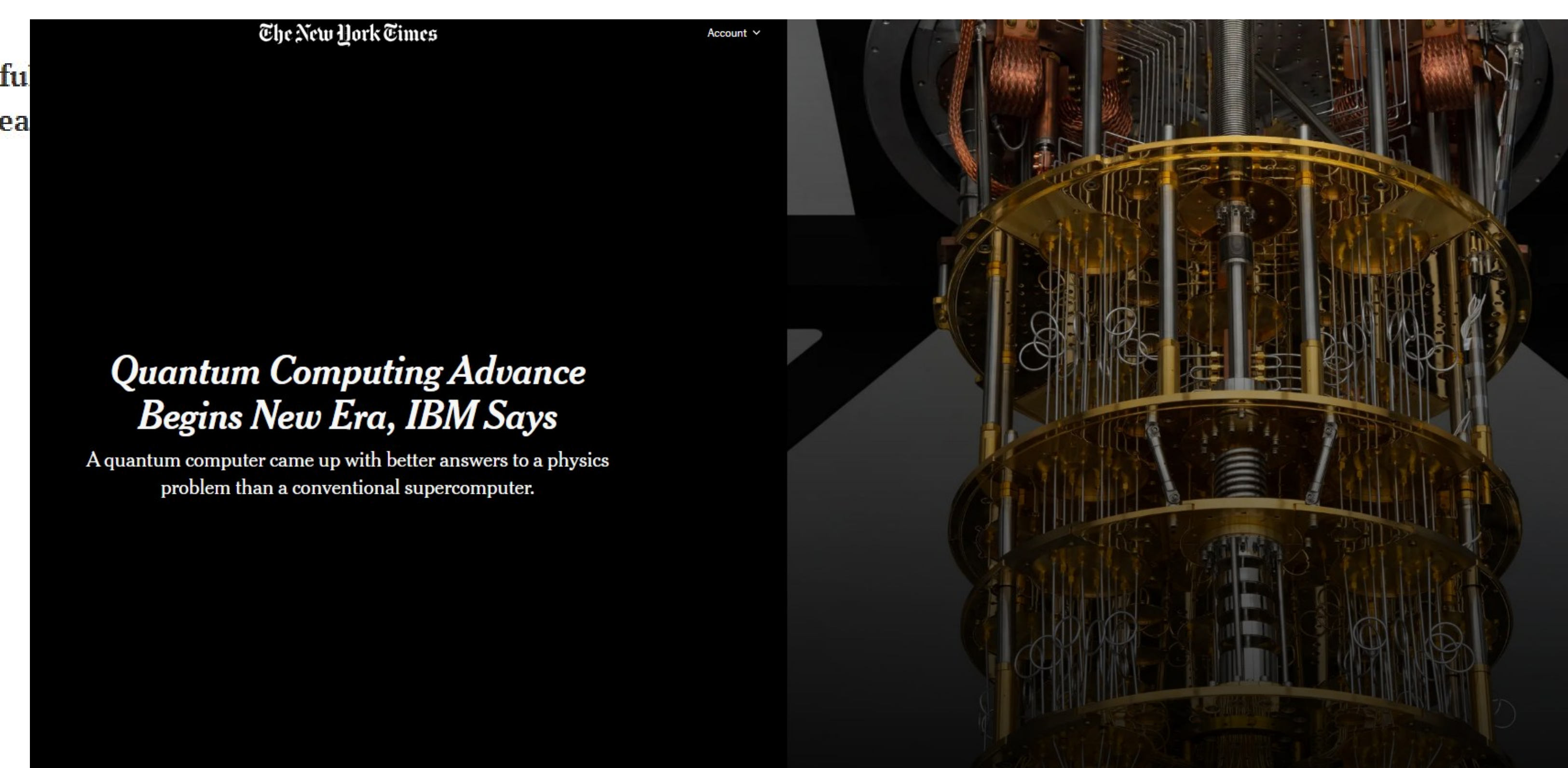
Aditya Shankar (with L. Chen)

Tim Littau

PhD applicant (with S. Wehner)

Recent Development





Recent Development

ChatGPT 4o

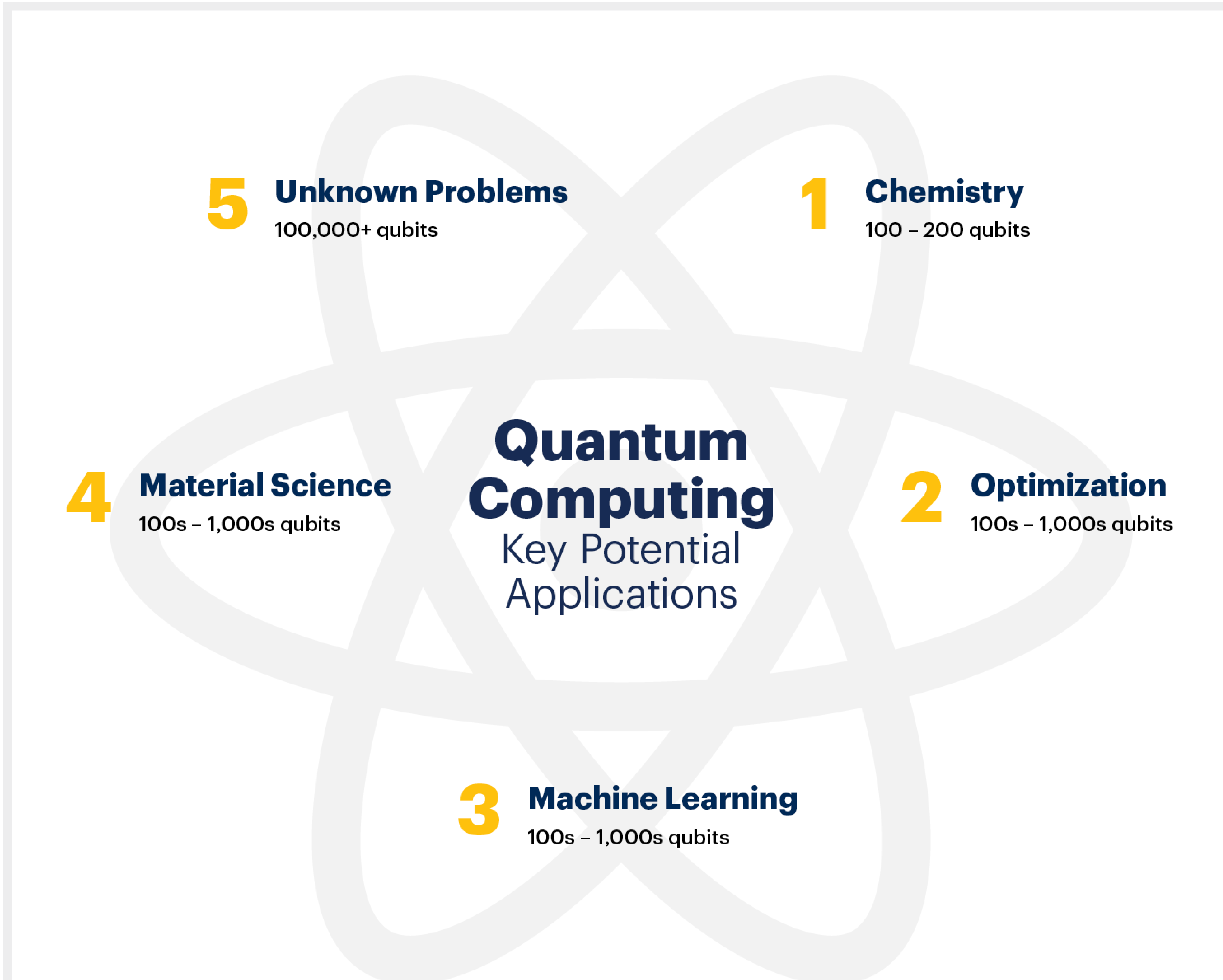
what are the hottest research topics in computer science?

The field of computer science is vast and continually evolving, with numerous research areas gaining attention. Here are some of the hottest research topics in computer science as of 2024:

1. **Artificial Intelligence and Machine Learning**:
   - **Deep Learning**: Advances in neural networks, including transformer architectures and generative models like GPT-4.
   - **Reinforcement Learning**: Applications in robotics, autonomous systems, and game playing.
   - **Explainable AI (XAI)**: Making AI decisions understandable to humans to ensure transparency and trust.
2. **Quantum Computing**:
   - **Quantum Algorithms**: Development of algorithms that can leverage quantum computing's potential.
   - **Quantum Cryptography**: Enhancing security using quantum key distribution.
   - **Quantum Supremacy**: Demonstrating practical advantages of quantum over classical computing.
3. **Cybersecurity**:

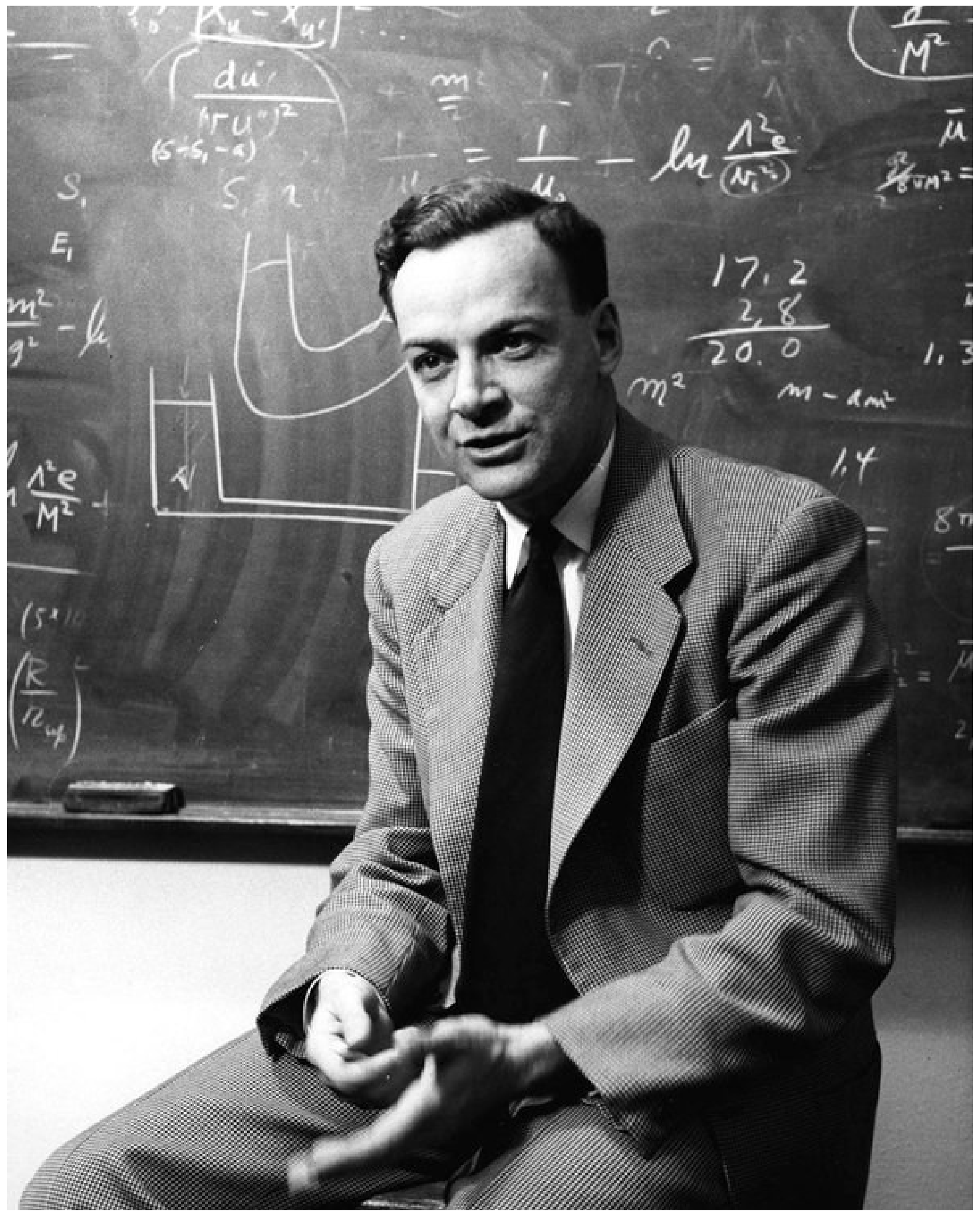
forbes.com/sites/chuckbrooks/2021/03/21/the-emerging-paths-of-quantum-computing/?sh=66cac7936613

Lots of (potential) use cases



https://www.gartner.com/smarterwithgartner/the-cios-guide-to-quantum-computing

The origin



International Journal of Theoretical Physics, Vol. 21, Nos. 6/7, 1982

Simulating Physics with Computers

Richard P. Feynman

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

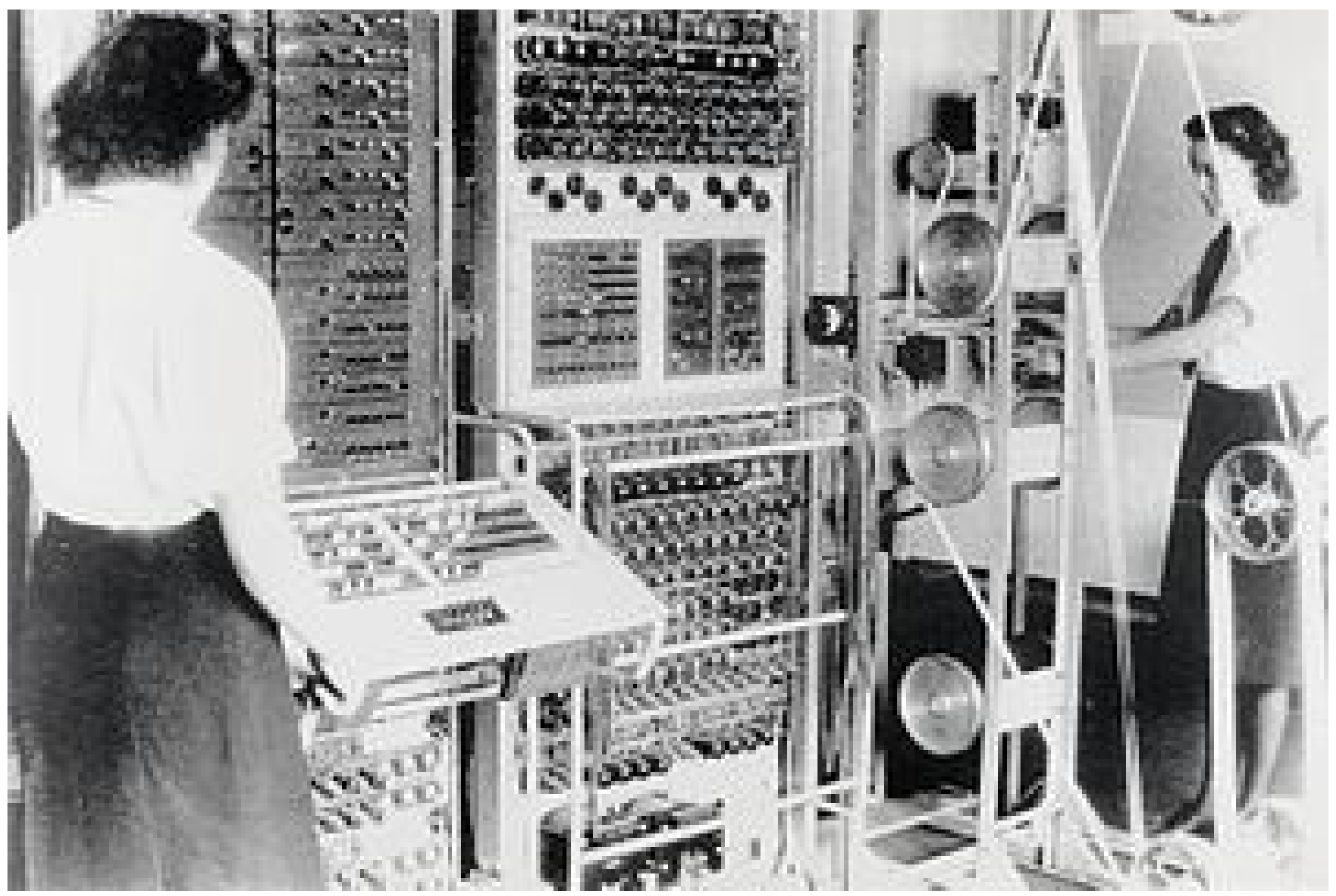
Received May 7, 1981

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.

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.

Classical computing and quantum computing



Colossus computer
1944

Quantum computer at TU Delft
2019

Quantum computing development roadmap

Development Roadmap

Quantum Computing

2012	2021	2025-2028	2030+
Development of the first single atom transistor	Development of first integrated circuit at the atomic scale	Development of the first commercially useful device	Error-corrected quantum processor

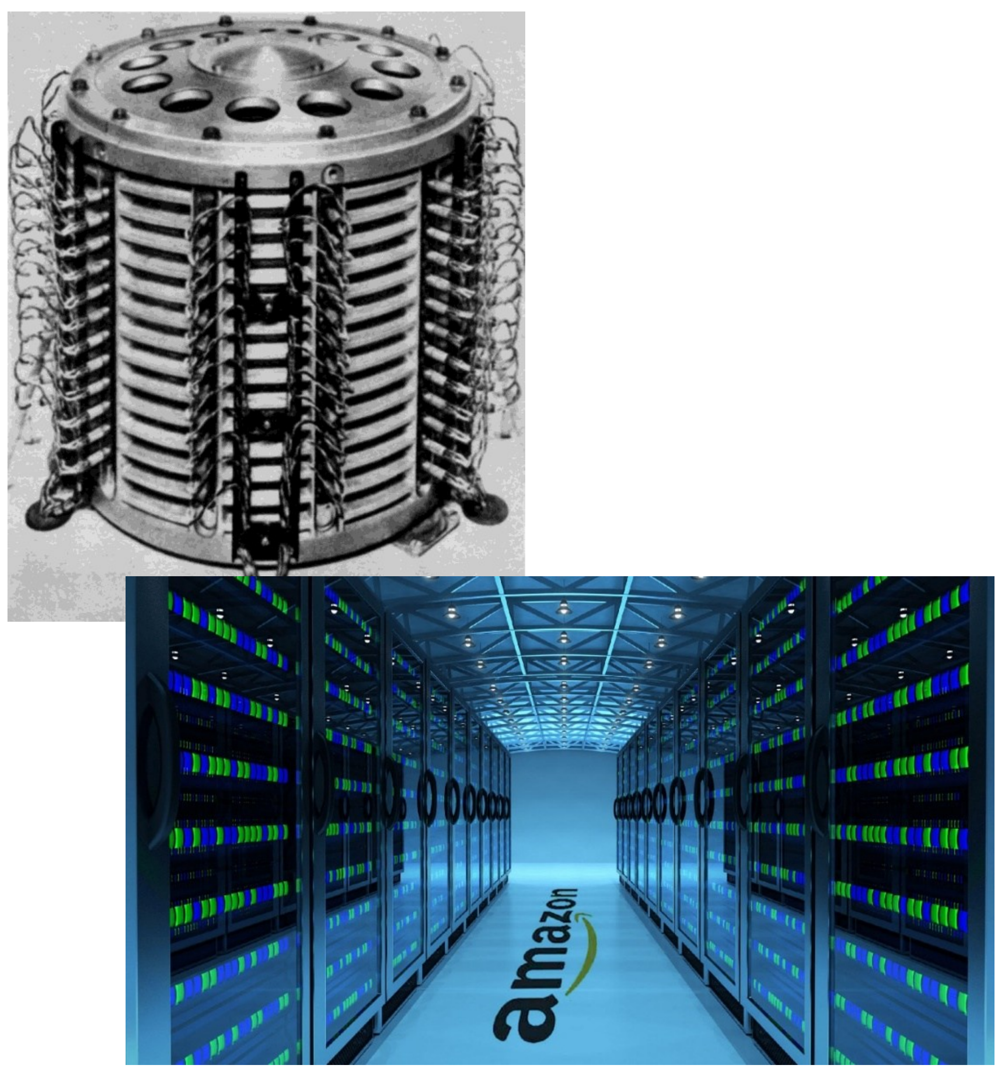
Classical Computing

1947	1958	1964	1971
Development of the first transistor	Development of the first integrated circuit	Use in the first commercial product	First semi-conductor based industrial computer

de.wikipedia.org/wiki/Trommelspeicher#/media/Datei:Pamiec_bebnowa_1.jpg
flaticon.com/de/kostenloses-icon/algorithmus_1119005
forbes.com/sites/tiriasresearch/2023/11/28/quantum-computing-is-coming-faster-than-you-think/

