Quantum Algorithms for Distributed Quantum Computing

Ioannis Lavdas

Quantum Algorithm R&D division

EDF-Teratec TQCI conference

14 November 2024

Outline

Distributed Quantum Computing

Outline

Algorithm Partitioning

Distributed Quantum Computing

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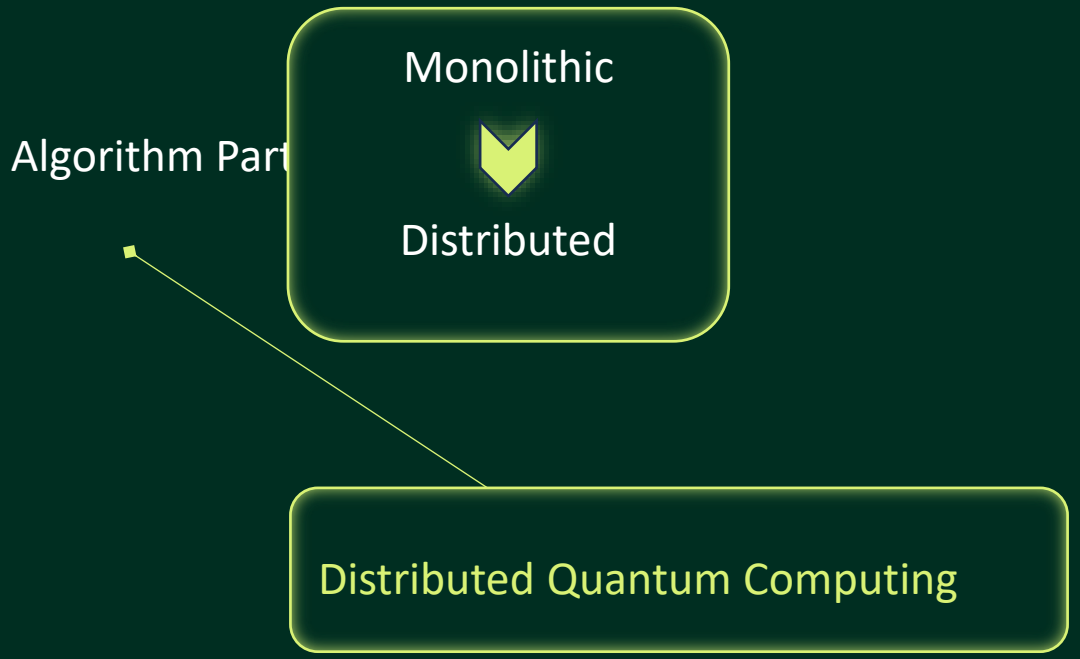
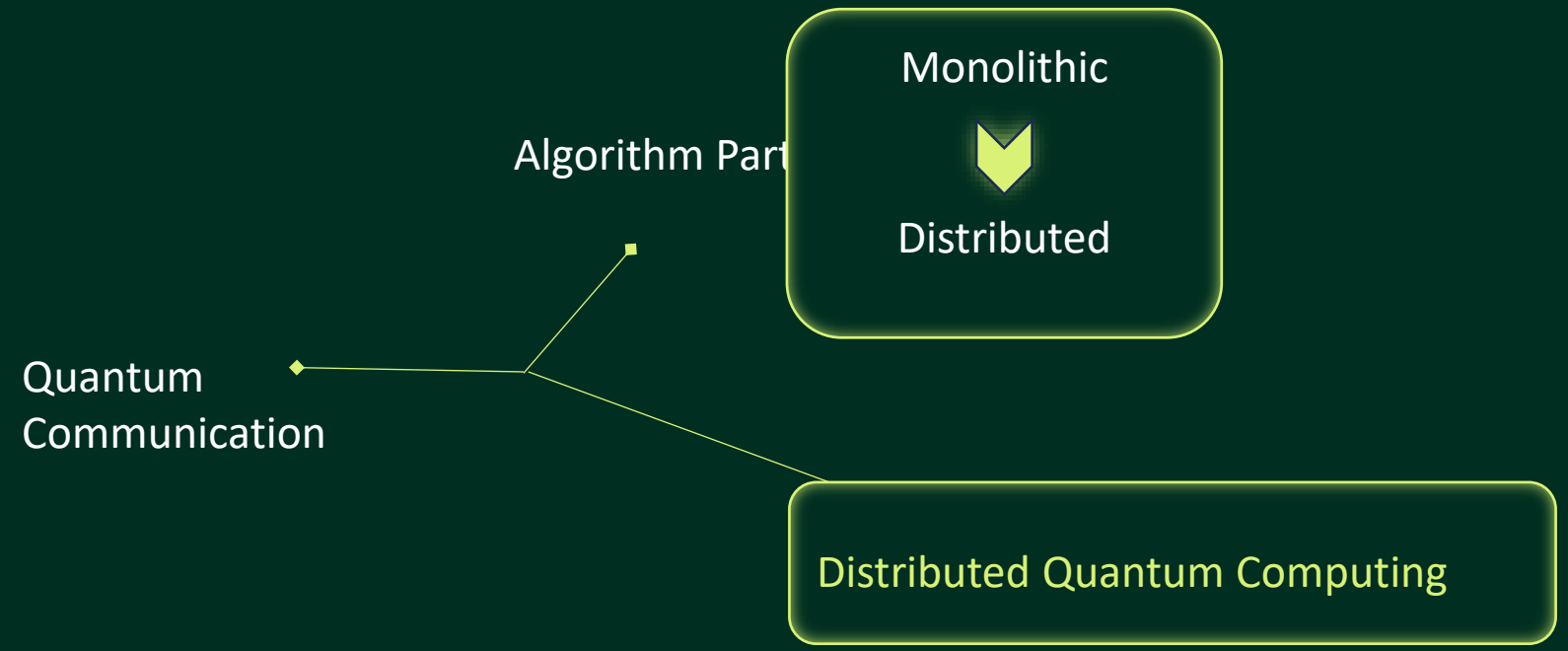