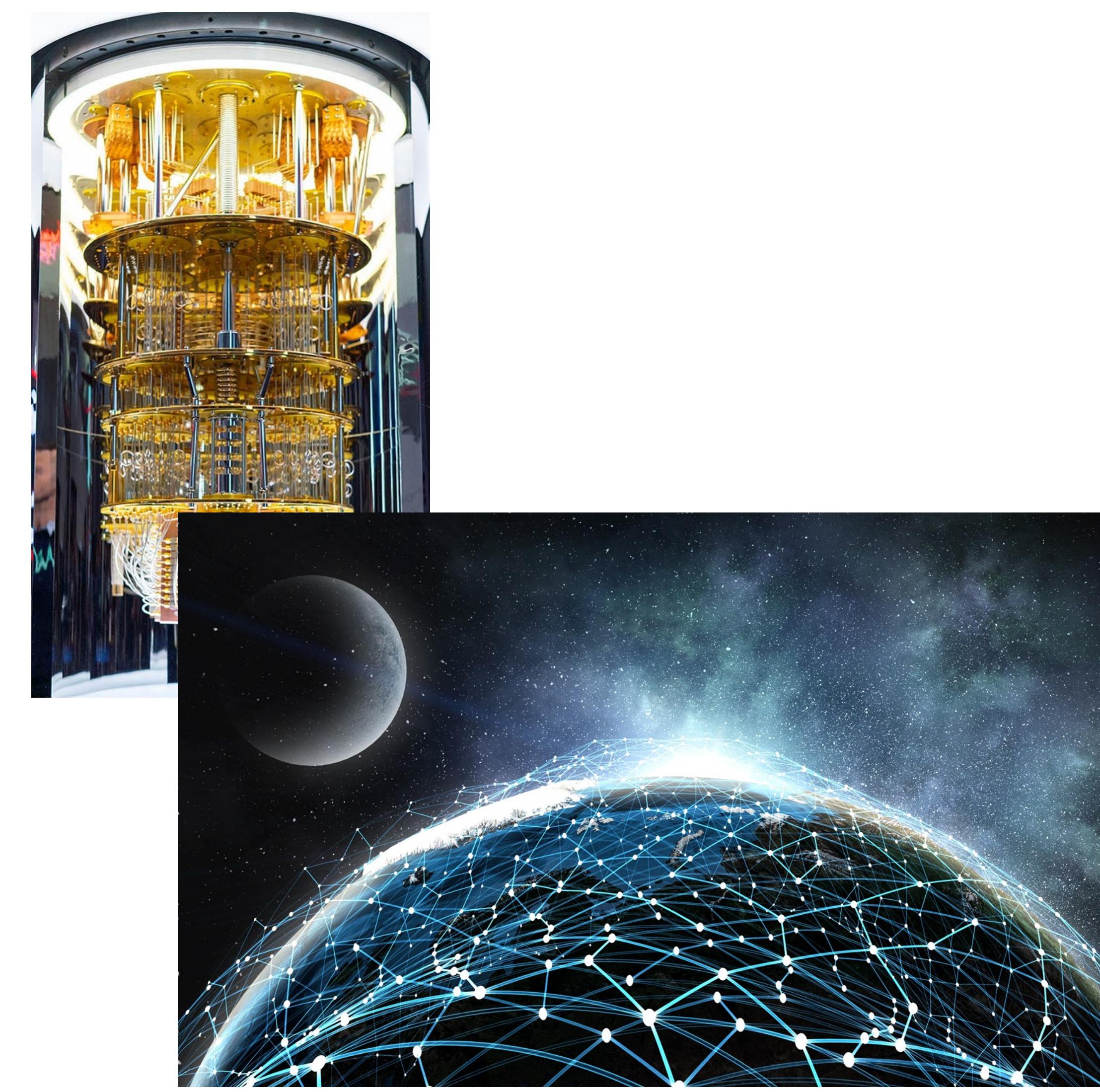
Goal for today

Entering the era of quantum computing, what is the future of data management?



Data management problems

?



Quantum computer and quantum Internet

Fundamentals of quantum computing

en.wikipedia.org/wiki/Quantum_computing#/media/File:IBM_Q_system_(Fraunhofer_2).jpg

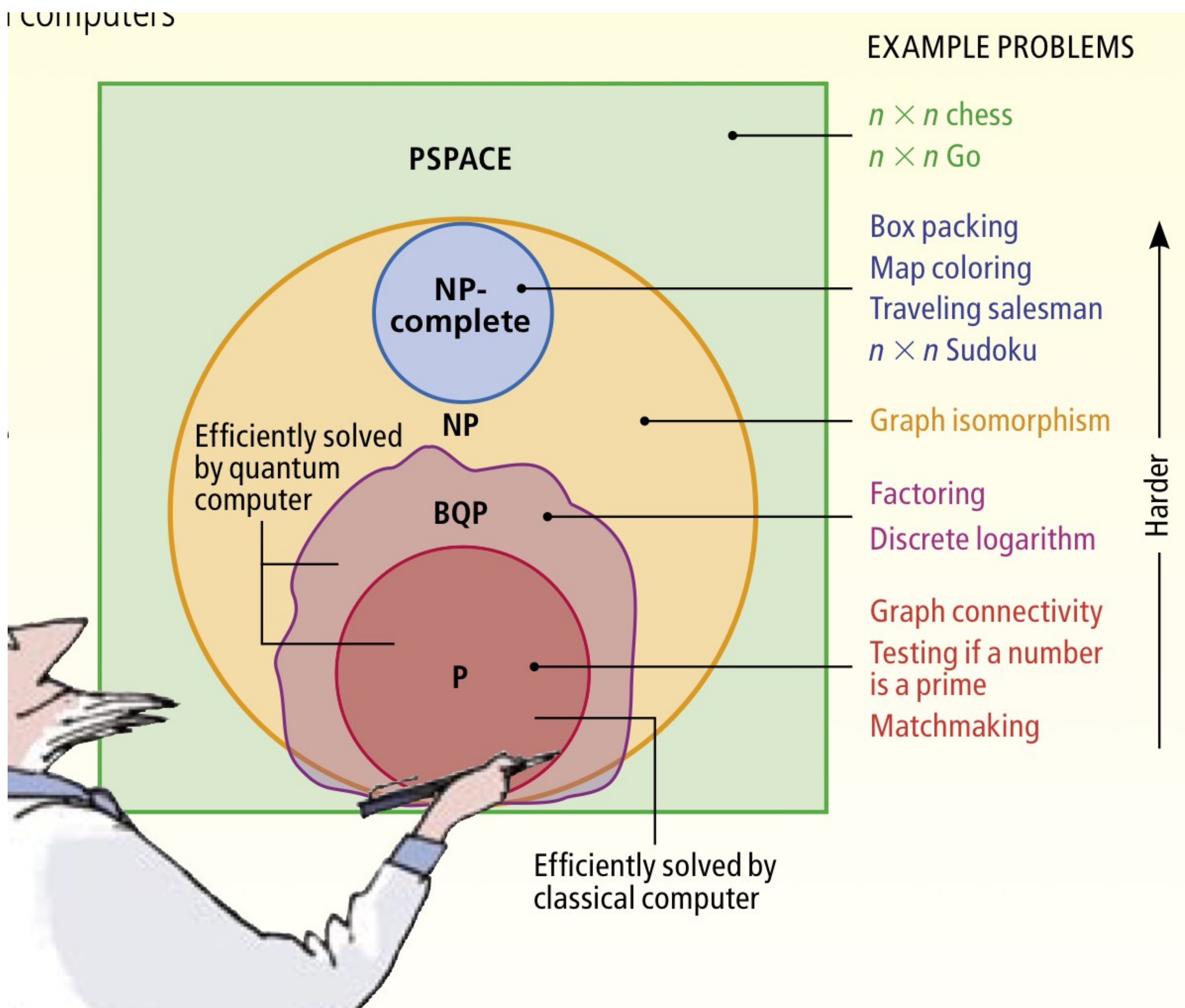
What exactly is a quantum computer?

- Often hidden behind a service

image.geo.de/30149980/t/UN/v3/w960/r0/-/perpetuum-mobile-s-157382423-jpg--85551-.jpg

What exactly is a quantum computer?

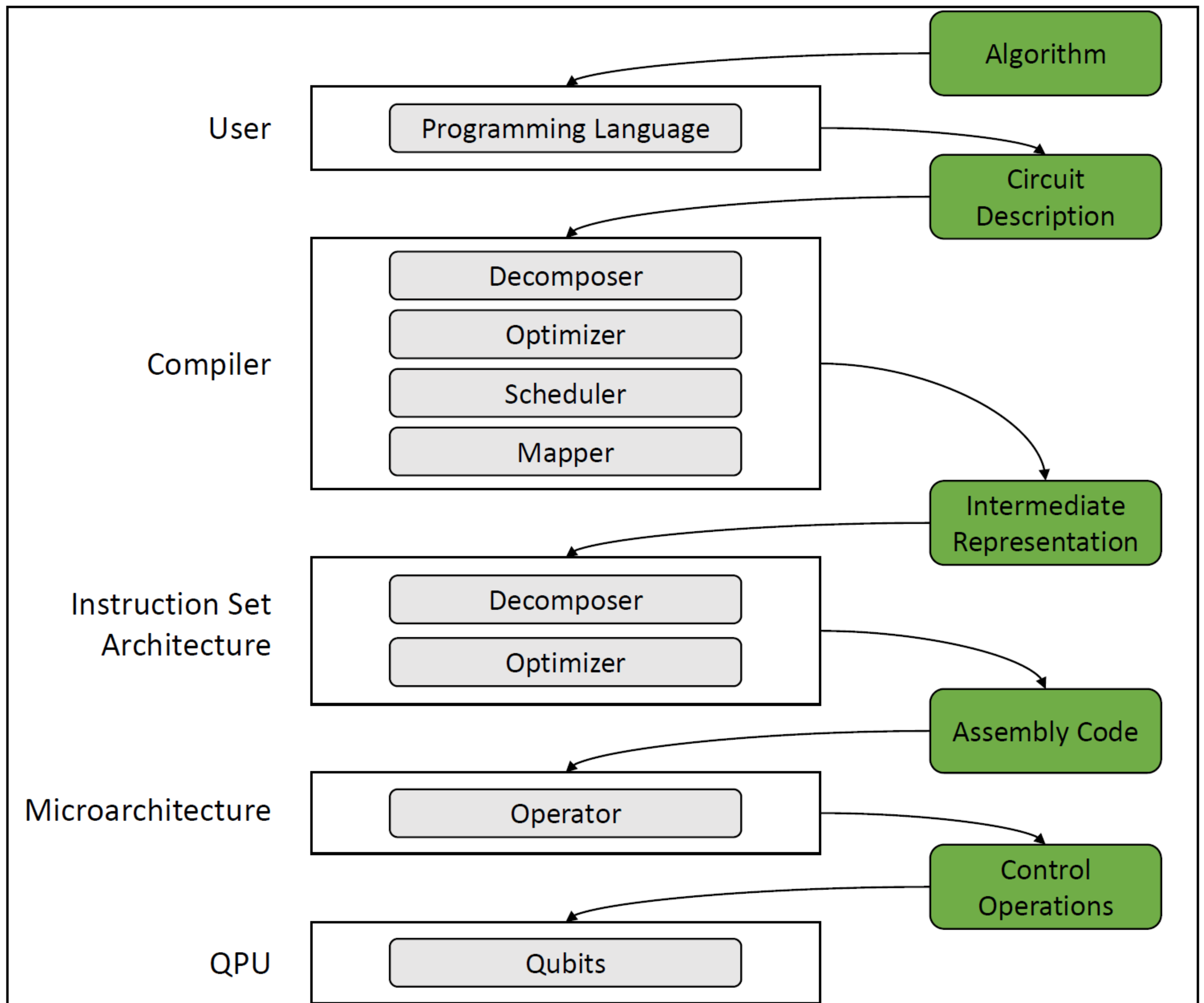
- It‘s not a magical wonder machine
- Quantum computing is turing-complete
- Quantum bit (qubit), the main building block



https://blog.acolyer.org/2018/02/02/polynomial-time-algorithms-for-prime-factorization-and-discrete-logarithms-on-a-quantum-computer/

What exactly is a quantum computer?

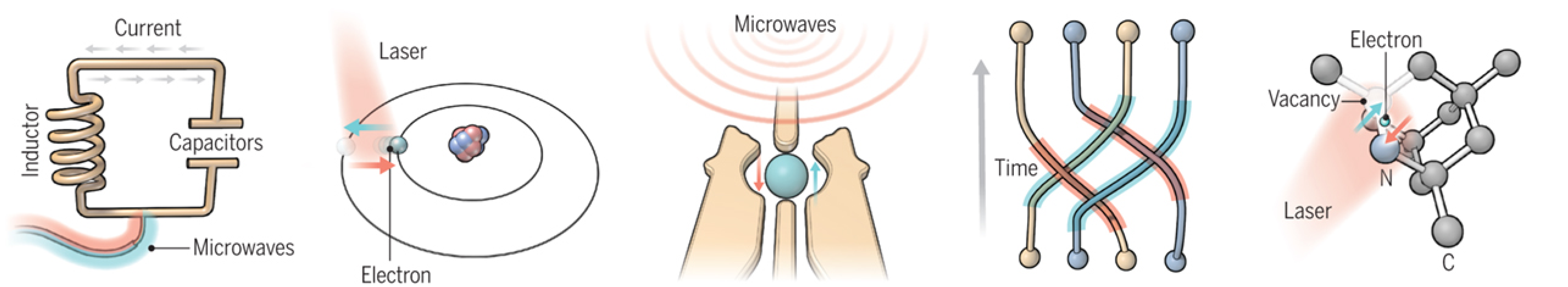
- Full-stack quantum computation



Different architectures to implement qubits

A bit of the action

In the race to build a quantum computer, companies are pursuing many types of quantum bits, or qubits, each with its own strengths and weaknesses.



	Superconducting loops	Trapped ions	Silicon quantum dots	Topological qubits	Diamond vacancies
	A resistance-free current oscillates back and forth around a circuit loop. An injected microwave signal excites the current into super-position states.	Electrically charged atoms, or ions, have quantum energies that depend on the location of electrons. Tuned lasers cool and trap the ions, and put them in superposition states.	These "artificial atoms" are made by adding an electron to a small piece of pure silicon. Microwaves control the electron's quantum state.	Quasiparticles can be seen in the behavior of electrons channeled through semi-conductor structures. Their braided paths can encode quantum information.	A nitrogen atom and a vacancy add an electron to a diamond lattice. Its quantum spin state, along with those of nearby carbon nuclei, can be controlled with light.
Longevity (seconds)	0.00005	>1000	0.03	N/A	10
Logic success rate	99.4%	99.9%	~99%	N/A	99.2%
Number entangled	9	14	2	N/A	6
Company support	Google, IBM, Quantum Circuits	ionQ	Intel	Microsoft, Bell Labs	Quantum Diamond Technologies
Pros	Fast working. Build on existing semiconductor industry.	Very stable. Highest achieved gate fidelities.	Stable. Build on existing semiconductor industry.	Greatly reduce errors.	Can operate at room temperature.
Cons	Collapse easily and must be kept cold.	Slow operation. Many lasers are needed.	Only a few entangled. Must be kept cold.	Existence not yet confirmed.	Difficult to entangle.

Note: Longevity is the record coherence time for a single qubit superposition state, logic success rate is the highest reported gate fidelity for logic operations on two qubits, and number entangled is the maximum number of qubits entangled and capable of performing two-qubit operations.

Source: https://www.science.org/doi/10.1126/science.354.6316.1090#F2

Different architectures to implement qubits

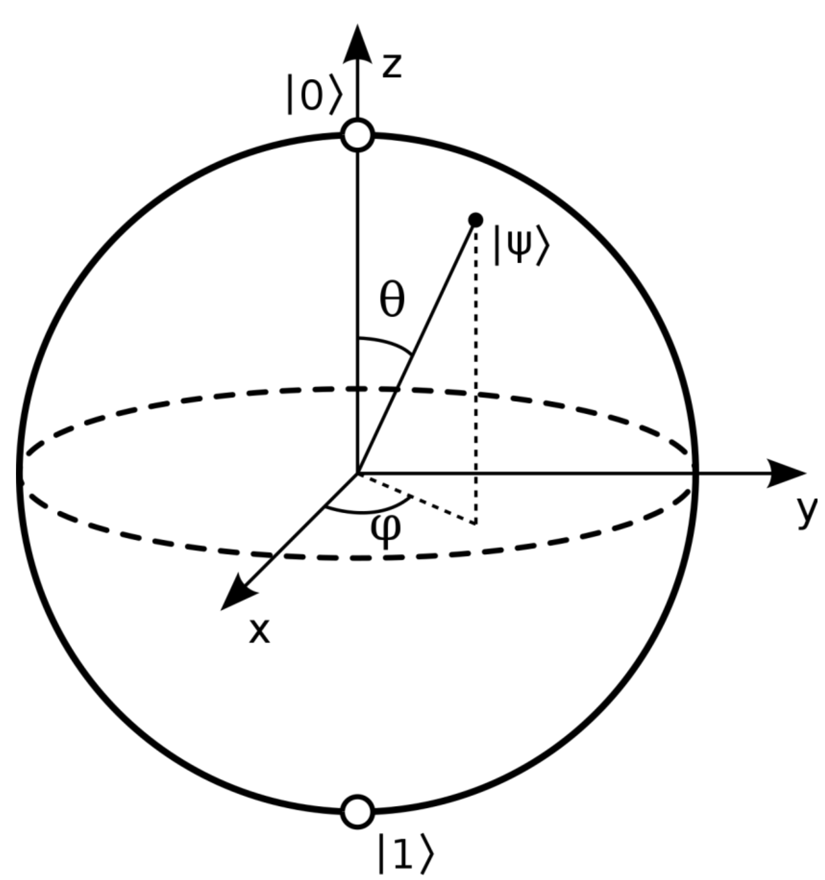
Qubit Type	Pros/Cons	Select Players
Superconducting	***Pros***: High gate speeds and fidelities. Can leverage standard lithographic processes. Among first qubit modalities so has a head start. ***Cons***: Requires cryogenic cooling; short coherence times; microwave interconnect frequencies still not well understood.	rigetti, Google, IBM Q, QuTech, OQC, IQM, qci Quantum Circuits, Inc, 本源量子 Origin Quantum
Trapped Ions	***Pros***: Extremely high gate fidelities and long coherence times. Extreme cryogenic cooling not required. Ions are perfect and consistent. ***Cons***: Slow gate times/ operations and low connectivity between qubits. Lasers hard to align and scale. Ultra-high vacuum required. Ion charges may restrict scalability.	IONQ, AQT, QUANTINUUM, oxford ionics, Universal Quantum
Photonics	***Pros***: Extremely fast gate speeds and promising fidelities. No cryogenics or vacuums required. Small overall footprint. Can leverage existing CMOS fabs. ***Cons***: Noise from photon loss; each program requires its own chip. Photons don't naturally interact so 2Q gate challenges.	PsiQuantum, XANADU, QUIX QUANTUM, ORCA Computing
Neutral Atoms	***Pros***: Long coherence times. Atoms are perfect and consistent. Strong connectivity, including more than 2Q. External cryogenics not required. ***Cons***: Requires ultra-high vacuums. Laser scaling challenging.	ColdQuanta, QuEra Computing Inc., atom computing, PASQAL
Silicon Spin/Quantum Dots	***Pros***: Leverages existing semiconductor technology. Strong gate fidelities and speeds. ***Cons***: Requires cryogenics. Only a few entangled gates to-date with low coherence times. Interference/cross-talk challenges.	intel, Silicon Quantum Computing, diraq, QUANTUM MOTION, QUANTUM BRILLIANCE

What is a qubit (for us)?

- A qubit is a linear combination of basis states

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

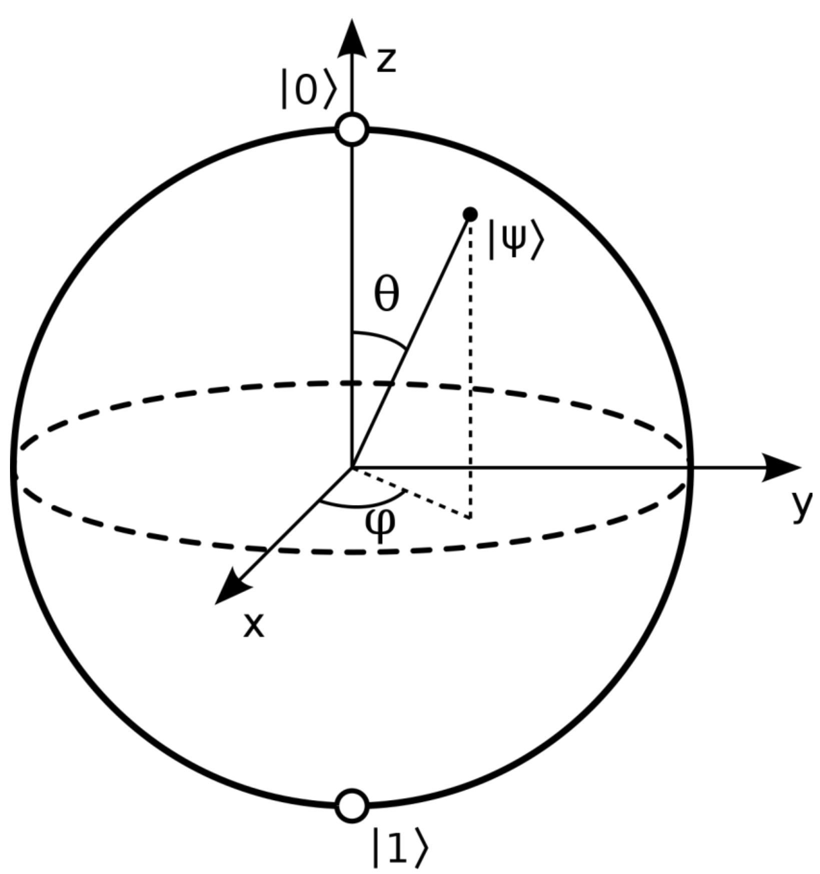
$$\alpha, \beta \in \mathbb{C} \text{ with } |\alpha|^2 + |\beta|^2 = 1$$



en.wikipedia.org/wiki/Bloch_sphere
en.m.wikipedia.org/wiki/File:Qcircuit_measure-arrow.svg

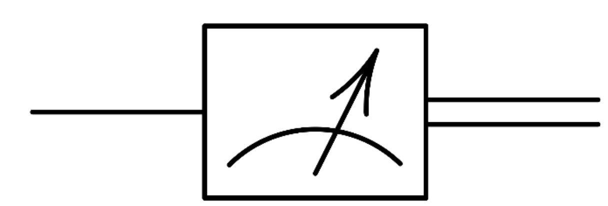
Measurement gives classical information

- α, β are called probability amplitudes
- When measuring, $|\alpha|^2$ is probability of finding qubit in state $|0\rangle$



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

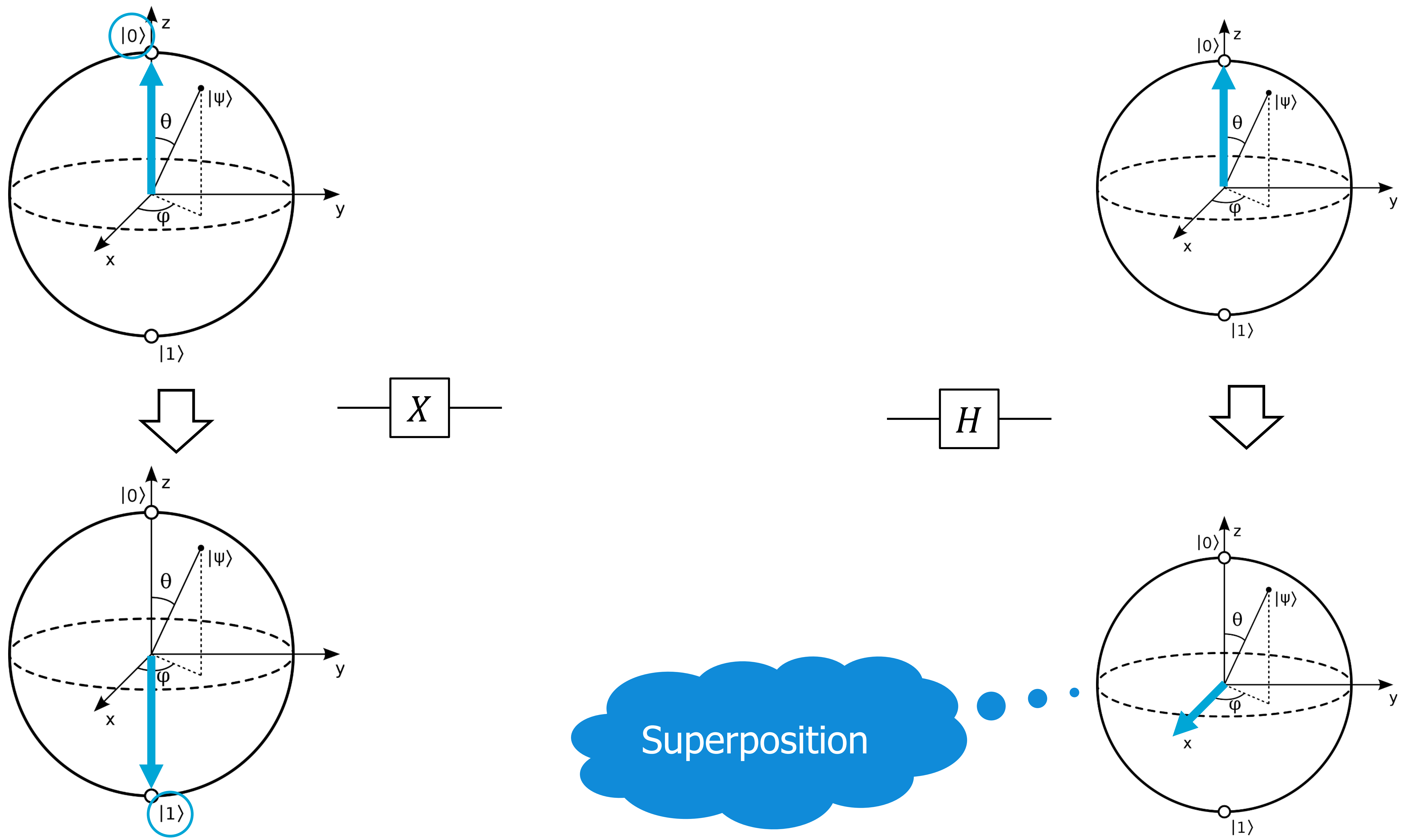
$$\alpha, \beta \in \mathbb{C} \text{ with } |\alpha|^2 + |\beta|^2 = 1$$

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

en.wikipedia.org/wiki/Bloch_sphere

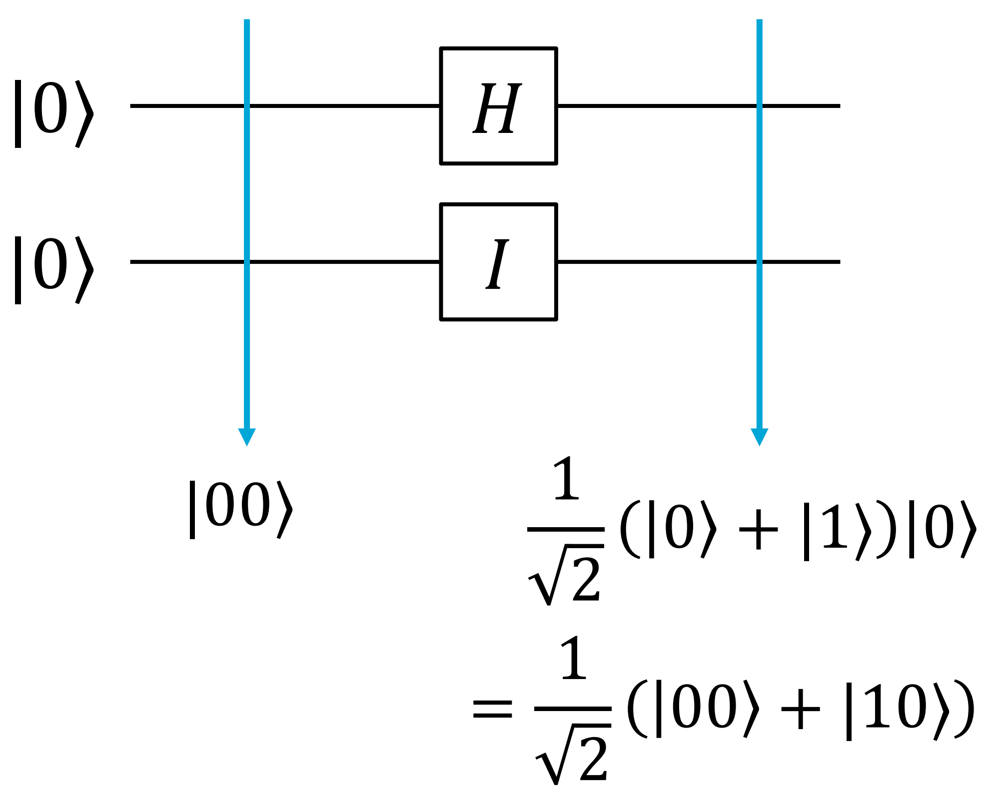
Gates

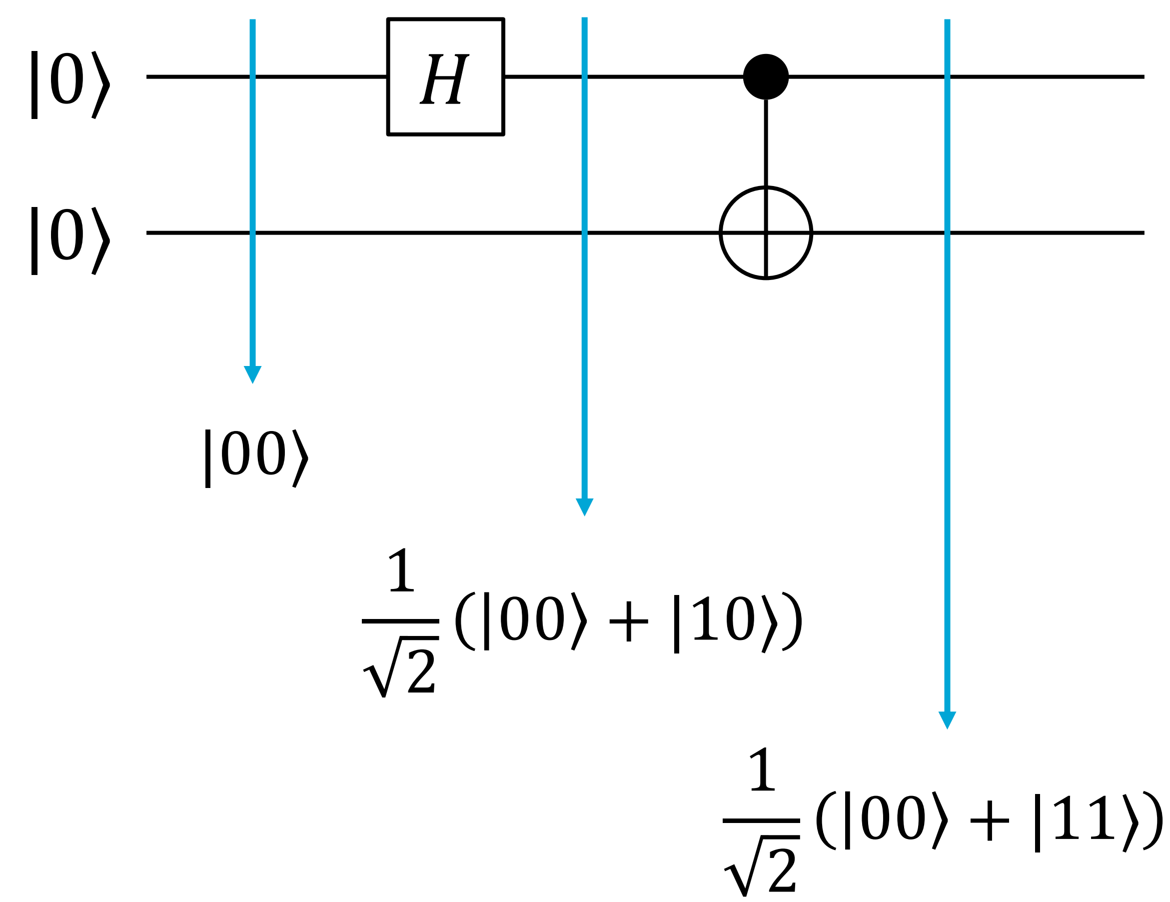
- Quantum gates operate on a quantum state
- Rotations around an axis, but also controlled operations

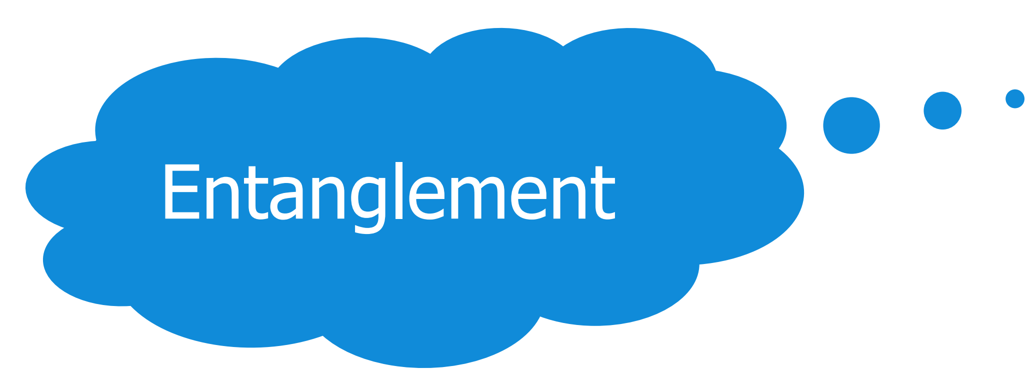


Gates

- Quantum gates operate on a quantum state
- Rotations around an axis, but also controlled operations

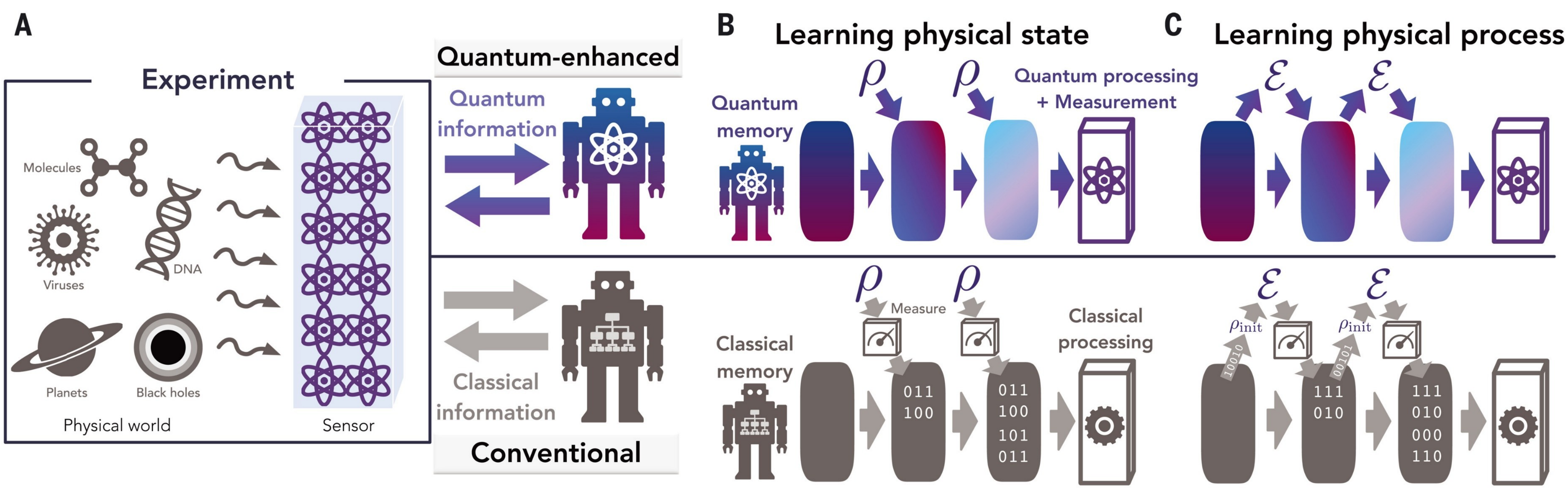






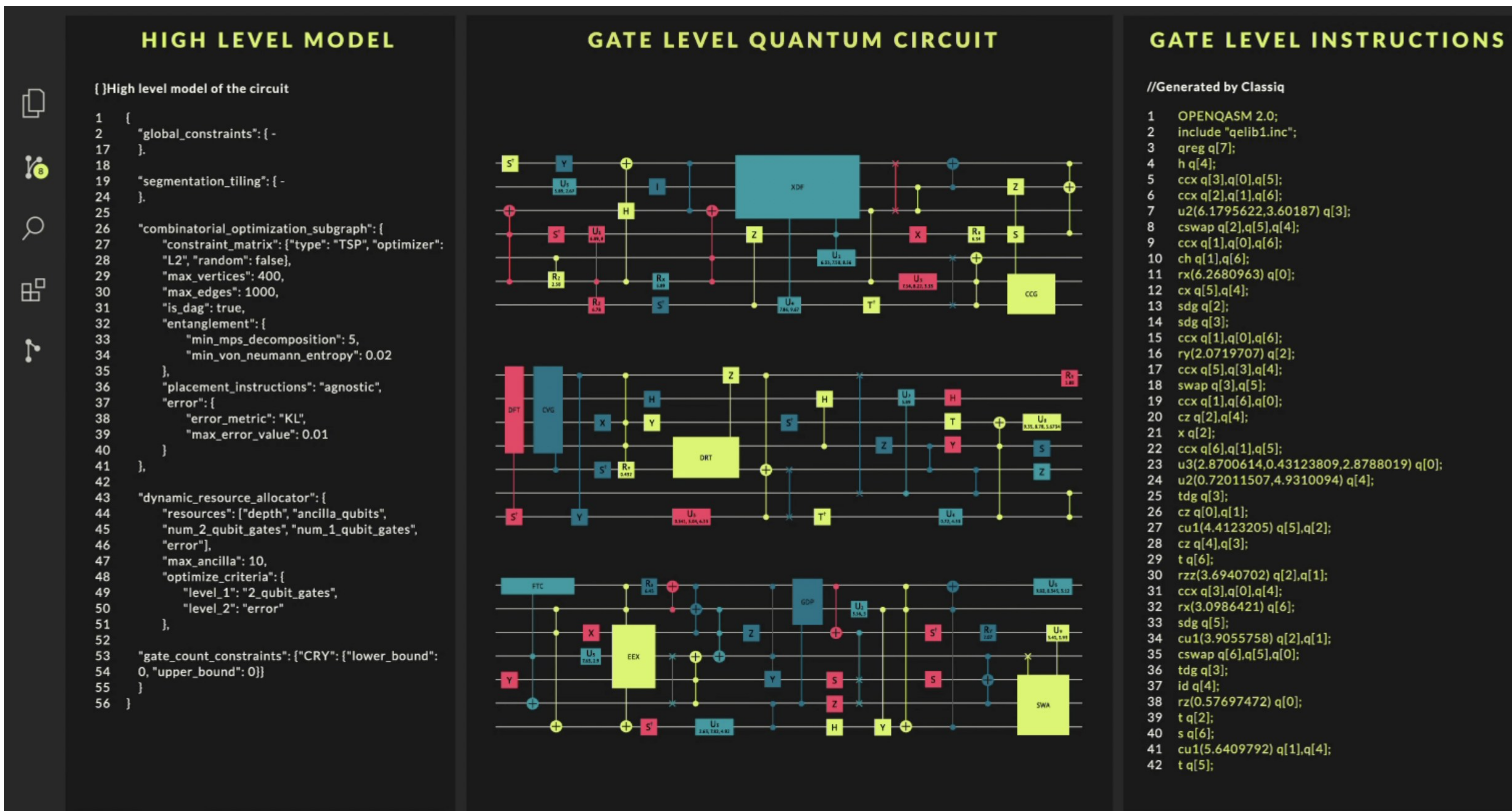
Some highlights

- Proven superiority, see for example „Quantum advantage in learning from experiments“



Some highlights

- Many successful efforts regarding abstraction, SDKs, APIs, …



How can YOU start?