Monolithic
Algorithm Part
Distributed
Distributed Quantum Computing

Outline


Monolithic
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Quantum
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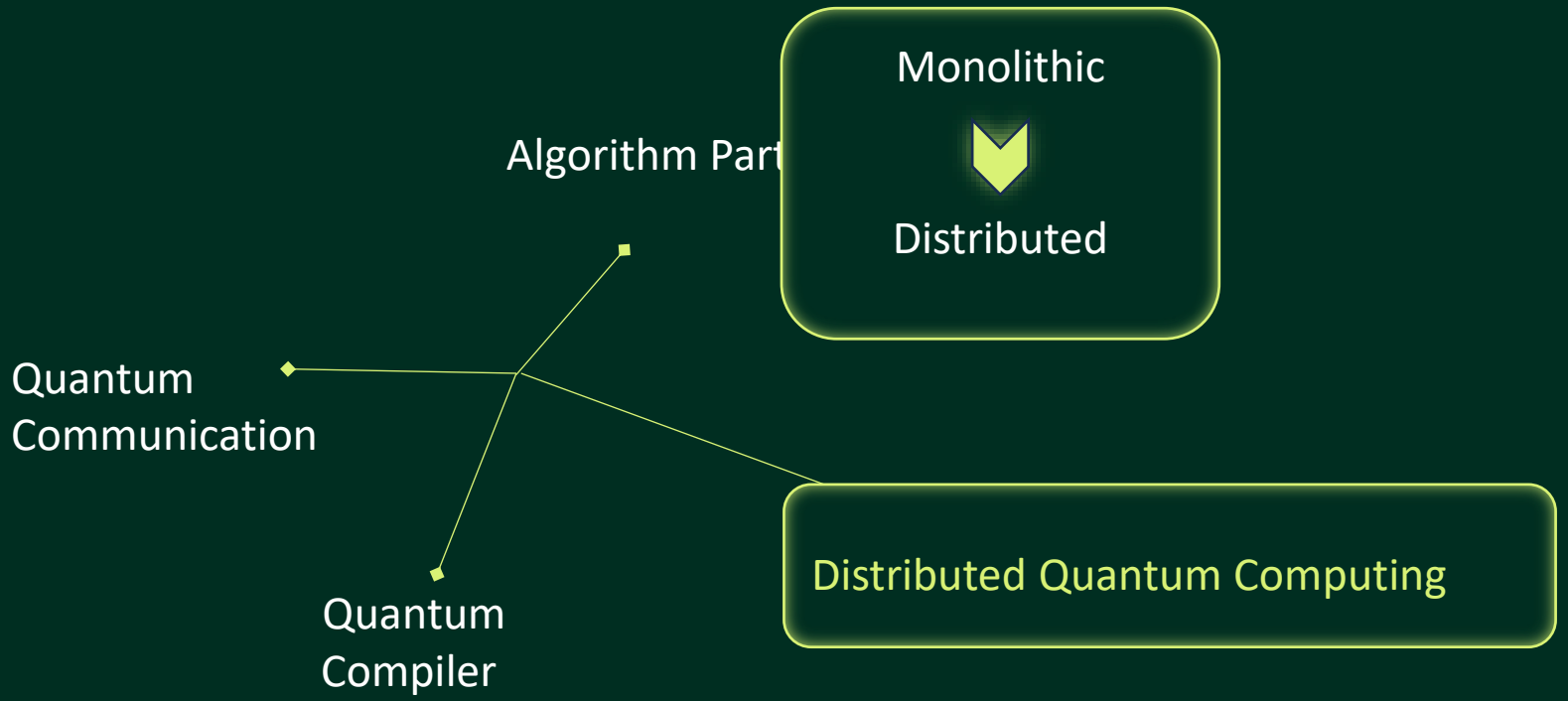
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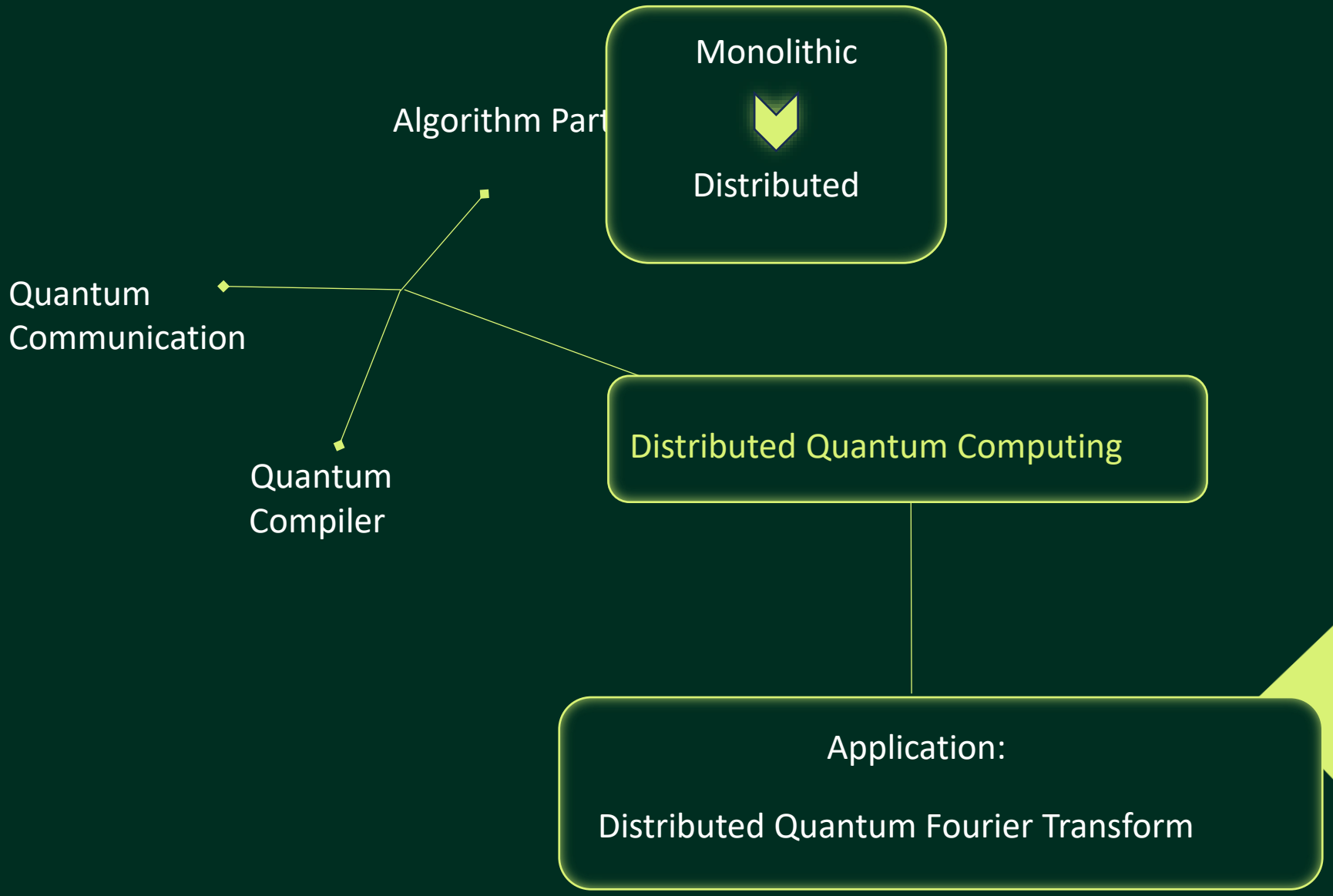
Monolithic
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Application:
Distributed Quantum Fourier Transform

Distributed Quantum Computing

Quantum advantage on real world applications

Demand for large-scale QC

Large qubit number

vs.

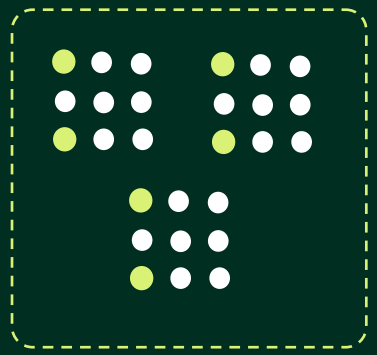
Performance factors

Distributed Quantum Computing:

- Viable path to *scalability*
- Quantum communication via entanglement

Distributed Quantum Algorithms

Distributed Quantum Architectures (DQA)