- The entrance barrier is lower than one thinks…

Qiskit

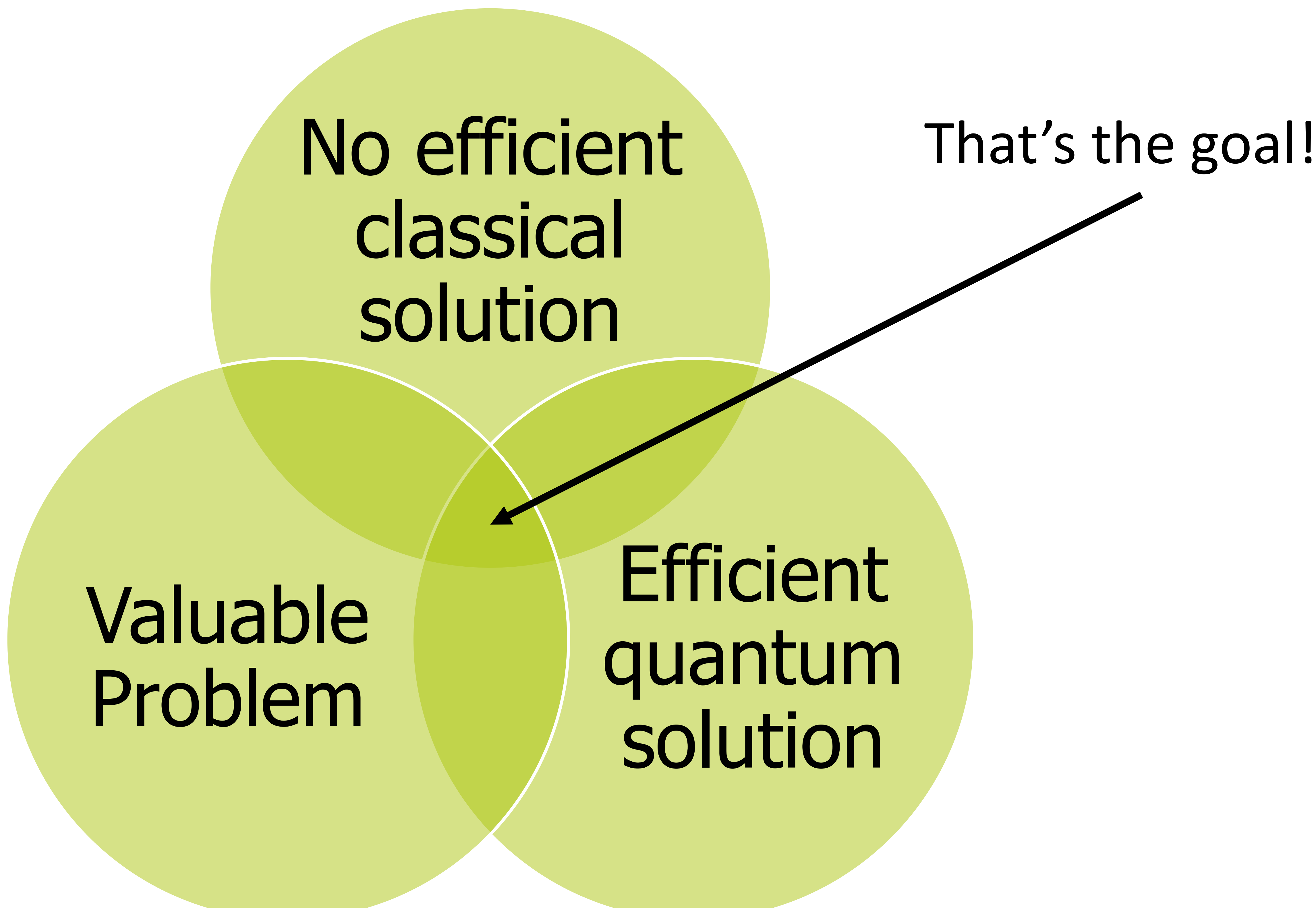
Cirq

Ocean

… and many more!

How can WE start?

- At least three things need to come together



Data Management using Quantum Computers
-- the Art of Encoding

LO and Assignment

- Learning Objective
  - Explain how to solve a data management problem on quantum computers

- Assignment
  - Design an approach that solves a data management or data science problem using quantum computers

Multiple Query Optimization

T. K. Sellis, Multiple-query optimization, TODS 1988

- Problem: multiple query optimization (MQO) studies how to choose query plans given a set of queries
  - Goal: minimize the total execution cost
  - Key: shared computation between different queries
  - Valid solution
    - A subset of plans selected for query execution
    - 1:1 mapping between the query and the query plan
  - Optimal solution
    - A valid solution with minimal execution cost among all valid solutions

Example

- Two queries

Query	Query plan	Cost
q_1	p_1	2
	p_2	4
q_2	p_3	3
	p_4	1

∗ Shared computation saving between p_2 and p_3 is 5

Which query plans to choose for q_1 and q_2?

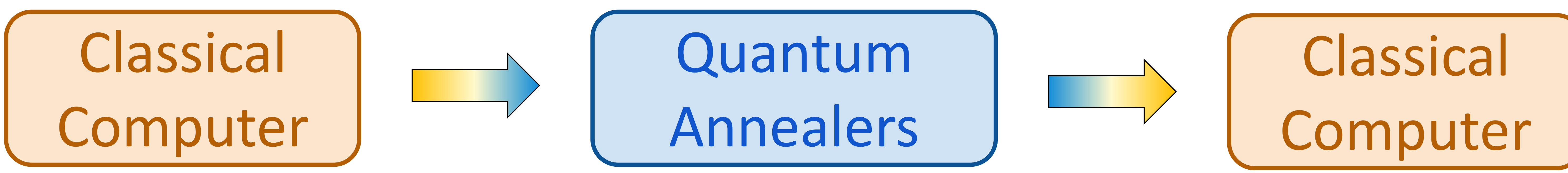
Quantum annealing

- Basically one vendor of quantum annealing
- But also: quantum-inspired hardware

Solve MQO Using Quantum Annealing

- Goal: find near-optimal MQO solution
  - Reduce execution cost by sharing computation among queries

- Solution



1. Logical mapping
2. Physical mapping

I. Trummer and C. Koch, Multiple query optimization on the D-Wave 2X adiabatic quantum computer," VLDB'16.

Encoding: Binary Variables

Logical level

$$x_p = \begin{cases} 1, \text{if query plan } p \text{ is selected} \\ 0, \text{otherwise} \end{cases}$$

Physical level

$$b_i = \begin{cases} 1, \text{if the } i-th \text{ qubit has the state of } 1 \\ 0, \text{if the } i-th \text{ qubit has the state of } 0 \end{cases}$$

Example

- Adding binary variable x_p

Query	Query plan	x_p	Cost
q_1	p_1	x_1	2
	p_2	x_2	4
q_2	p_3	x_3	3
	p_4	x_4	1

$*$ Shared computation saving between p_2 and p_3 is 5

Logical Mapping

- Design logical mapping:
  - Transform the MQO problem into a QUBO problem
  - **Minimize** the logical energy formula

Obtain valid solutions

Each query has **at least** one plan

Each query has **at most** one plan

Lower cost

Cost of each plan

Cost saving by intermediate results

Logical Mapping

Query	Query plan	$x_p \in \{0,1\}$	Cost
q_1	p_1	x_1	2
	p_2	x_2	4
q_2	p_3	x_3	3
	p_4	x_4	1

* Shared computation saving between p_2 and p_3 is 5

1. *Each query has at least one plan*

$$E_L = -\sum_{p \in P} x_p$$

2. *Each query has* ***at most*** *one plan*

$$E_L = -x_1 - x_2 - x_3 - x_4$$

$x_1 \rightarrow 1$
$x_2 \rightarrow 1$
$x_3 \rightarrow 1$
$x_4 \rightarrow 1$

NOT what we want!

Logical Mapping

Query	Query plan	$x_p \in \{0,1\}$	Cost
q_1	p_1	x_1	2
	p_2	x_2	4
q_2	p_3	x_3	3
	p_4	x_4	1

$*$ Shared computation saving between p_2 and p_3 is 5

1. *Each query has at least one plan*

$$E_L = -\sum_{p \in P} x_p$$

2. *Each query has **at most** one plan*

$$E_M = \sum_{q \in Q} \sum_{\{p1, p2 \subseteq Pq\}} x_{p1} x_{p2}$$

for q_1: $x_1 \ x_2 \rightarrow 0$
for q_2: $x_3 \ x_4 \rightarrow 0$

Logical Mapping

Query	Query plan	$x_p \in \{0, 1\}$	Cost
q_1	p_1	x_1	2
	p_2	x_2	4
q_2	p_3	x_3	3
	p_4	x_4	1

$*$ Shared computation saving between p_2 and p_3 is 5

3. *Sum up the cost of each plan*

$$E_C = \sum_{p \in P} c_p x_p$$

If we choose p_2 for q_1, p_3 for q_2:

$x_1 \rightarrow 0$
$x_2 \rightarrow 1$
$x_3 \rightarrow 1$
$x_4 \rightarrow 0$

$$E_C = 0 * 2 + 1 * 4 + 1*3 + 0*1 = 7$$

Logical Mapping

Query	Query plan	$x_p \in \{0, 1\}$	Cost
q_1	p_1	x_1	2
	p_2	x_2	4
q_2	p_3	x_3	3
	p_4	x_4	1

* ***Shared computation saving between p_2 and p_3 is 5***

4. *Deduct the cost saved by intermediate results*

$$E_S = -\sum_{\{p1,p2 \subseteq P\}} s_{p1,p2} x_{p1} x_{p2}$$

If we choose p_2 for q_1, p_3 for q_2:

$x_1 \rightarrow 0$
$x_2 \rightarrow 1$
$x_3 \rightarrow 1$
$x_4 \rightarrow 0$

$$E_S = -5*1*1 = -5$$

Logical Mapping

I. Trummer and C. Koch, Multiple query optimization on the D-Wave 2X adiabatic quantum computer," VLDB'16.

- Final logical energy formula

Obtain valid solutions

Each query has **at least** one plan

Each query has **at most** one plan

Lower cost

Cost of each plan

Cost saving by intermediate results

$$w_L E_L + w_M E_M + E_C + E_S$$

Physical Plan

- Physical mapping
  - Logical energy formula → **physical energy formula** of qubit states
  - Key challenge: mapping variables to qubit

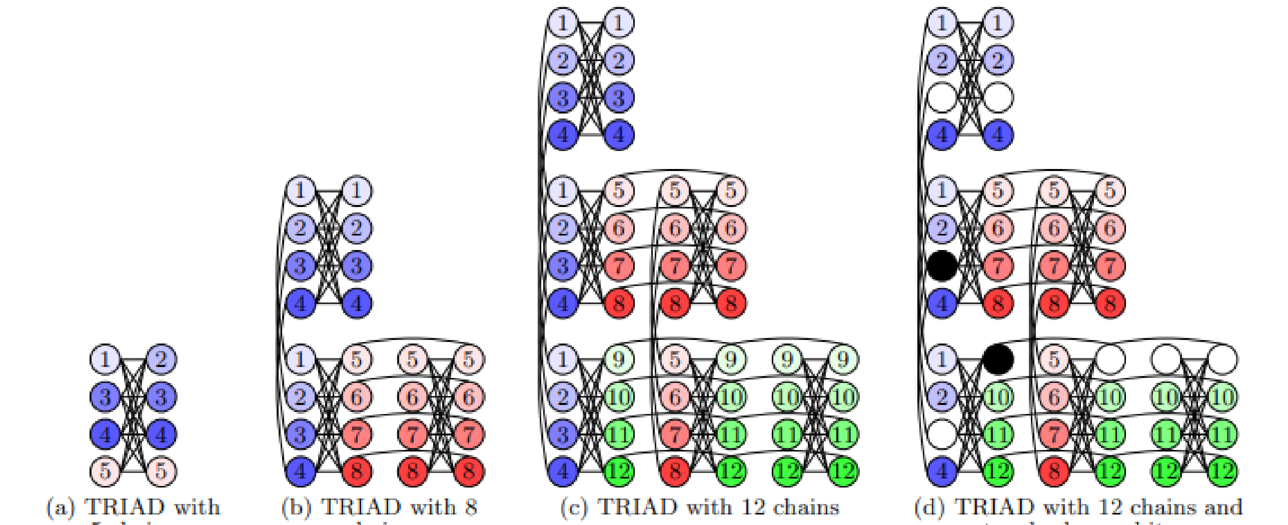


Figure 2: TRIAD pattern in different sizes: we show qubits as circles, annotated by the ID of the logical variable that they represent. The mapping from variables to qubits assures that each variable shares at least one connection (in black) with each of the other variables.

- Hardware-specific constraint:
  - Sparse qubit connectivity
  - All qubits representing the same variable form a chain
  - Logical variables in a quadratic term need to be represented by connected groups of qubits
  - Broken qubits

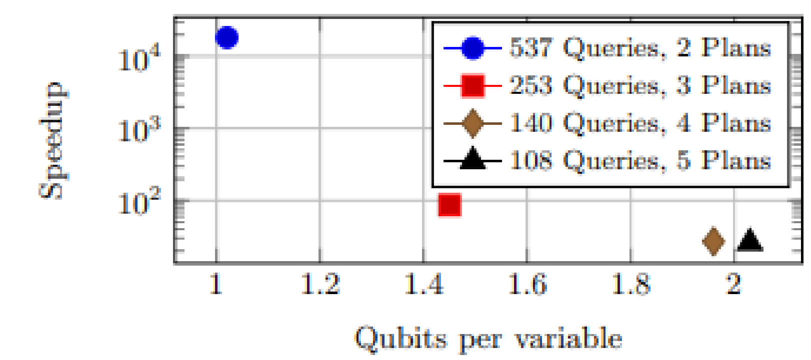


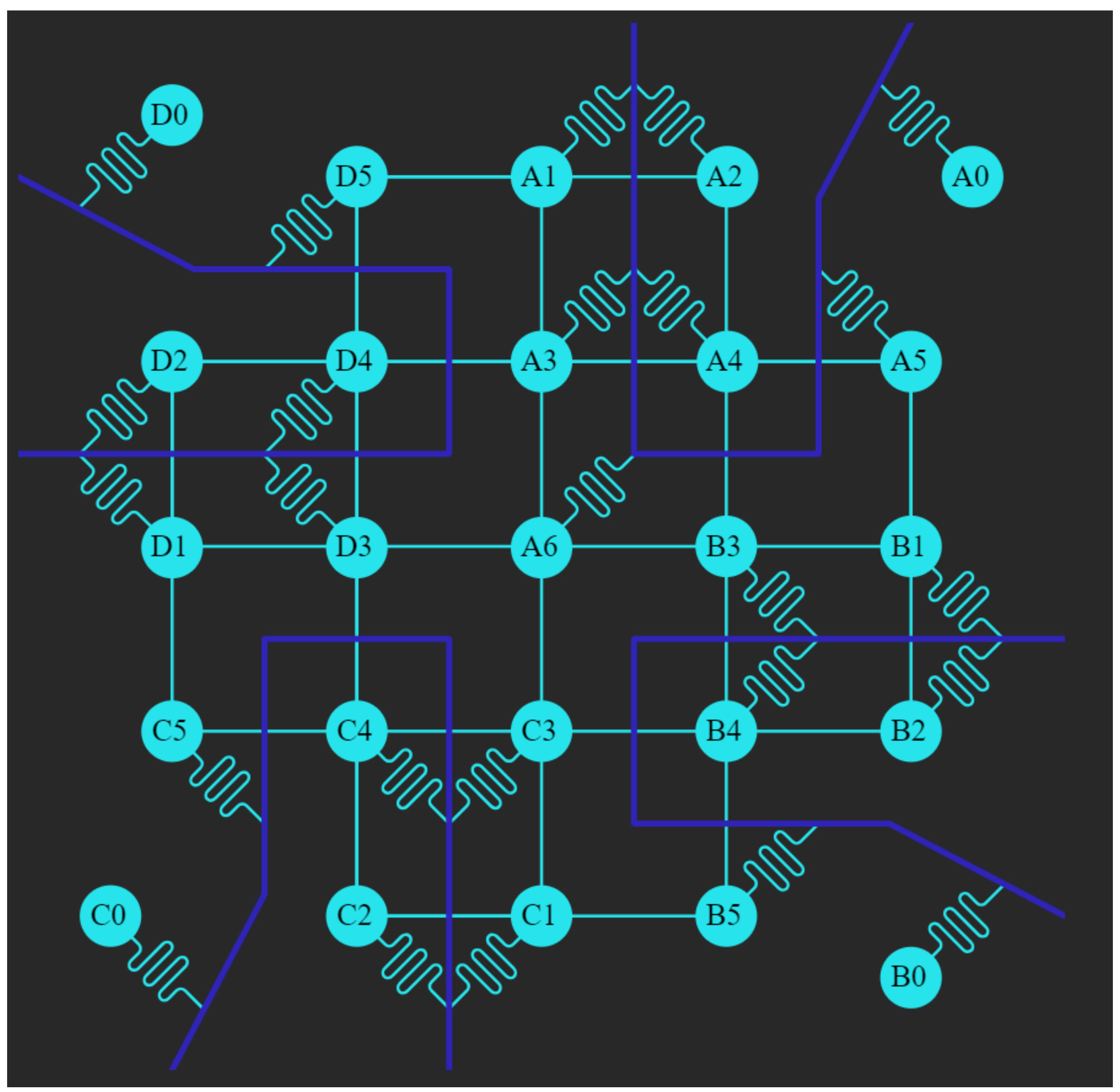
Figure 6: Average quantum speedup for different classes of test cases: having to use more qubits per problem variable decreases the speedup.

Results: 1000x speedup

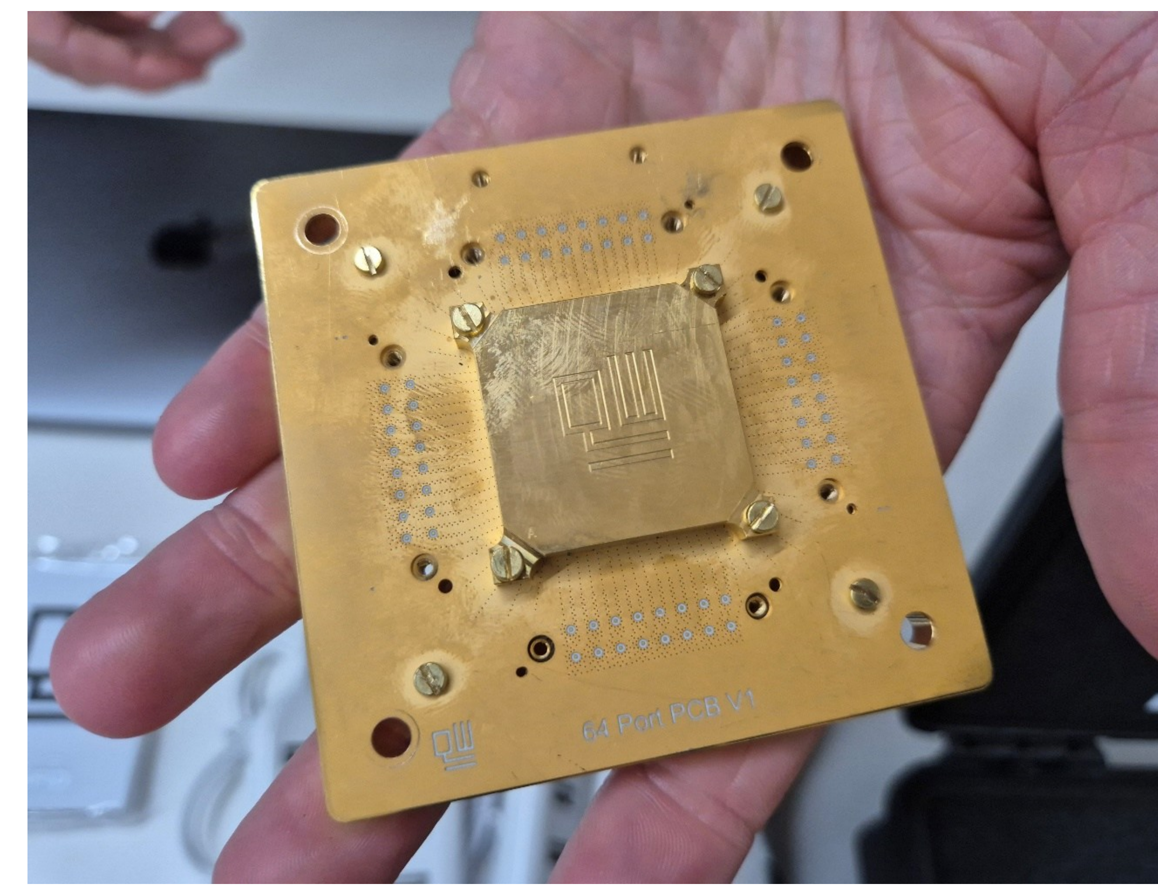
When fewer qubits per variable

Hardware

25 Qubits: 21 fully connected +
4 isolated qubits



QuantWare



Extend MQO to Gate-based QC

- Gate-based quantum computer, more **universal** than quantum annealing
- Hybrid classical-quantum algorithms like the Quantum Approximate Optimization Algorithm (QAOA)
- Similar logical mapping, more effective physical mapping
- Limited scalability due to the number of qubits of gate-based QCs

	Trummer and Koch	This work
Max. # of queries	537 queries, 2 plans	7 queries, 2 plans
Qubits used	1074 / 1097 (98%)	14 / 14 (100%)
Max. # of plans	108 queries, 5 plans	2 queries, 7 plans
Qubits used	540 / 1097 (49%)	14 / 14 (100%)

T. Fankhauser, M. E. Soler, R. M. Fuchslin, and K. Stockinger, "Multiple query optimization using a gate-based quantum computer," IEEE Access, 2023.