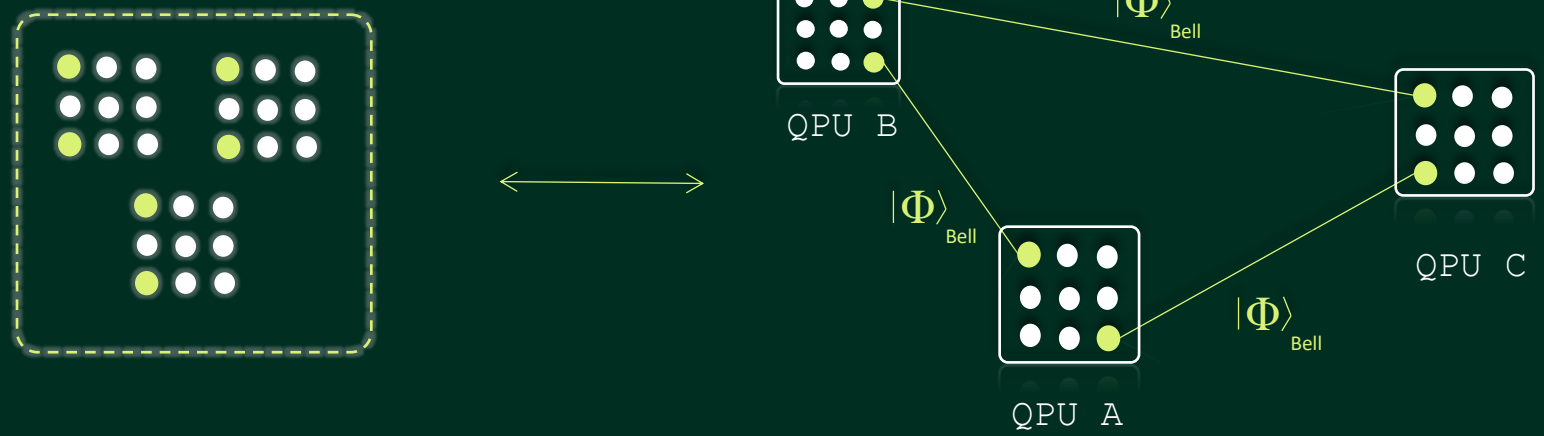
- Emulating large quantum computers as networks of ***interconnected*** smaller quantum computers

Quantum Processing Unit (QPU)

Qubits distinguished into two sets:

- **Data** qubits ( ) for ***processing***
- **Communication** qubits ( ) for ***interconnection***

Distributed Quantum Architectures (DQA)



- Emulating large quantum computers as networks of ***interconnected*** smaller quantum computers
- Algorithms demanding large number of qubits are ***partitioned***, with its fragments executed on QPUs of smaller qubit capacity, constituting a ***quantum network***
- How is algorithm distribution implemented & optimized..?

Quantum Processing Unit (QPU)

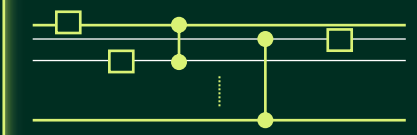
Qubits distinguished into two sets:

- **Data** qubits ( ) for ***processing***
- **Communication** qubits (●) for ***interconnection***

Quantum Channels (⟷) set by distributing entanglement (links/ Bell pairs $|\Phi\rangle_{Bell}$) over communication qubits

Quantum Algorithm

Quantum Algorithm partitions

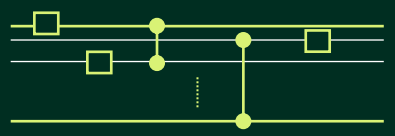


Quantum Circuit

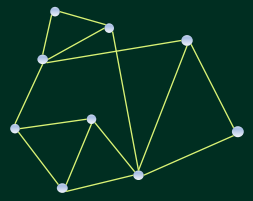
$$\mathcal{C}(q_i, U_{ij})$$

Quantum Algorithm

Quantum Algorithm partitions



Mapping



Quantum Circuit

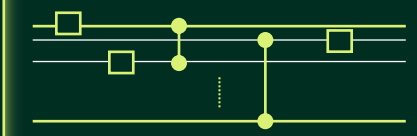
Graph

$\mathcal{C}(q_i, U_{ij})$

$G(V, E)$

Quantum Algorithm

Quantum Algorithm partitions



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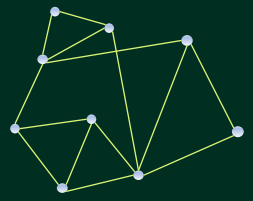
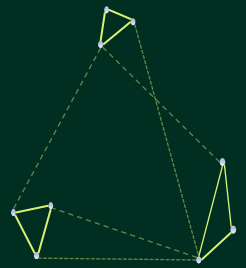


Partitioning



Quantum Circuit

Graph

Sub-graphs

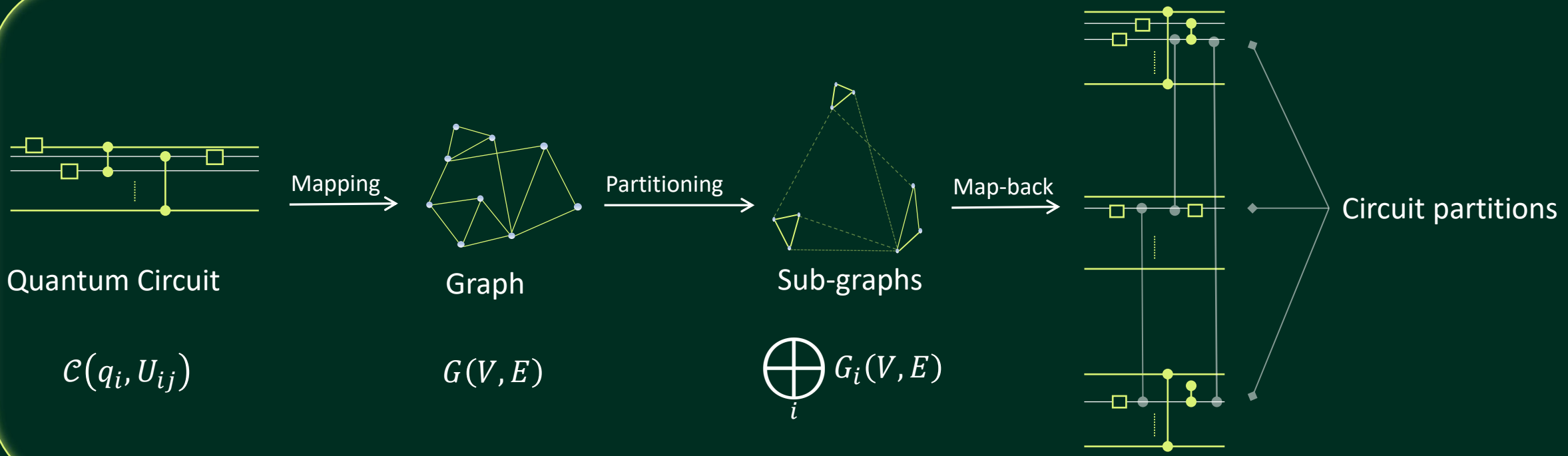
$\mathcal{C}(q_i, U_{ij})$

$G(V, E)$

$\bigoplus_i G_i(V, E)$

Quantum Algorithm

Quantum Algorithm partitions

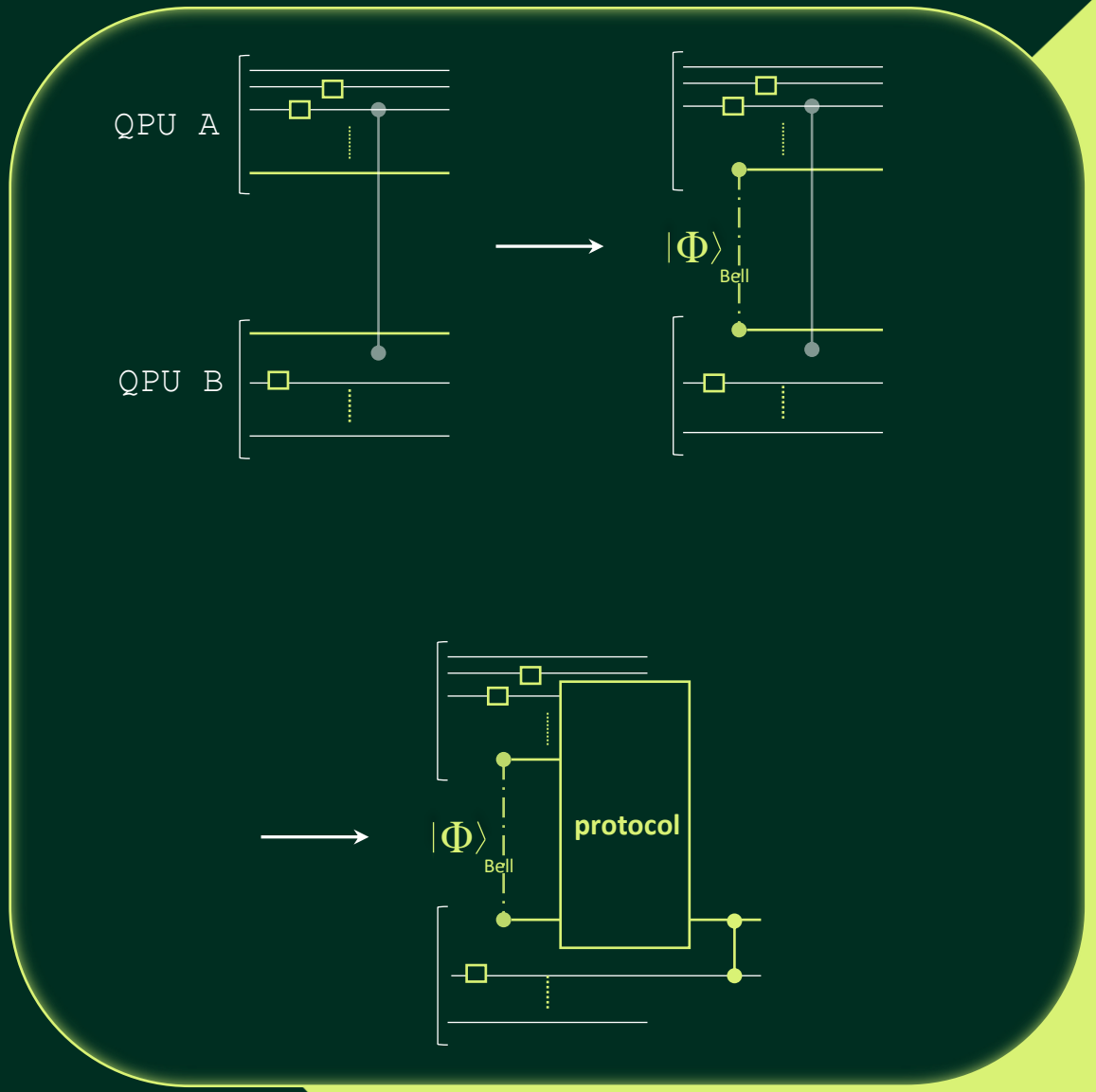


- How to implement non-local operations ( )?

Distribution Toolbox:
Quantum Communication protocols for interconnected QPUs via entaglement

- Optimal partitioning given QPU connectivity constraints?

Quantum Compiler


QPU A
QPU B
|Φ⟩
Bell
|Φ⟩
Bell
protocol

Distribution Toolbox

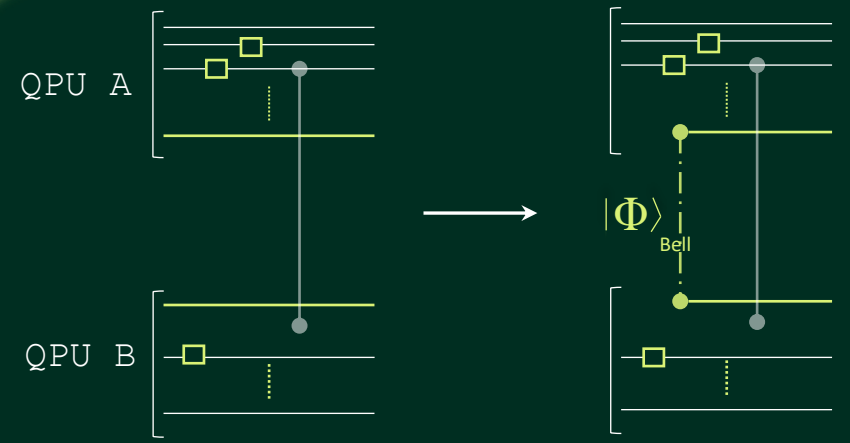
Quantum communication Protocols

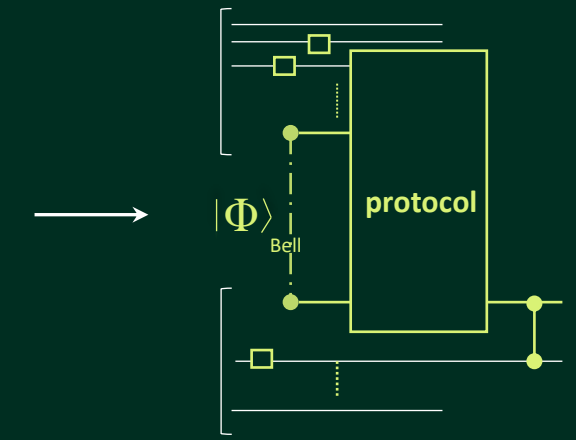
Introduce **quantum link** to interconnect & use **entanglement** to apply:

Communication **Primitives**

- `Teleport`

Communication ***Protocols***





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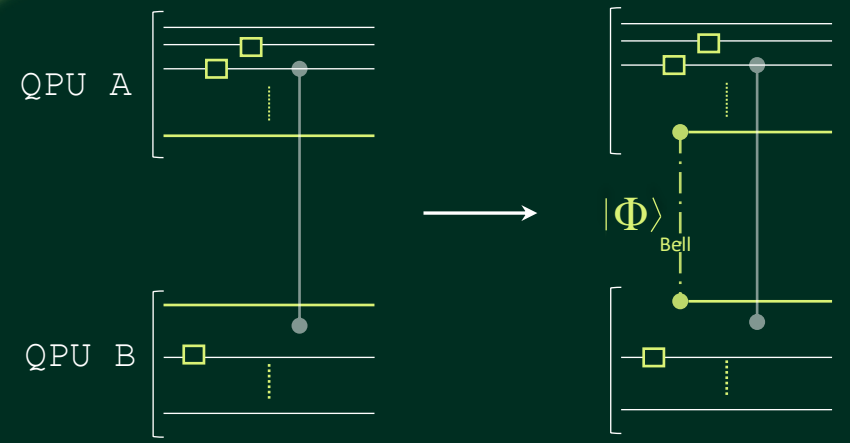