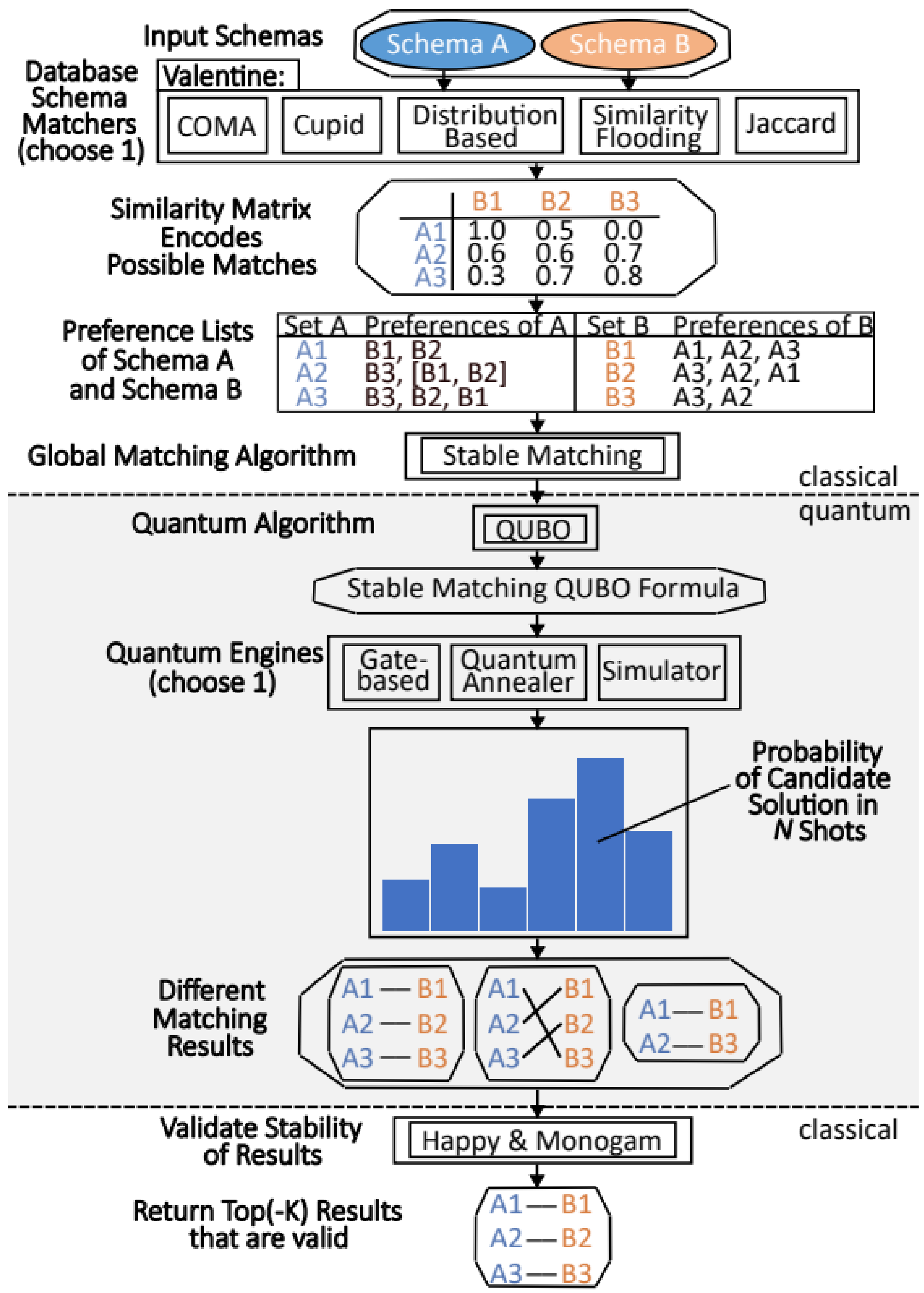
More References on Join Ordering Using Quantum Computers

1. **M. Schonberger, I. Trummer, and W. Mauerer. "Quantum-Inspired Digital Annealing for Join Ordering." Proceedings of the VLDB Endowment 17.3 (2023): 511-524.**
2. **M. Schonberger, S. Scherzinger, and W. Mauerer, “Ready to leap (by ¨ co-design)? join order optimisation on quantum hardware,” Proceedings of the ACM on Management of Data, vol. 1, no. 1, pp. 1–27, 2023.**
3. M. Schonberger, I. Trummer, and W. Mauerer, “Quantum Optimisation ¨ of General Join Trees,” in Joint Workshops at 49th International Conference on Very Large Data Bases (VLDBW’23)—International Workshop on Quantum Data Science and Management (QDSM’23), 2023.
4. N. Nayak, J. Rehfeld, T. Winker, B. Warnke, U. C¸ alikyilmaz, and S. Groppe, “Constructing Optimal Bushy Join Trees by Solving QUBO Problems on Quantum Hardware and Simulators,” in Proceedings of the International Workshop on Big Data in Emergent Distributed Environments, ser. BiDEDE ’23. 2023.
5. T. Winker, U. C¸ alikyilmaz, L. Gruenwald, and S. Groppe, “Quantum Machine Learning for Join Order Optimization Using Variational Quantum Circuits,” in Proceedings of the International Workshop on Big Data in Emergent Distributed Environments, ser. BiDEDE ’23, 2023.

DB Problems Solved Using QPUs

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		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	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

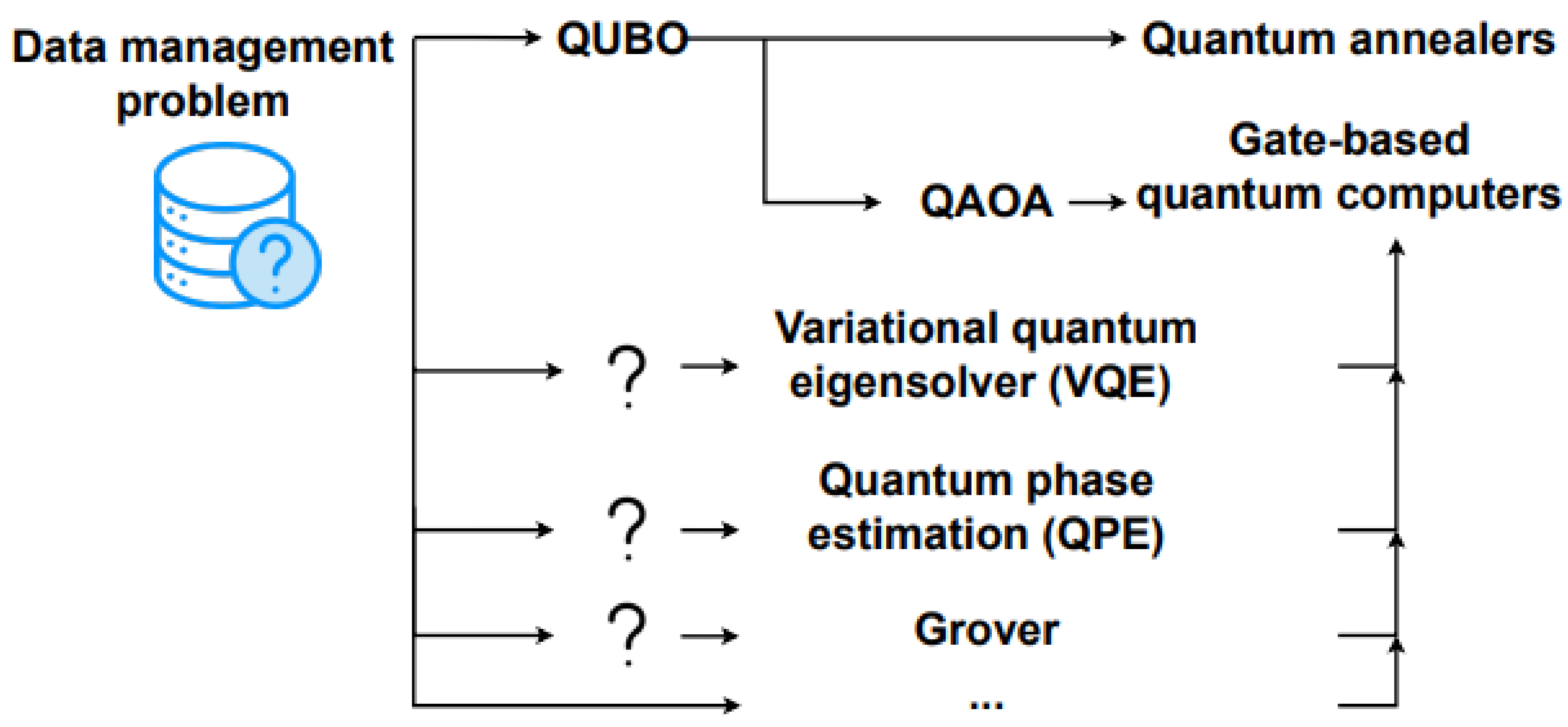
Hybrid Classical and Quantum Workflow



K. Fritsch et al., VLDB'23 Demo

Roadmap

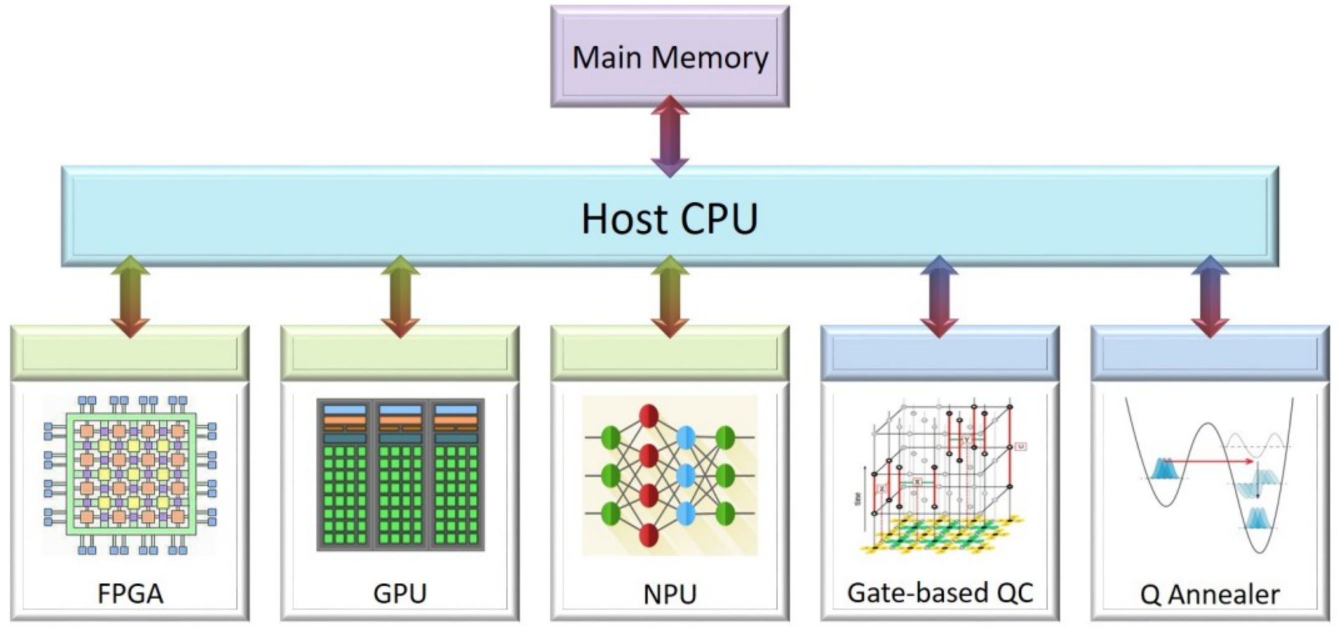
- Solving data management problems on quantum computers
  - Problem benefit from **quantum advantage**, and practically useful
    - Optimization problem
    - Classical approaches have scaling limits
    - Yet it does not require to load a large classical dataset
  - Convert a data management solution to quantum algorithms
  - **Constraints** of current quantum hardware



Opportunities

- DB problem **reformulation**
- **Hybrid** approach on classical and quantum computers
- Optimization given quantum computer **constraints**

Quantum computer will enhance, not replace, current HPC systems

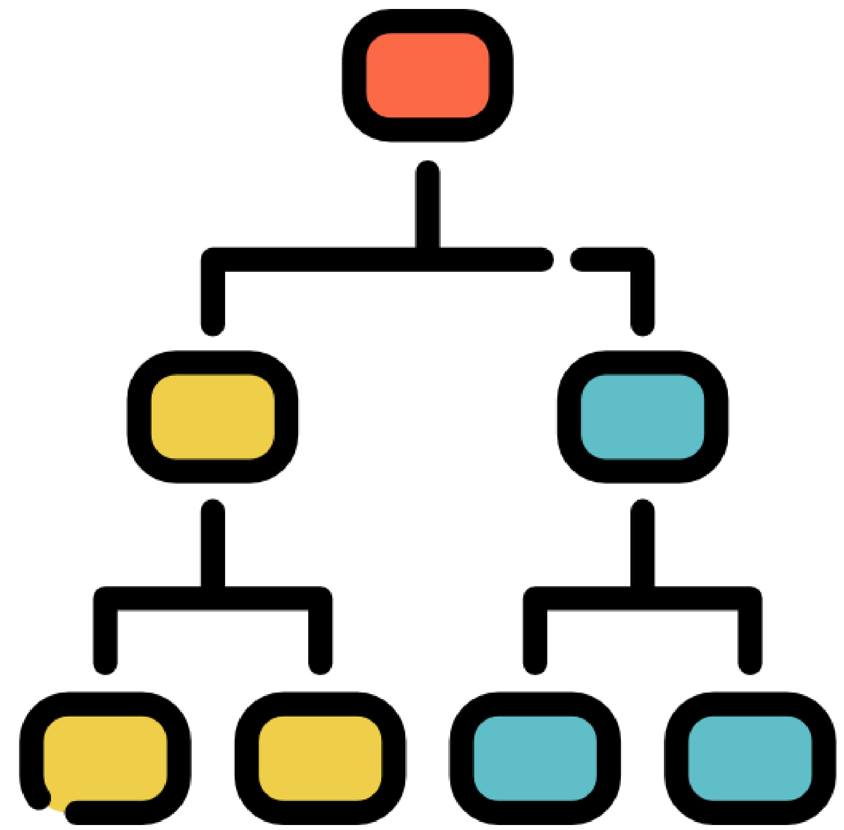



Data Management via
Quantum Internet

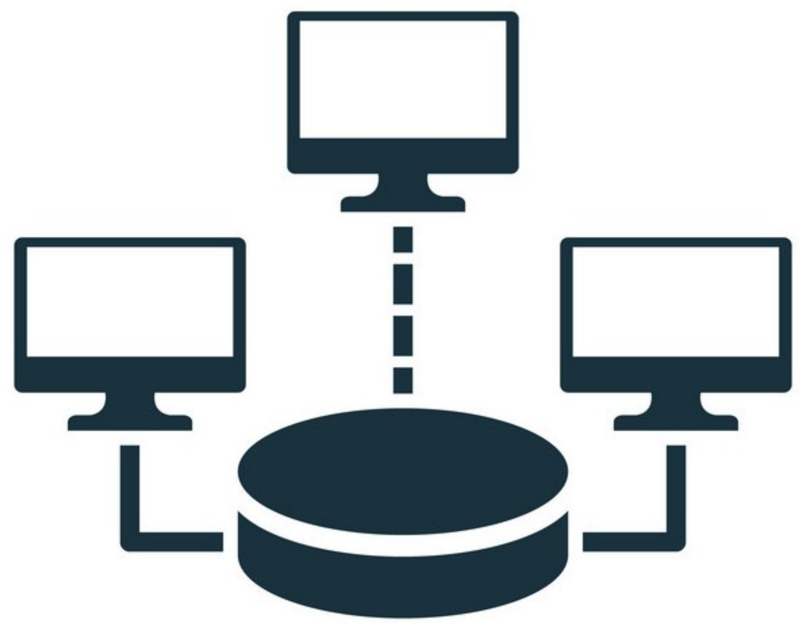
What is a Quantum Internet?