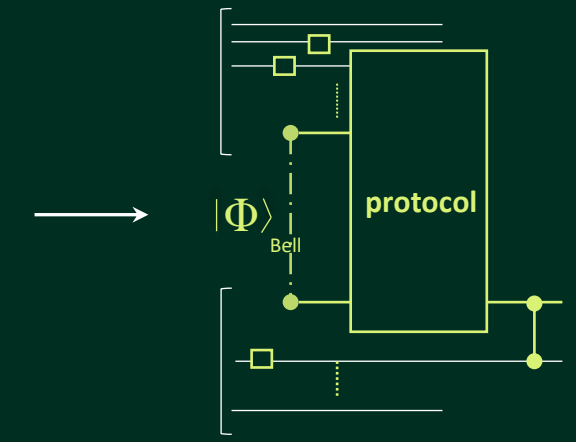

Distribution Toolbox

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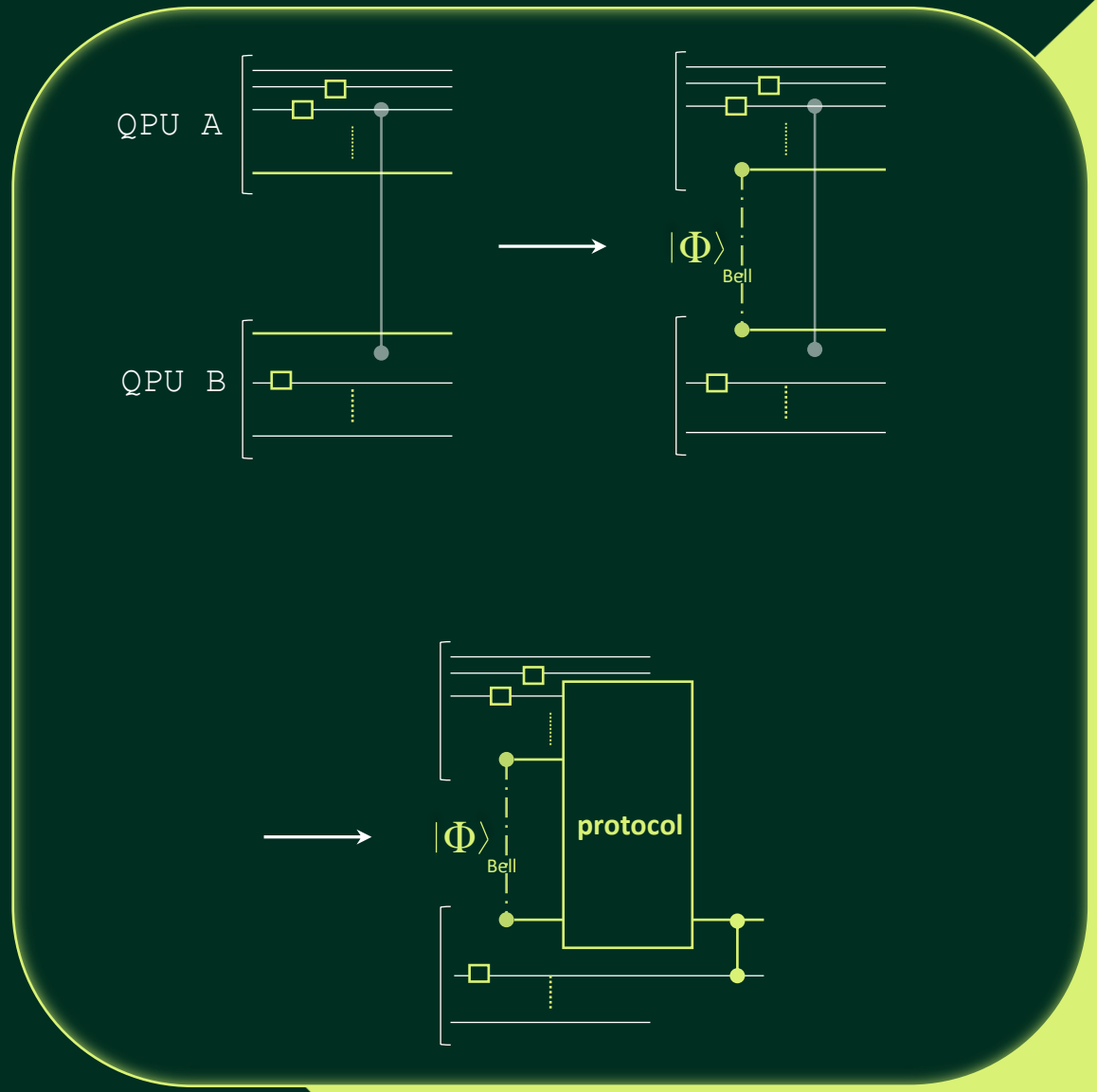
- `Cat-Entangler`
- `Cat-DisEntangler`

Communication ***Protocols***

- `TeleGate`
- `TeleData`



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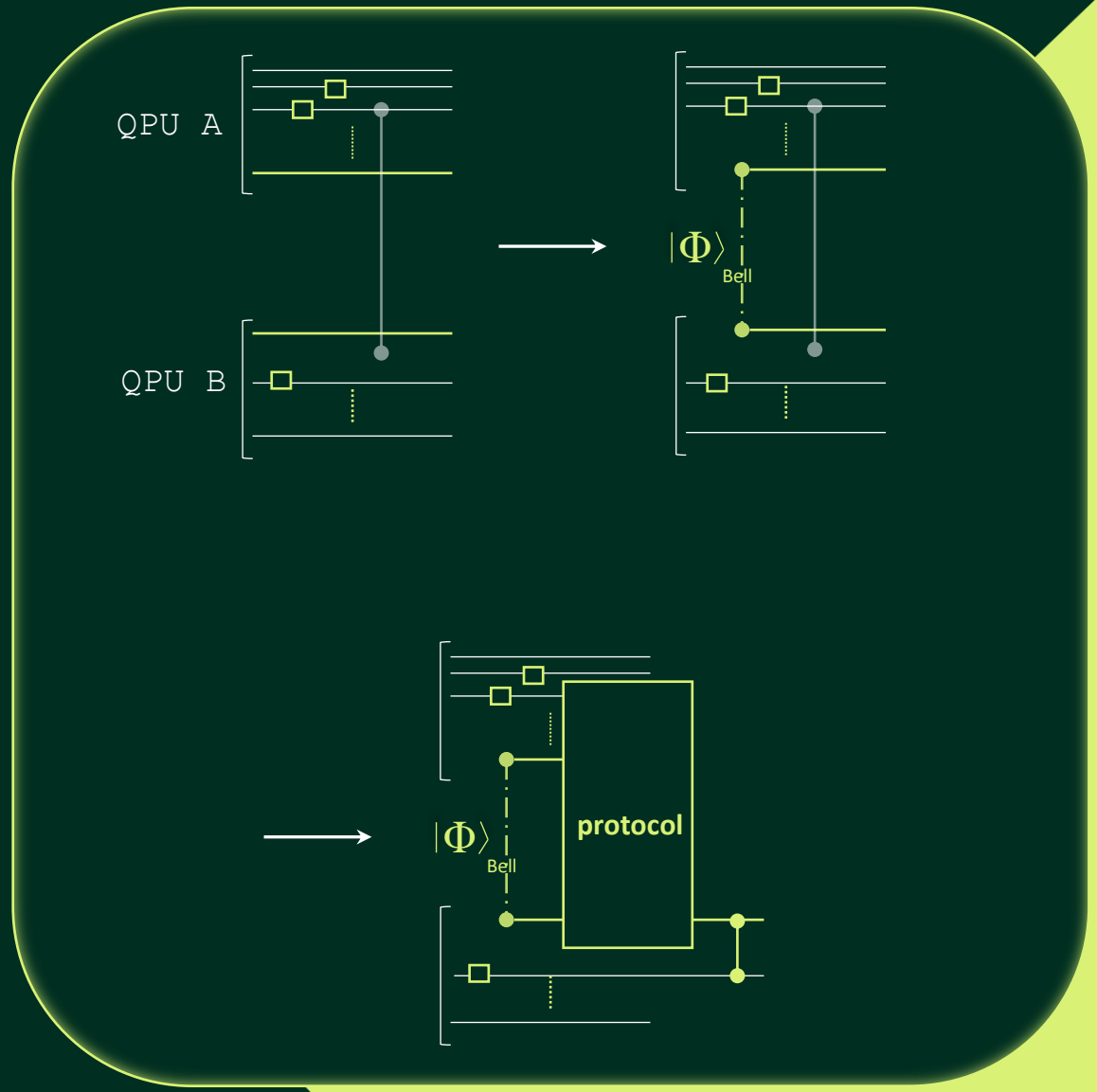


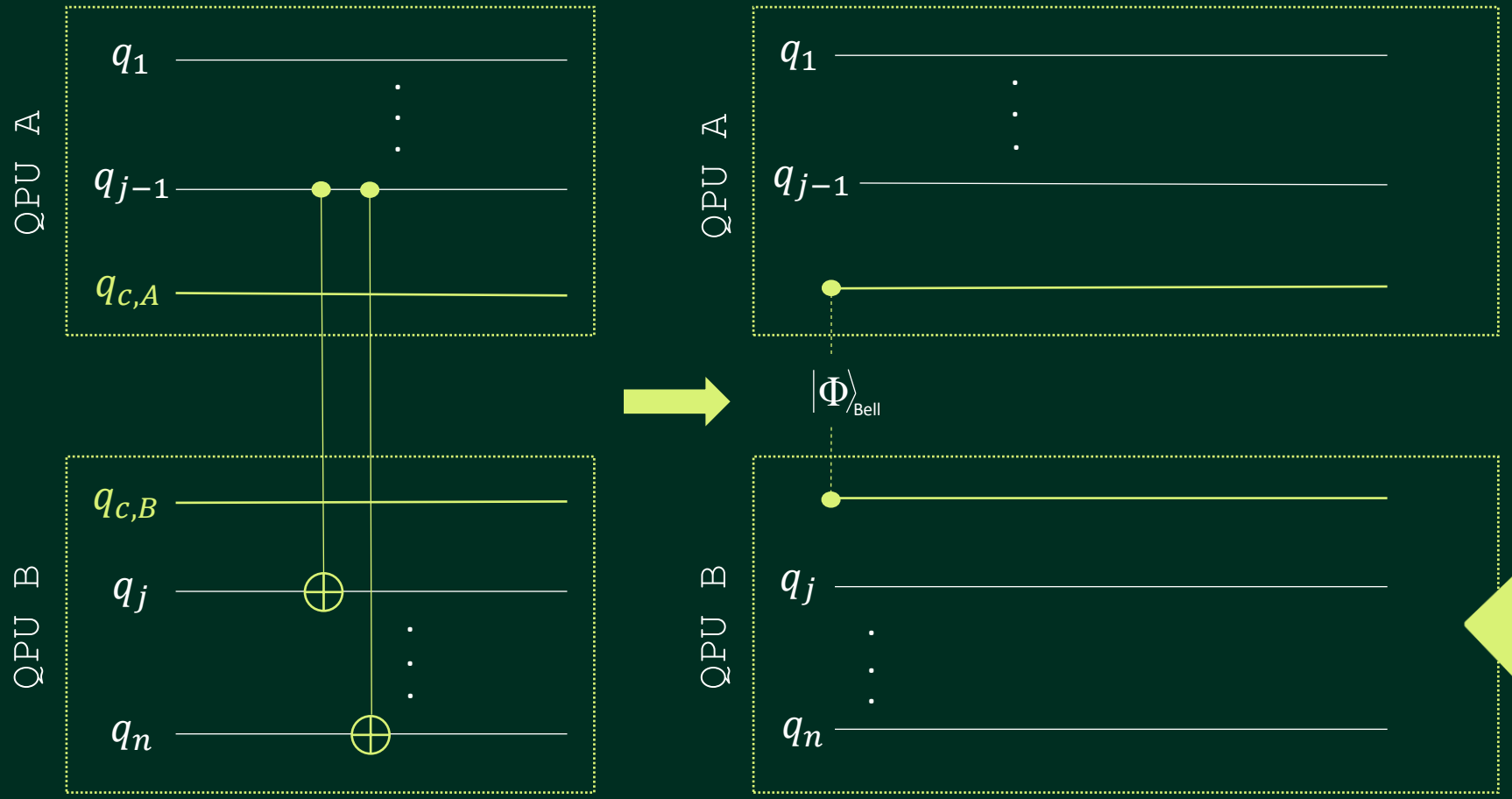
Alternatively: `Circuit-Cutting`

Cut into sub-circuits and execute in parallel. ***No physical entanglement used***, but rather simulated.