Data Management Related Challenges

Data quality



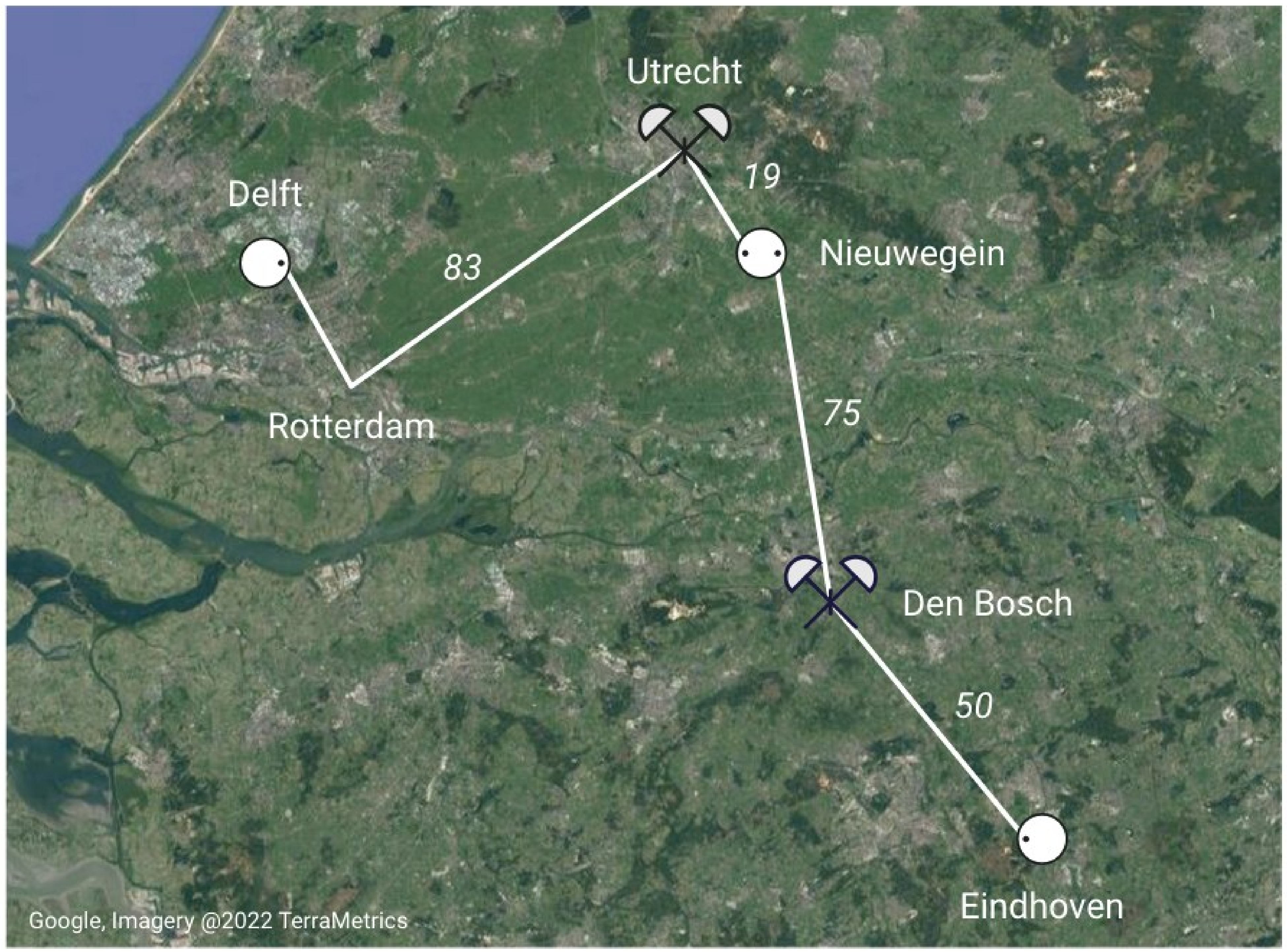
Data structure



Distributed database systems

Hypothetical Quantum Internet Connection

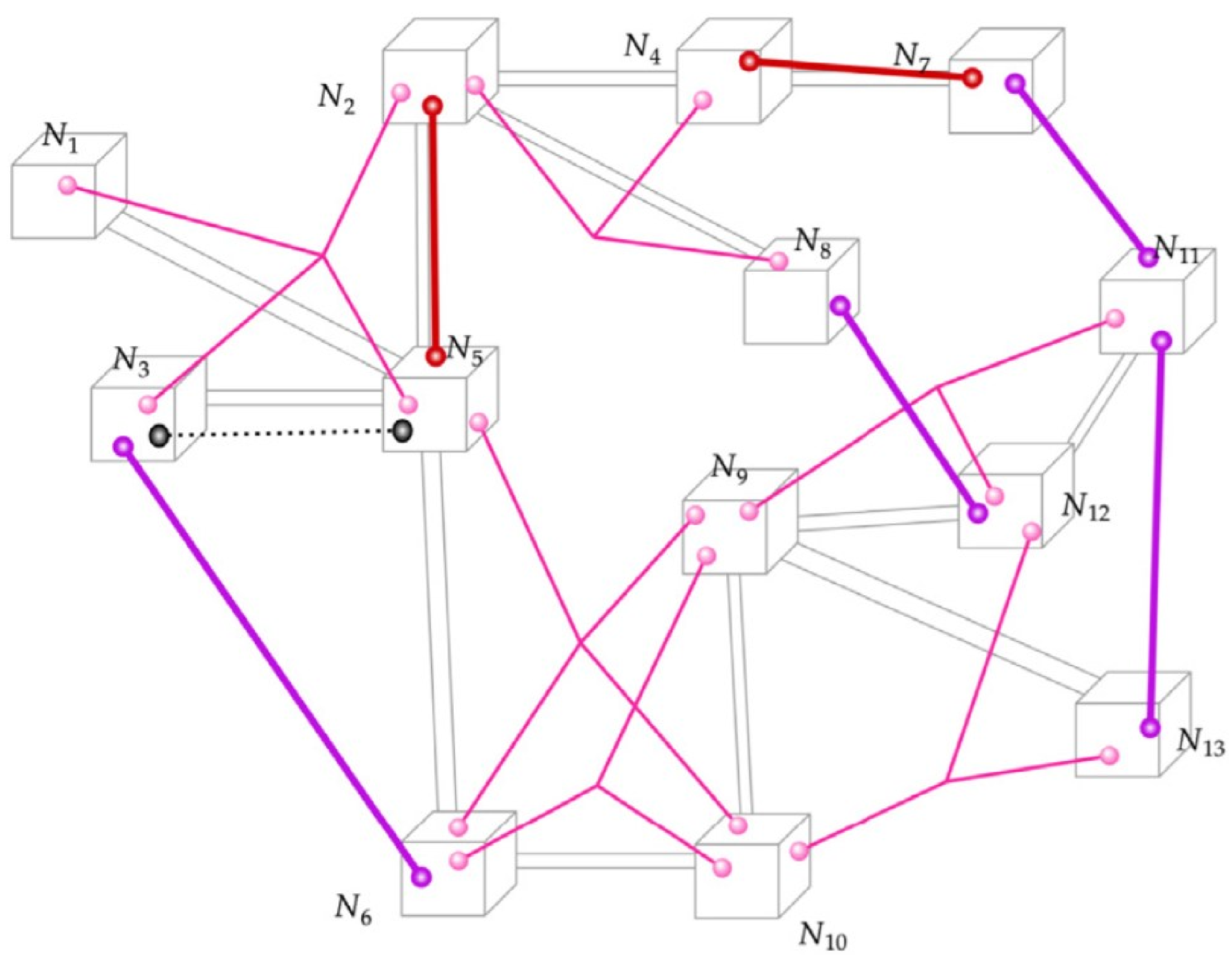
Total fiber distance between Delft and Eindhoven of **226.5** km



Avis, Guus, et al. "Requirements for a processing-node quantum repeater on a real-world fiber grid." NPJ Quantum Information 9.1 (2023): 100.

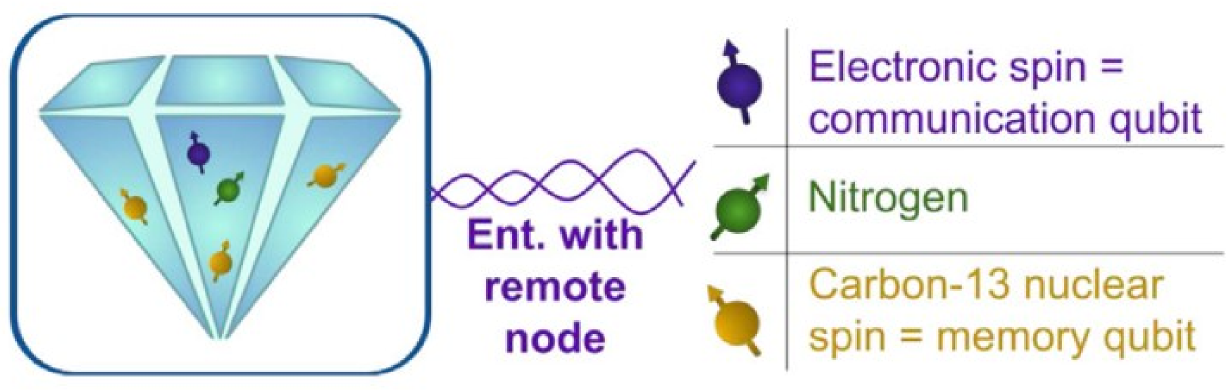
Quantum Internet

- Like classical internet, quantum internet (QI) allows for information exchange between nodes.
  - QI extends CI to allow joint quantum information processing
  - Physical links: channels established to exchange classical messages
  - **Virtual links**: shared **entangled states** between the nodes



Illiano, Jessica, et al. "Quantum internet protocol stack: A comprehensive survey." Computer Networks 213 (2022): 109092.

Quantum Internet Nodes



(a) the single-NV architecture

Heralded entanglement 1.3km

Mirrors and filters guide the laser beams to the diamond chip

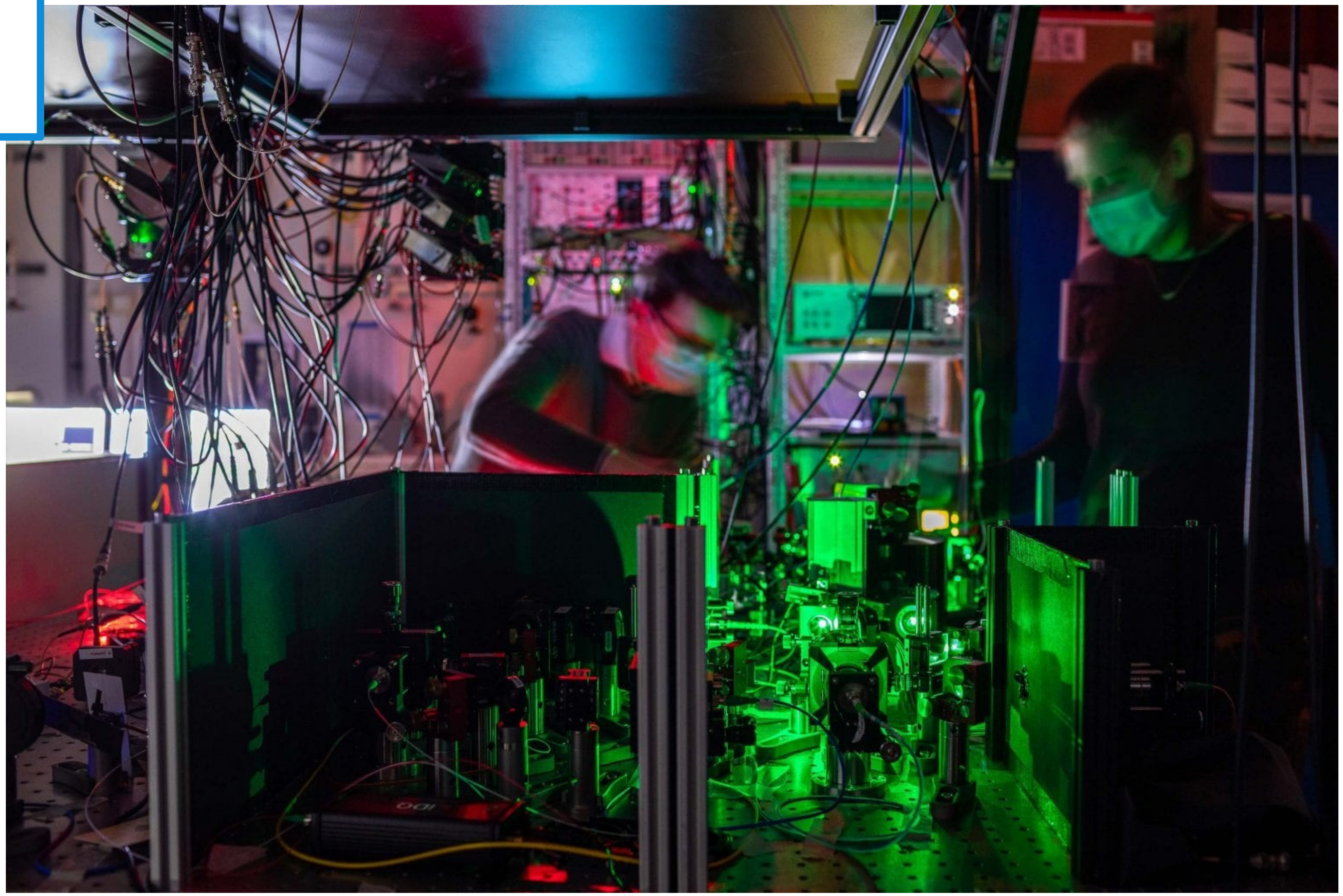
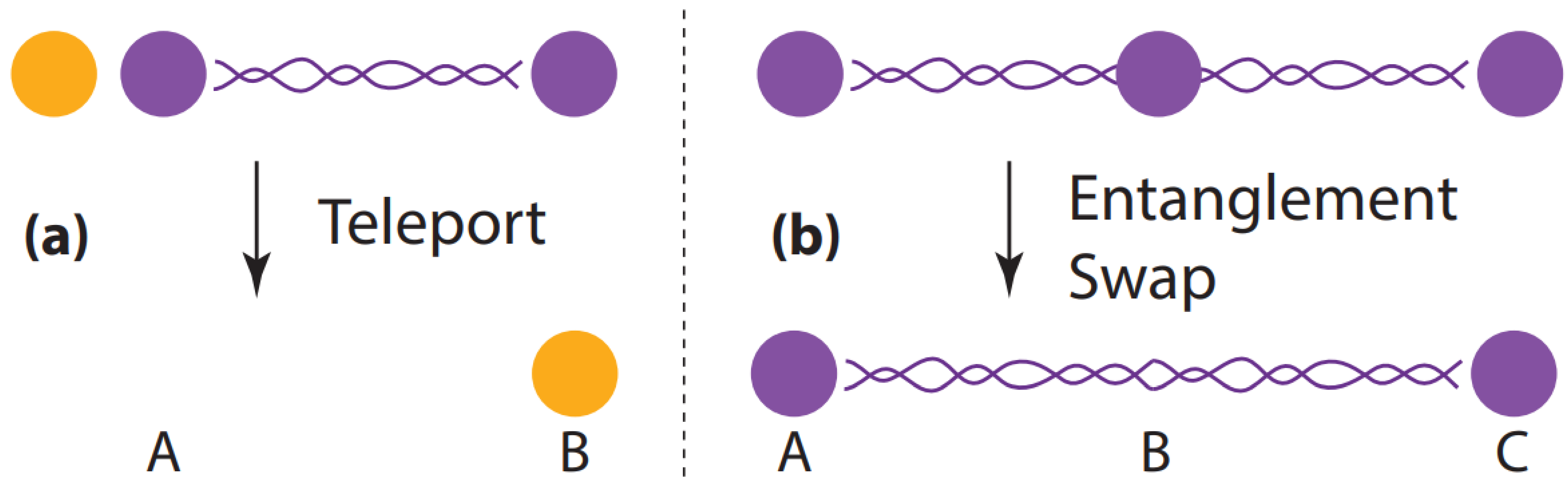


Photo by Marieke de Lorijn for QuTech

How to Distribute Entanglements?

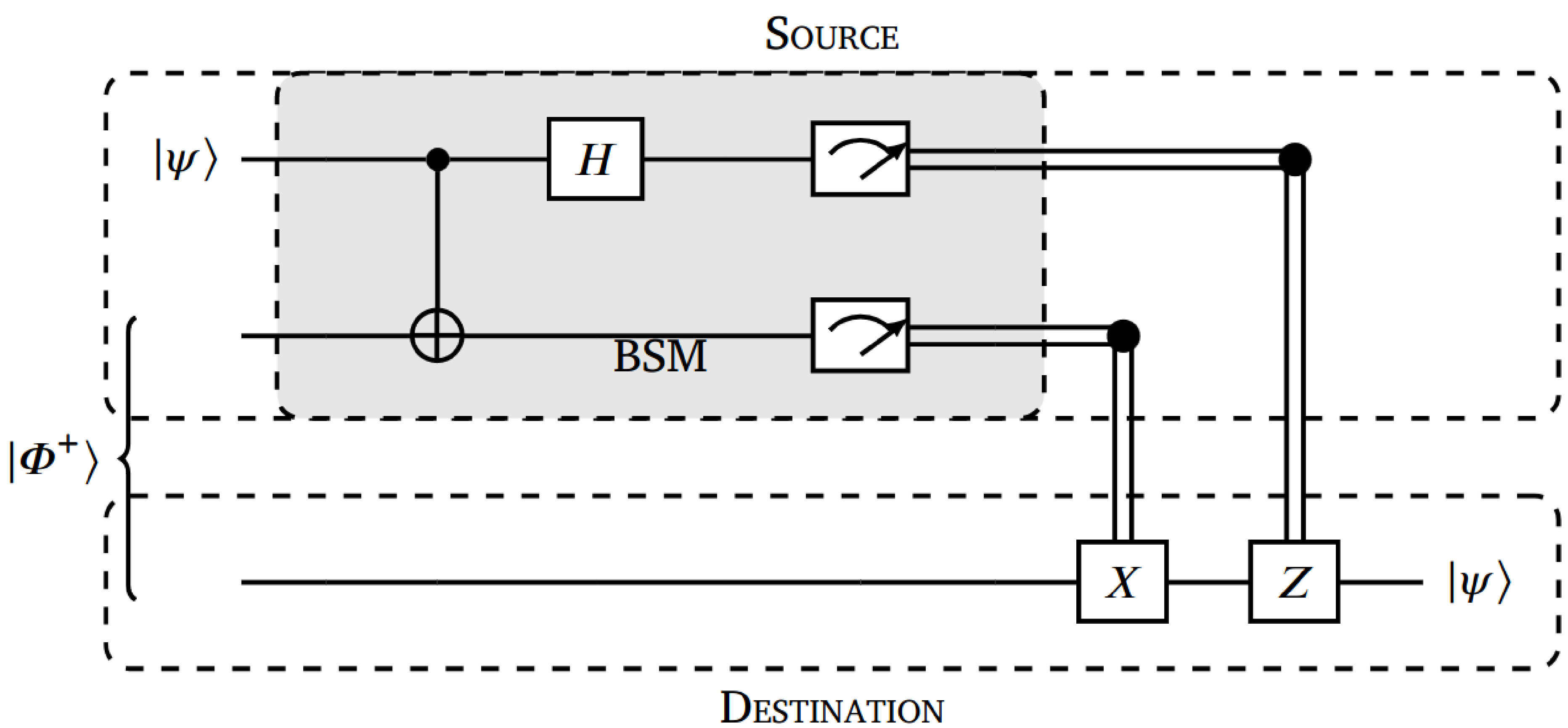


Quantum Teleportation

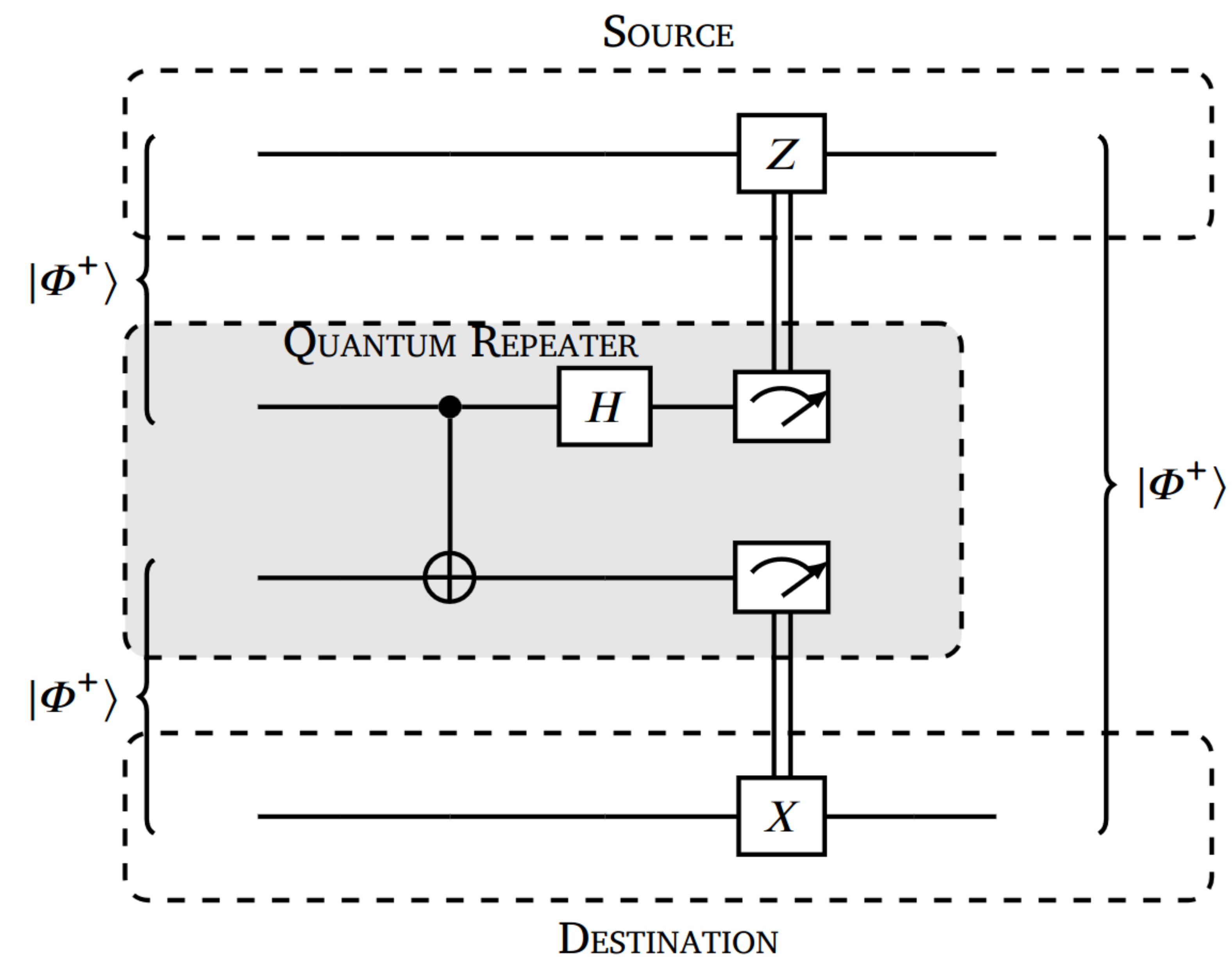
Entanglement Swapping

Dahlberg, Axel, Matthew Skrzypczyk, Tim Coopmans, Leon Wubben, Filip Rozpędek, Matteo Pompili, Arian Stolk et al. "A link layer protocol for quantum networks." In Proceedings of the ACM special interest group on data communication, pp. 159-173. 2019.