DOI: 10.1145/3445814.3446758

Quantum Communication

The `TeleGate` protocol



Quantum Communication

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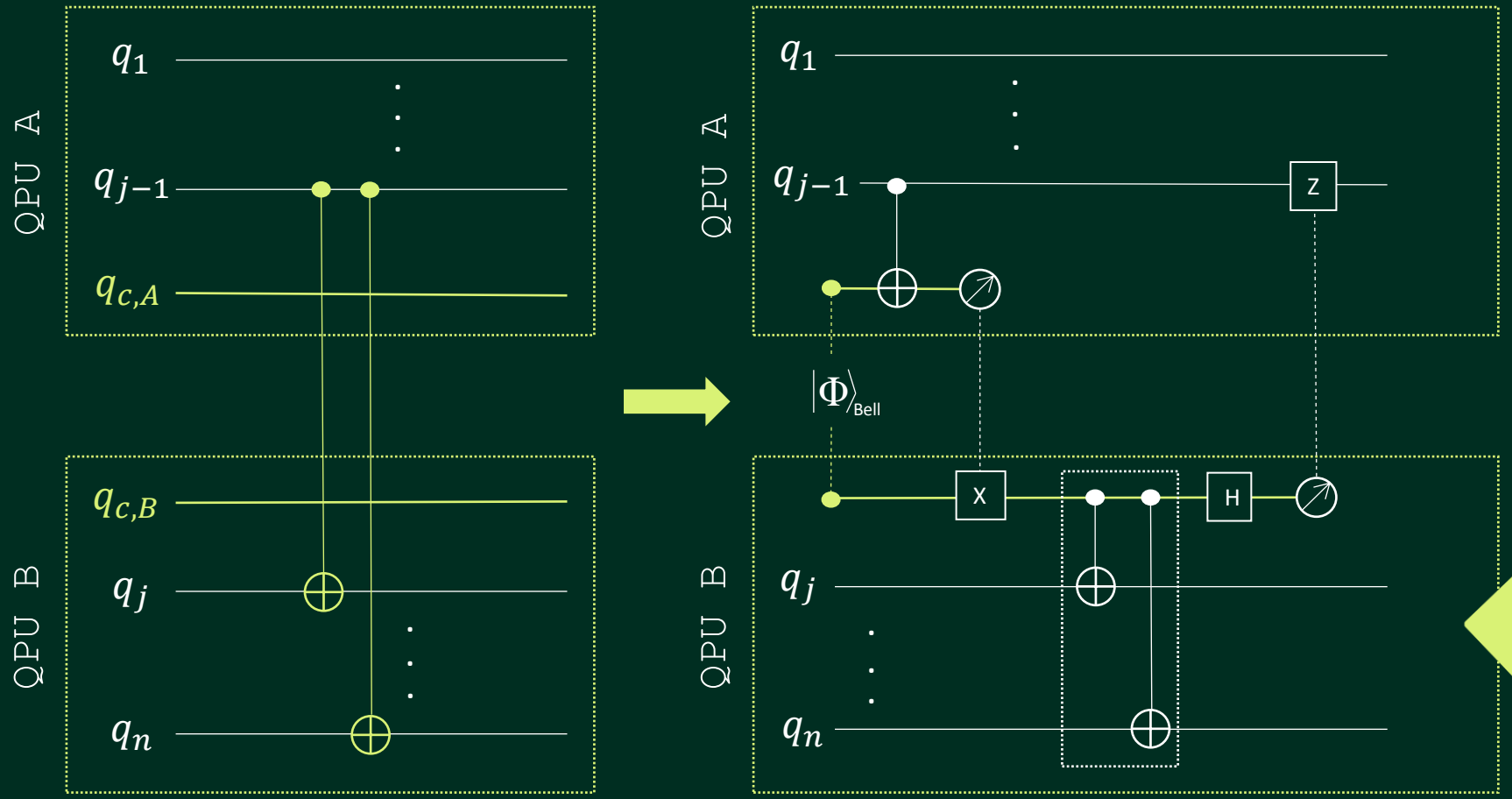
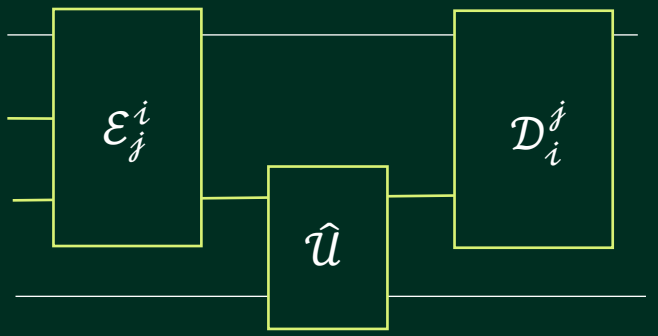
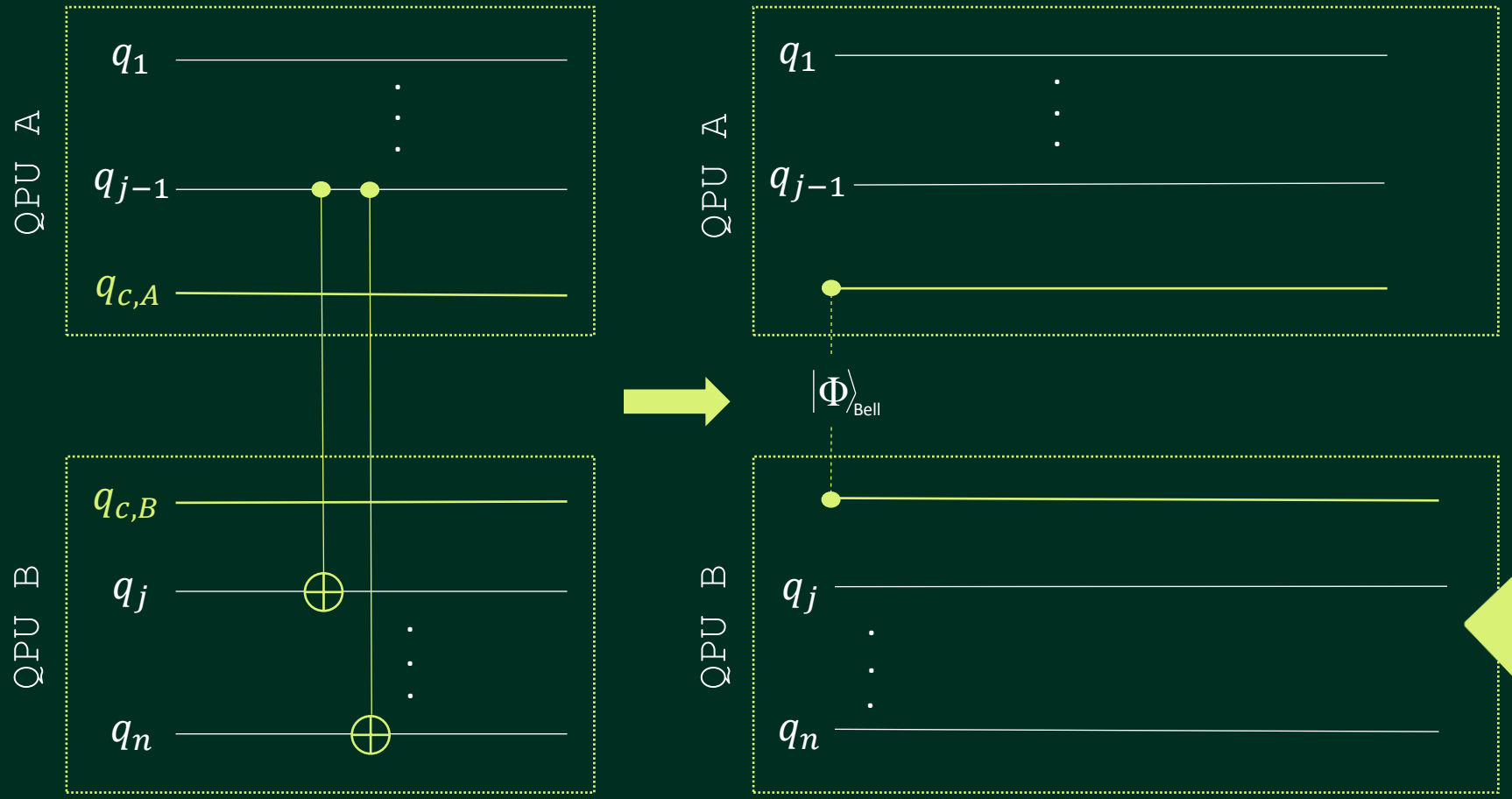




PhysRevA.62.052317

Quantum Communication

The `TeleData` protocol



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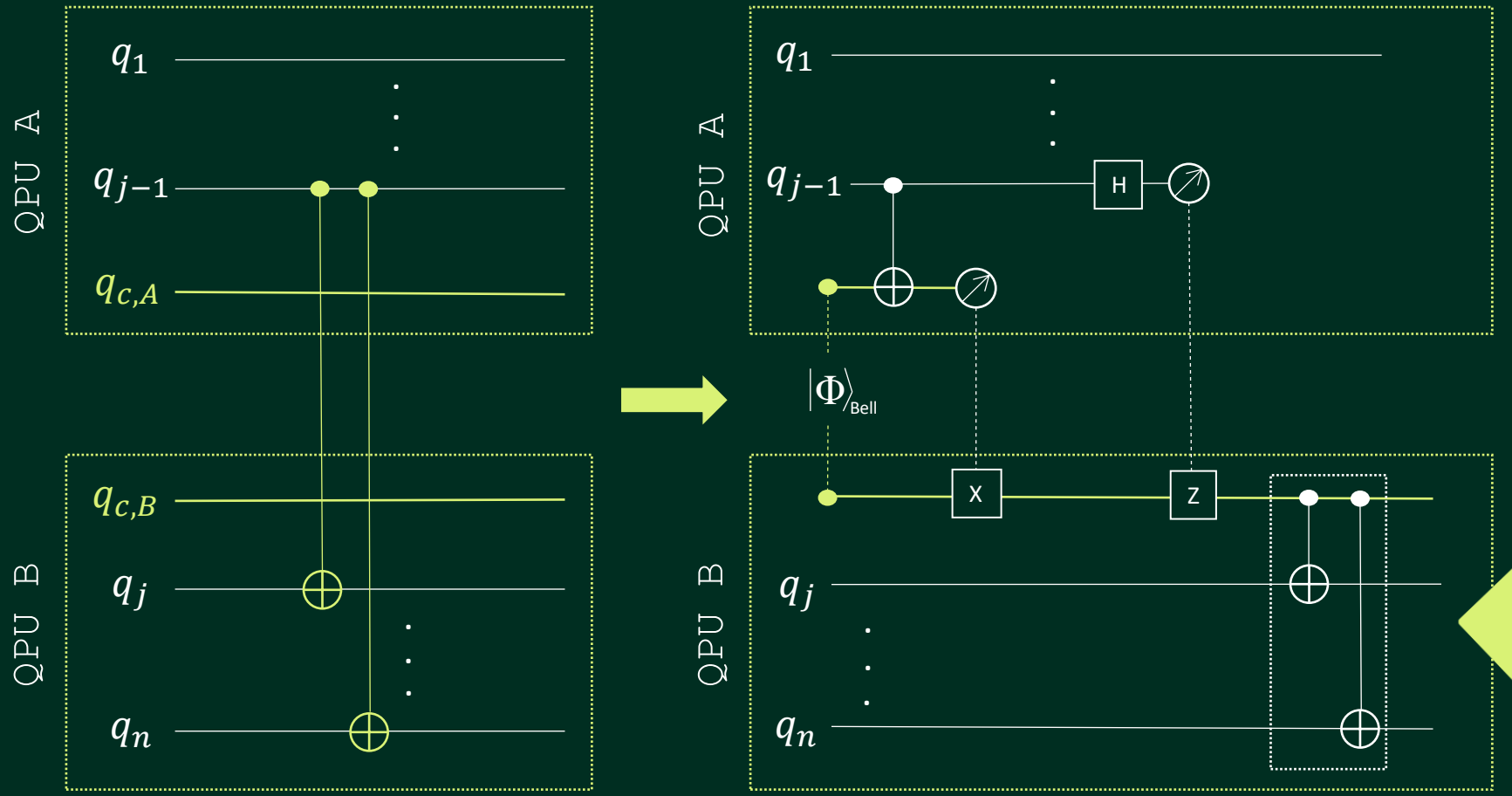
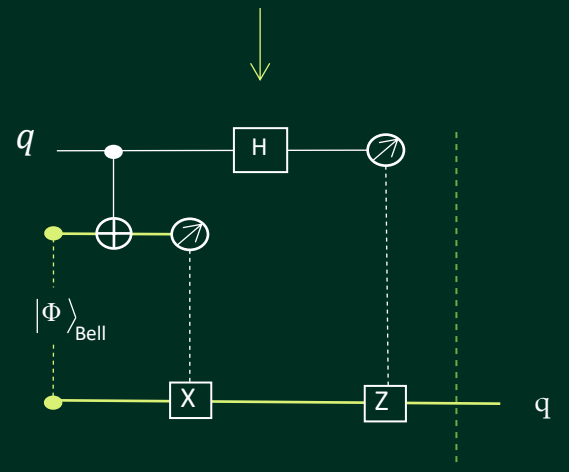