How to Distribute Entanglements?



Quantum Teleportation



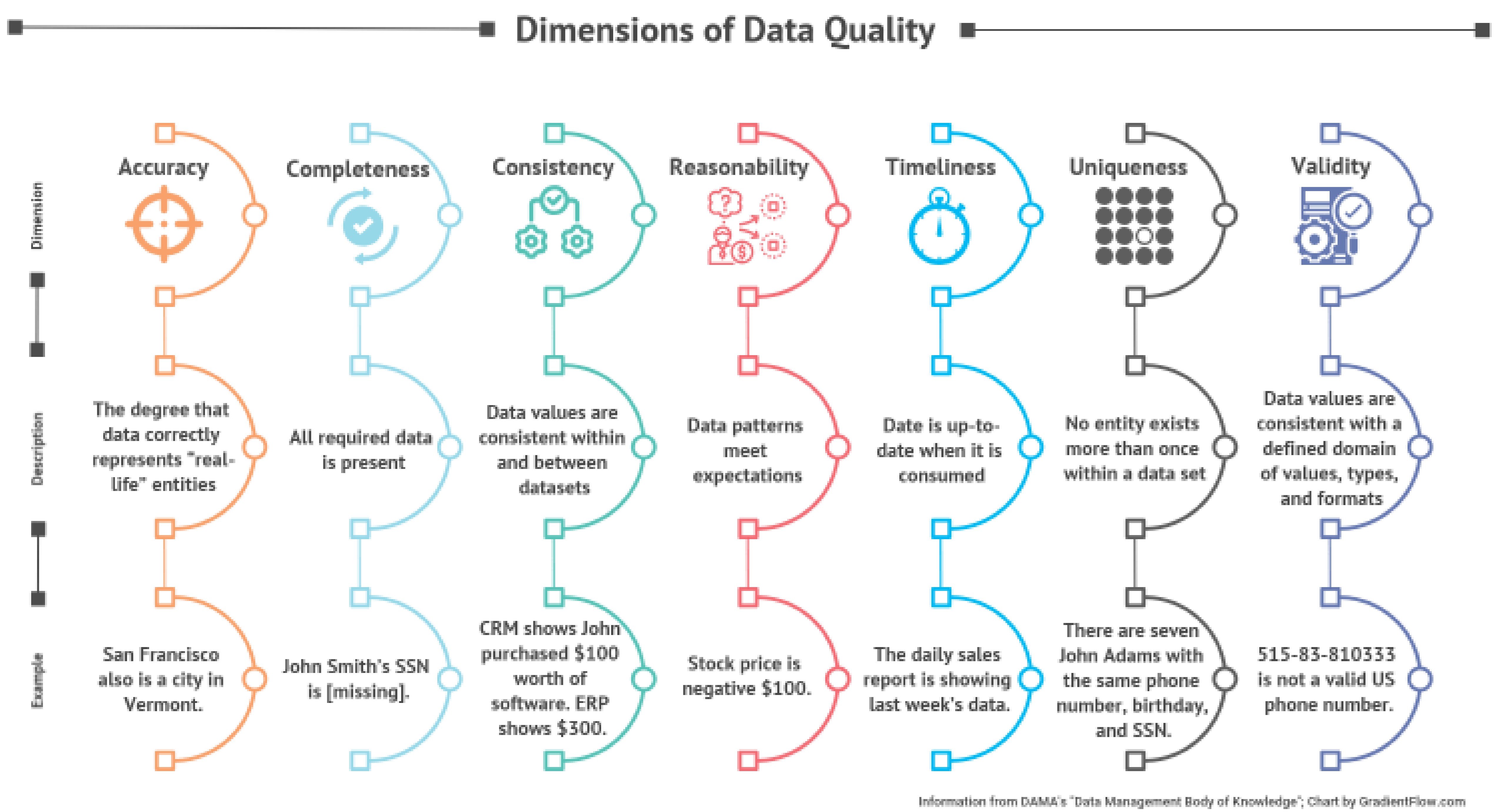
Entanglement Swapping

Illiano, Jessica, et al. "Quantum internet protocol stack: A comprehensive survey." Computer Networks 213 (2022): 109092.

Classical Analogy: Data Quality

- Definition

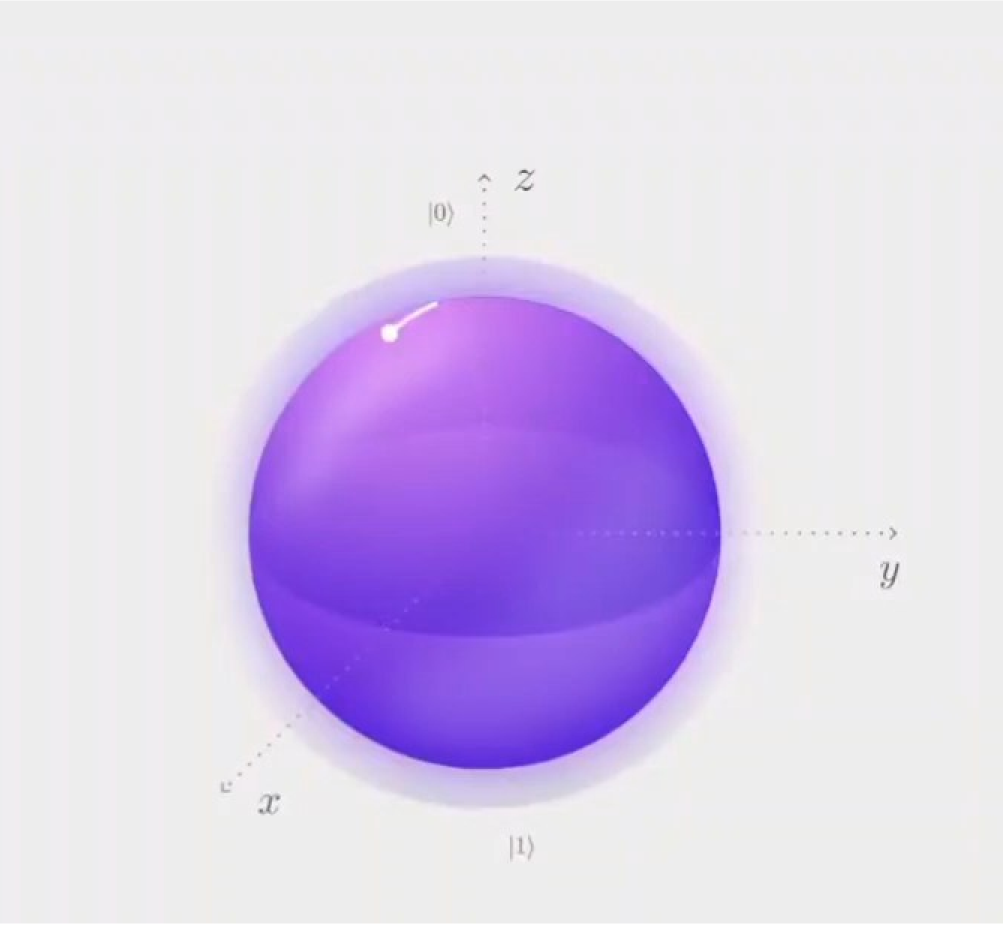
Data as a product: fitness for use [Redman, 1997]



Quantum Noise

- Quantum noise makes it hard to extract information from a quantum computer

- Quantum noise results from unwanted coupling with the environment
  - Depolarizing
  - Bit & phase flipping
  - Amplitude & phase damping

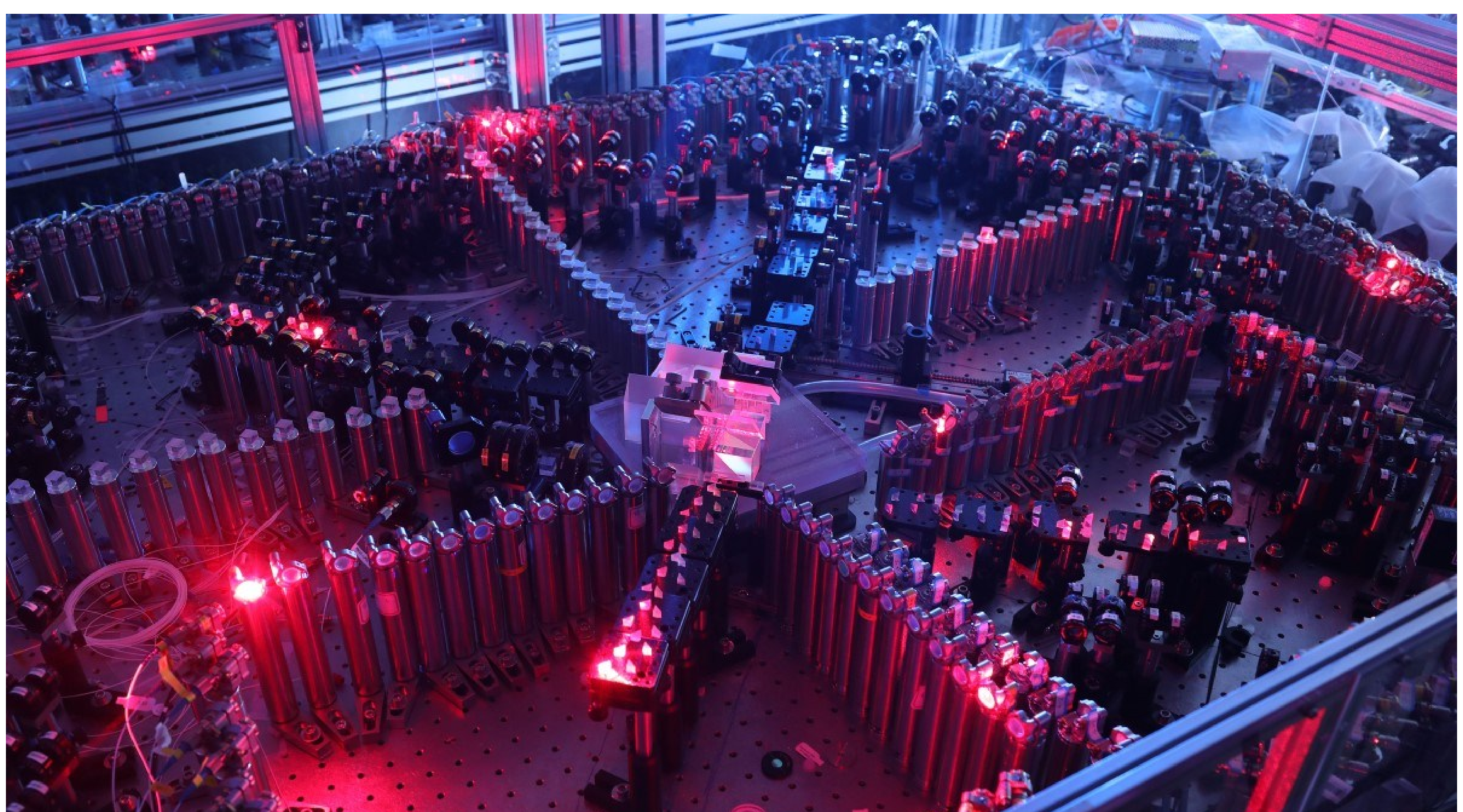


https://physicsworld.com/a/putting-quantum-noise-to-work/
https://www.youtube.com/watch?v=AUAkoEiutOE

Detect Incorrect Quantum Info Processing?

- We expect to only have **noisy intermediate-scale quantum (NISQ)** devices in the near future
  - Handle quantum noise by fixing or removing corruption of quantum data?
  - Detect incorrect quantum operations
  - Generate robust entanglements

Google's Sycamore

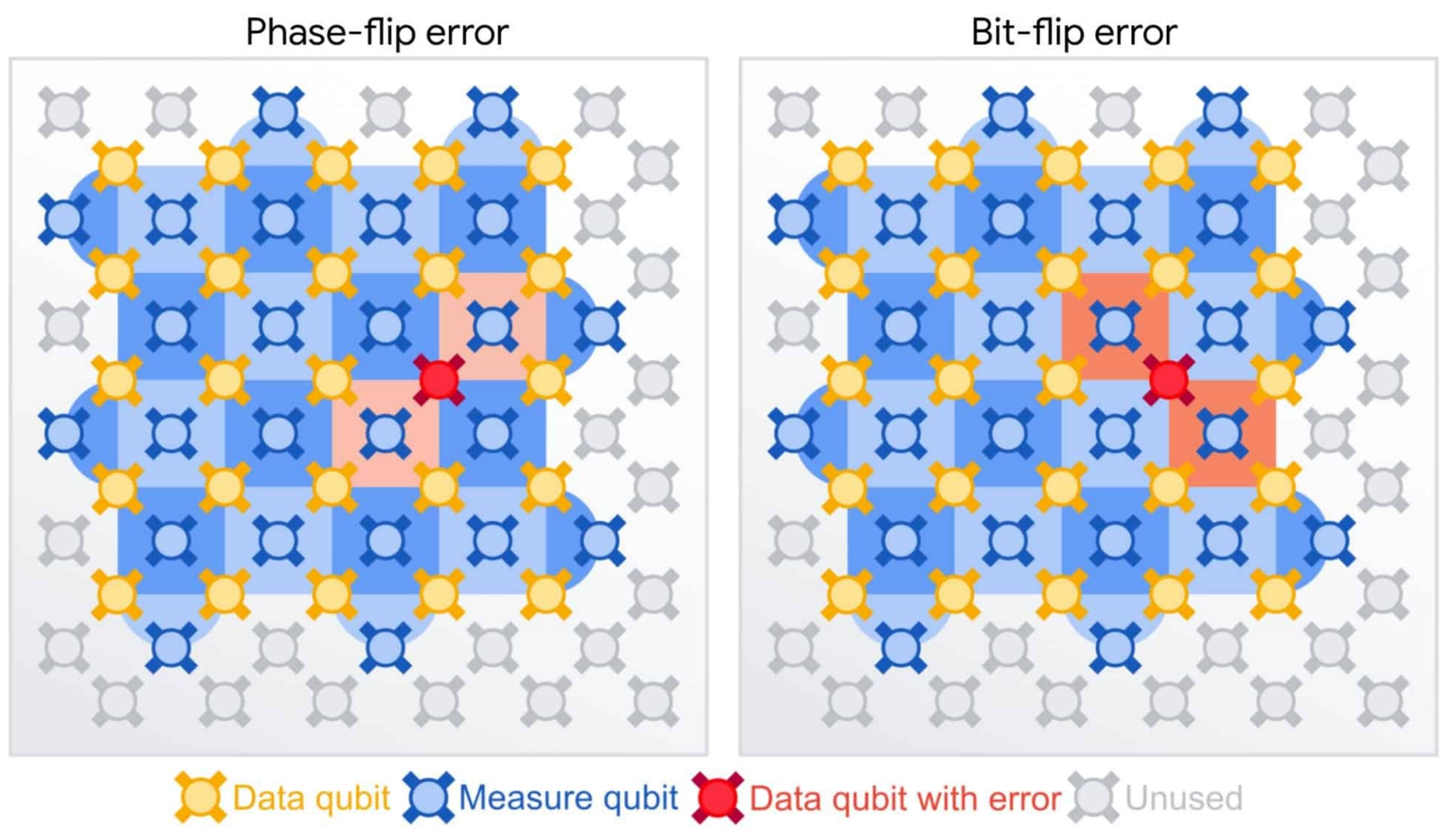


USTC's Jiuzhang

research.google/blog/suppressing-quantum-errors-by-scaling-a-surface-code-logical-qubit/

Error correction

- High noise levels make extensive error correction protocols necessary



What does Quantum Internet Give?

- Full-fledged quantum internet seems necessary for multiparty quantum computation

- Seems a good way to avoid the **synchronous problem**?
  - Einstein–Podolsky–Rosen (EPR) paradox

- Entanglements enhance data integrity
  - Nonlocal games are useful to detect **information leakage** and **incorrect operations,** e.g., quantum key distribution (impossible classically)
  - Enhance security of communication impossible by purely classical means

Beyond the Binary Alphabet

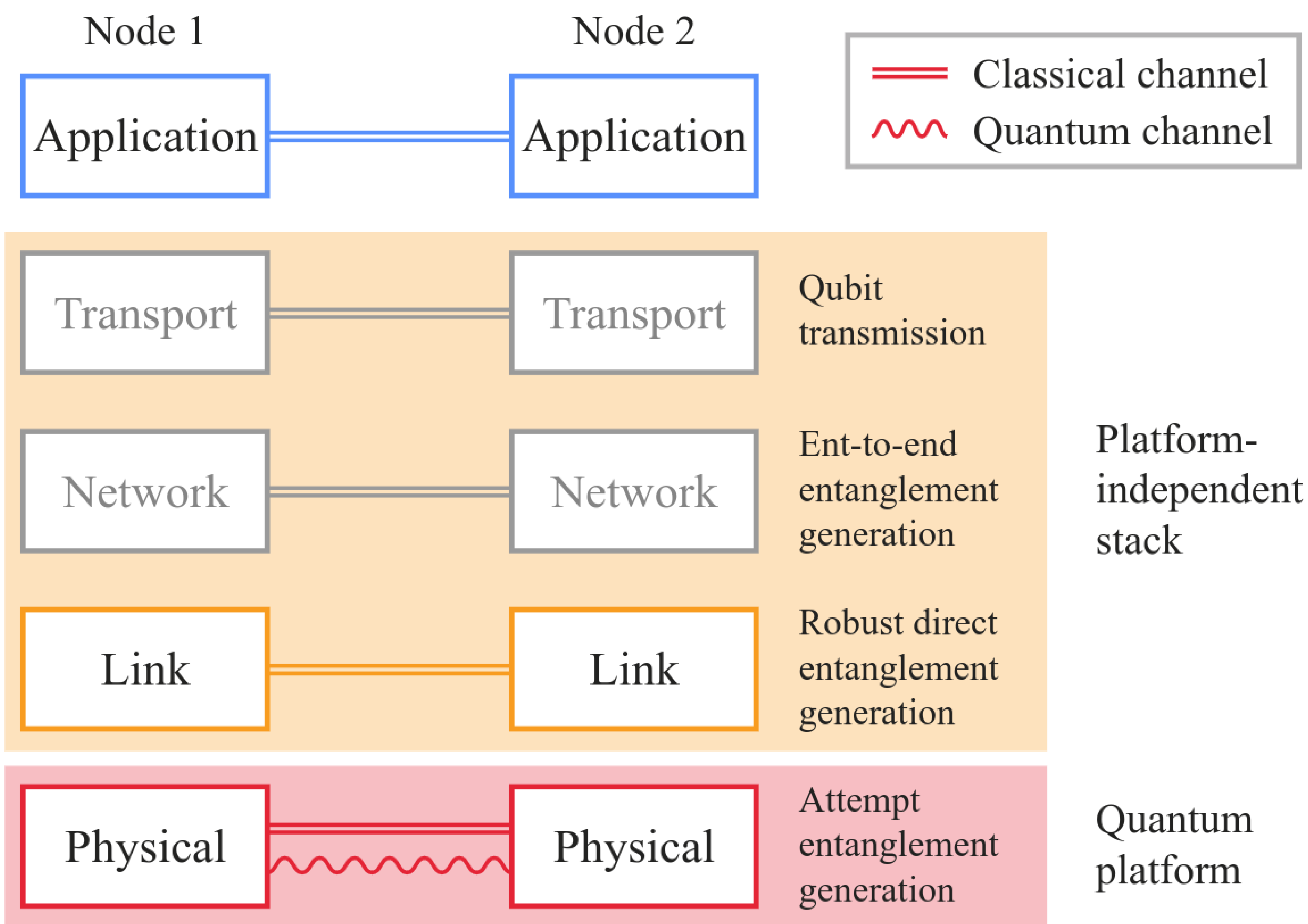
For data management, it is essential to consider the space of data beyond binary strings.

- The tests may be generalized to "qudits," which takes values from an alphabet of size $d>2$ (as opposed to $\{0,1\}$).

pname	gender	age	resting HR	mortality
Alice	0	96	60	0
Bob	1	35	70	1
Charlie	1	22	65	1

Quantum Internet Protocol Stacks

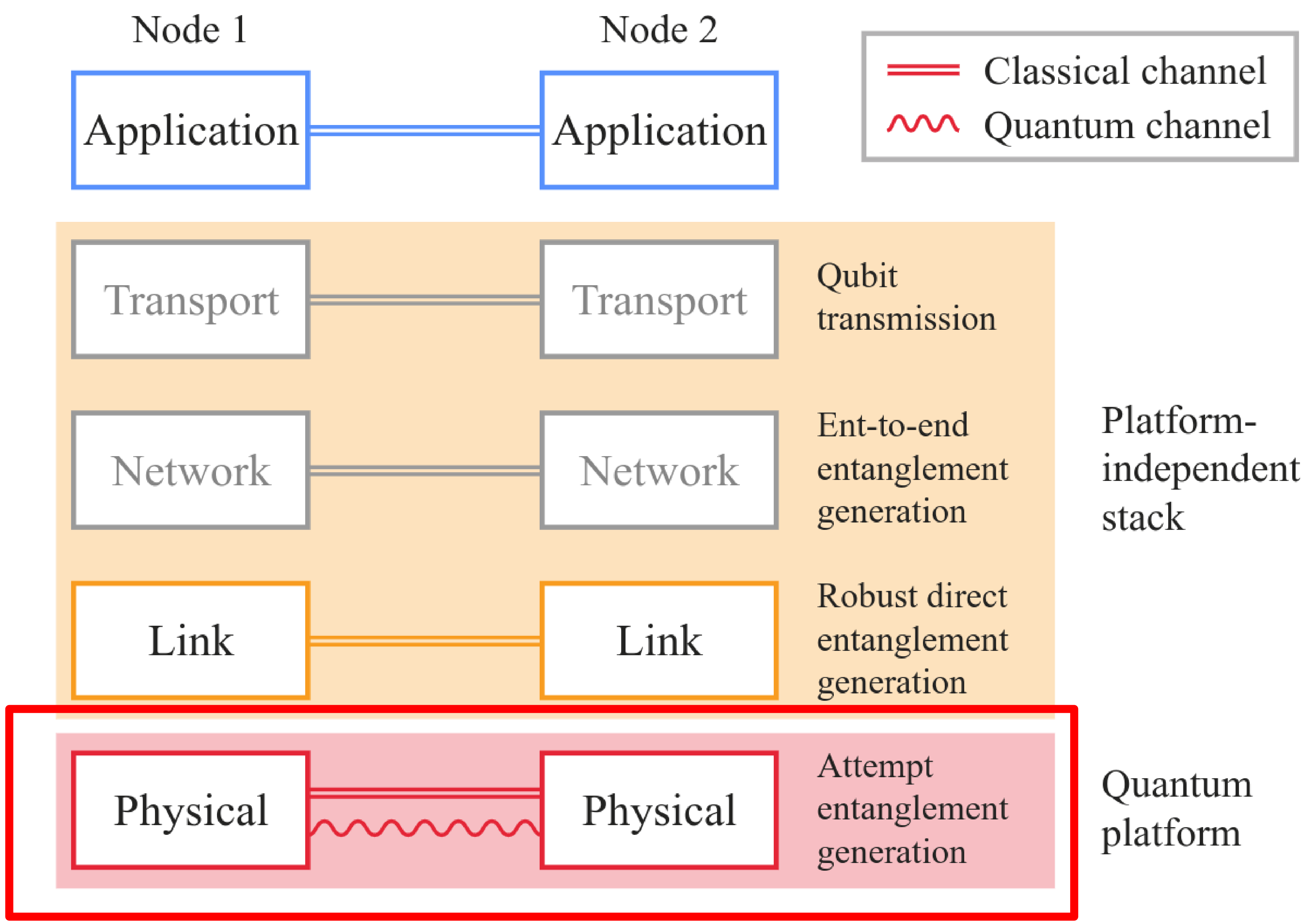
Protocols for scheduling the generation and distribution of quantum entanglements in a quantum network



Pompili, Matteo, et al. "Experimental demonstration of entanglement delivery using a quantum network stack." npj Quantum Information 8.1 (2022): 121.

Quantum Internet Protocol Stacks

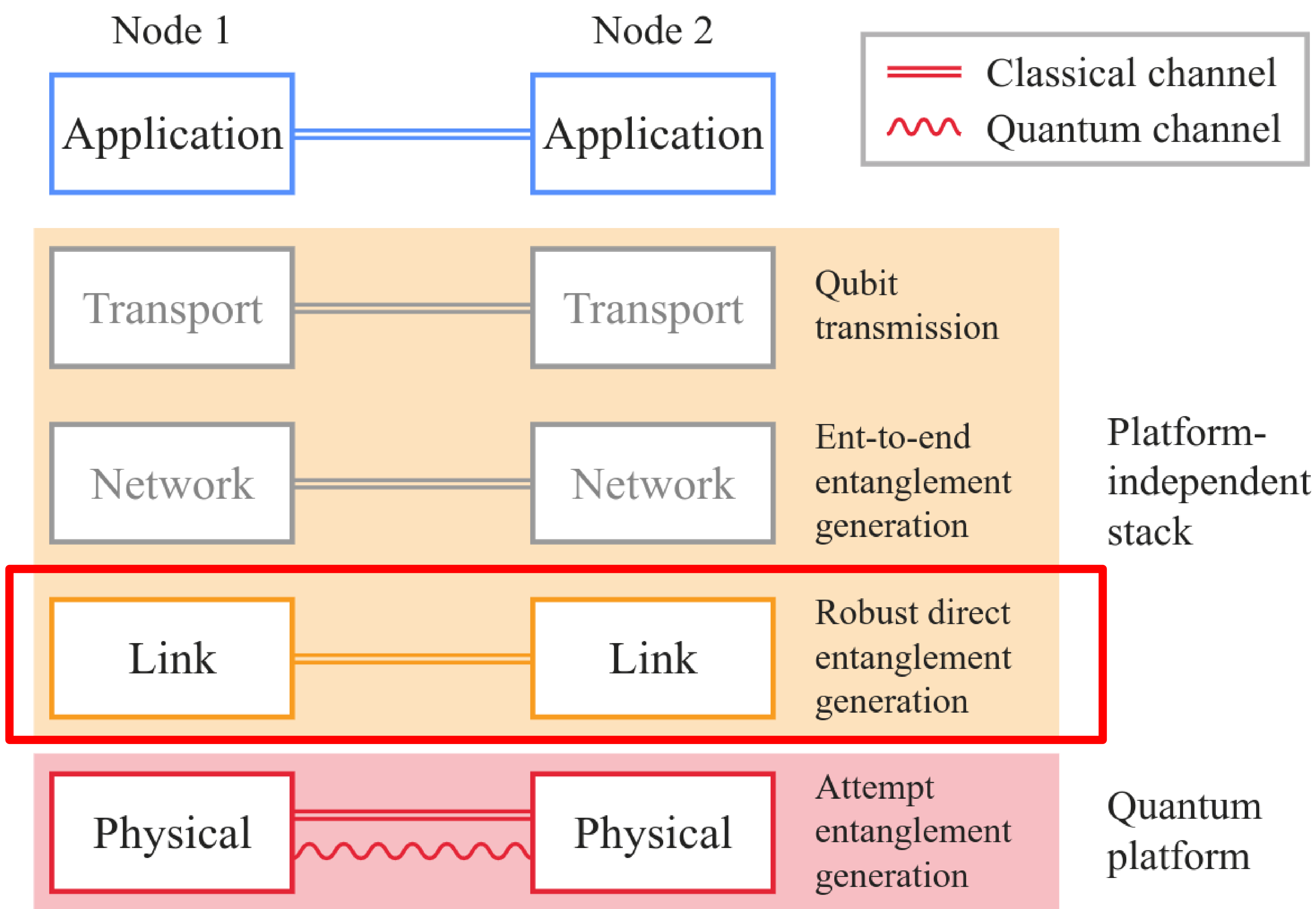
Protocols for scheduling the generation and distribution of quantum entanglements in a quantum network



The **Physical Layer** attempts to generate entanglements between two nodes in a well-defined time slot.

Quantum Internet Protocol Stacks

Protocols for scheduling the generation and distribution of quantum entanglements in a quantum network

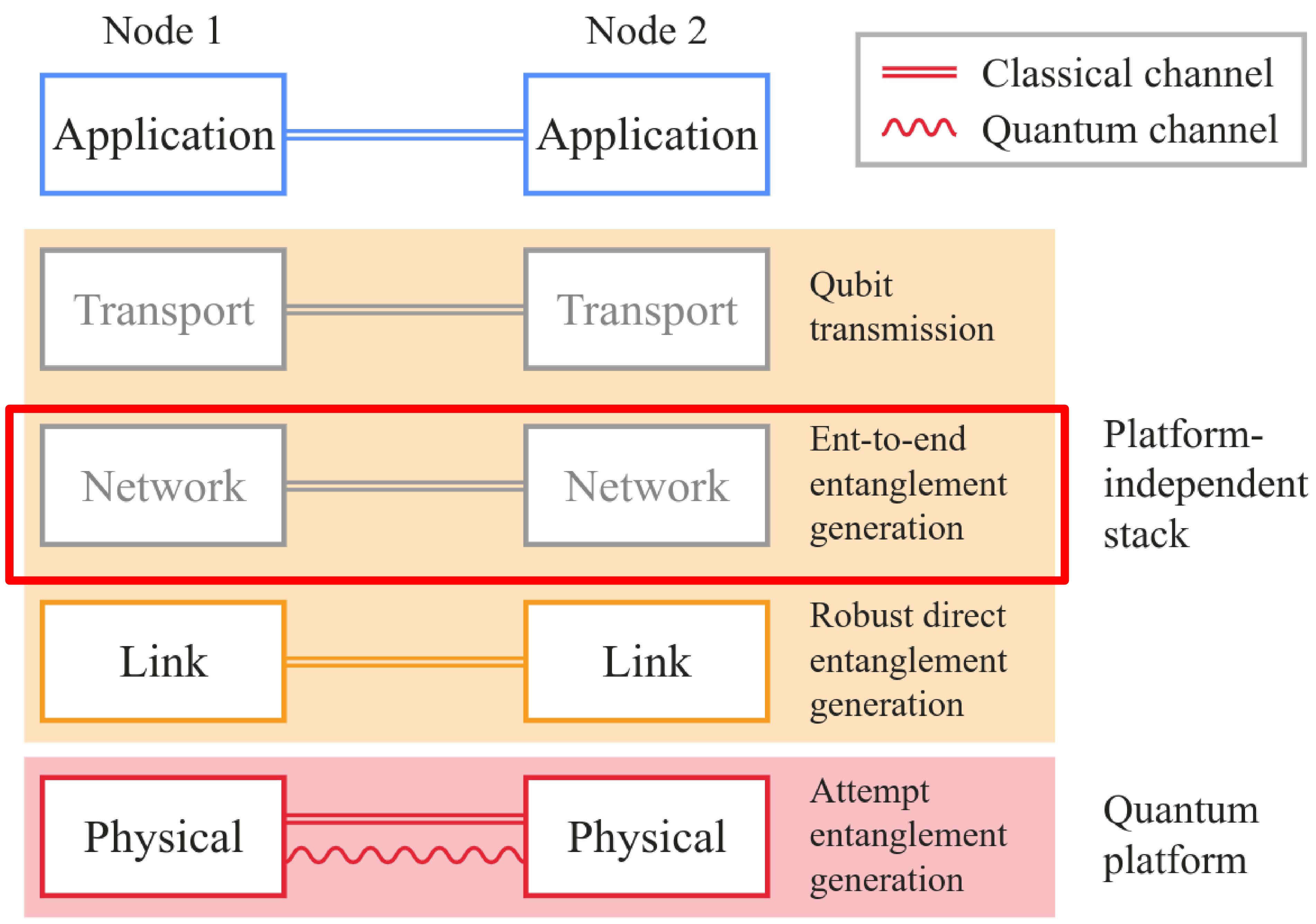


The **Link Layer** manages to generate robust entanglements:

- Receives generation requests
- Perform fidelity evaluation
- Scheduling generation

Quantum Internet Protocol Stacks

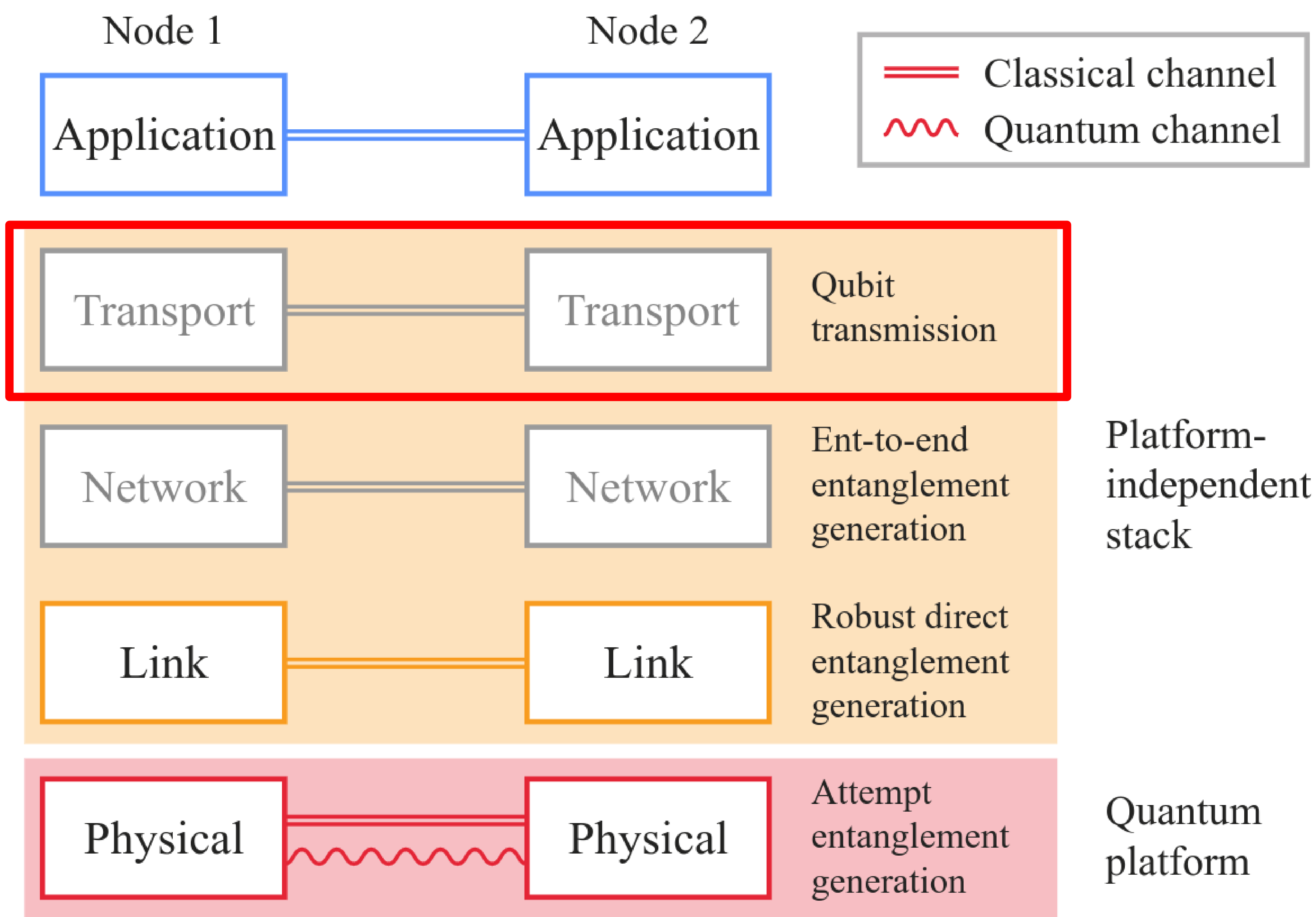
Protocols for scheduling the generation and distribution of quantum entanglements in a quantum network



The **Network Layer** is for producing long-distance entanglements using functionalities provided by the link layer.

Quantum Internet Protocol Stacks

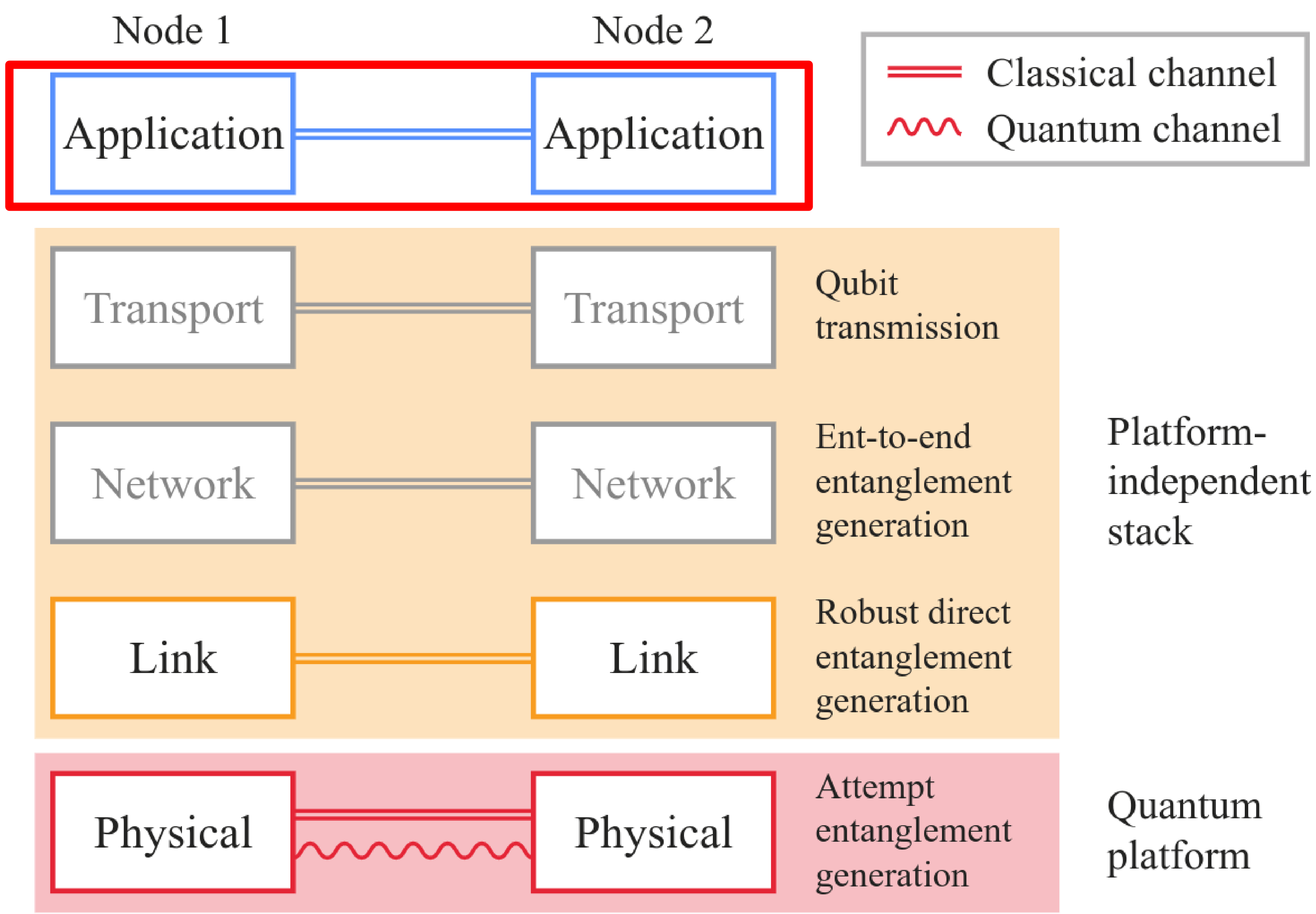
Protocols for scheduling the generation and distribution of quantum entanglements in a quantum network



The **Transport Layer** transmits qubits by using the teleportation process.

Quantum Internet Protocol Stacks

Protocols for scheduling the generation and distribution of quantum entanglements in a quantum network



The **Application Layer** controls the network abstractly to distribute quantum information and to perform joint quantum computation.

Q&A

- What challenge do you want to tackle in the NISQ era?

Quantum Computer

Quantum Internet

References

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3. Tim Bittner and Sven Groppe, “Hardware accelerating the optimization of transaction schedules via quantum annealing by avoiding blocking, OJCC’20.
4. S. Groppe and J. Groppe, “Optimizing transaction schedules on universal quantum computers via code generation for grover’s search algorithm, IDEAS’21.
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6. G. Yuan, et al. "Quantum Computing for Databases: A Short Survey and Vision." Joint Workshops at 49th International Conference on Very Large Data Bases (VLDBW’23)—International Workshop on Quantum Data Science and Management (QDSM’23). 2023.