The quantum state is transferred via teleportation and the operations are executed *locally* in QPU$_B$

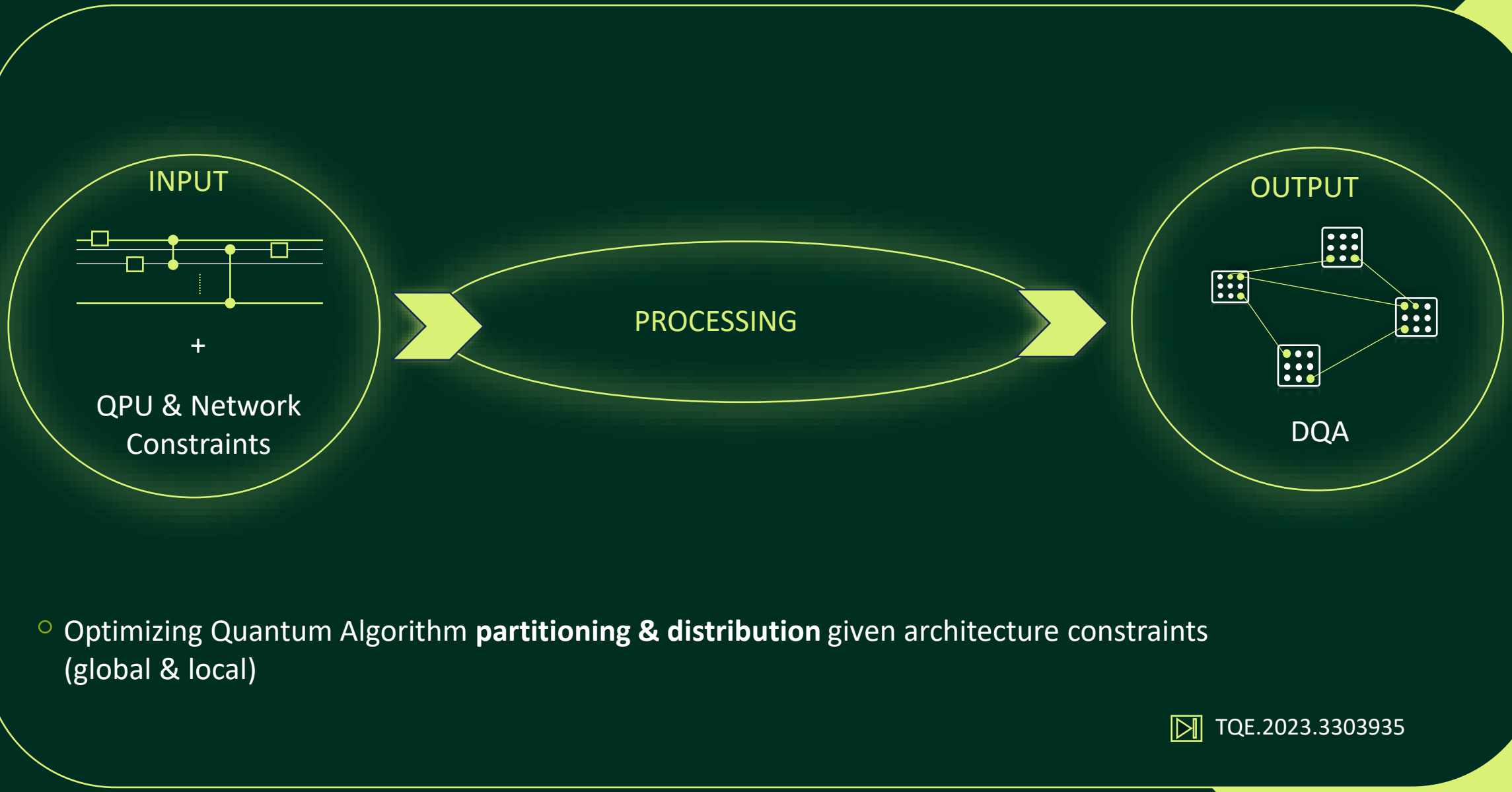


PhysRevLett.70.1895

Quantum Compiler

- Optimizing Quantum Algorithm **partitioning & distribution** given architecture constraints (global & local)

Quantum Compiler



- Optimizing Quantum Algorithm **partitioning & distribution** given architecture constraints (global & local)

TQE.2023.3303935

A Bottom-Up approach

Distributed Quantum Algorithm
natively exploiting hardware and network

Hardware (QPU & Net)

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Distributed Quantum Algorithm
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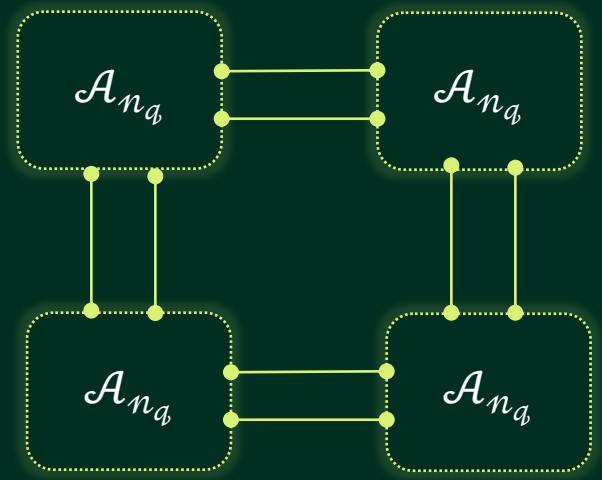
Hardware (QPU & Net)

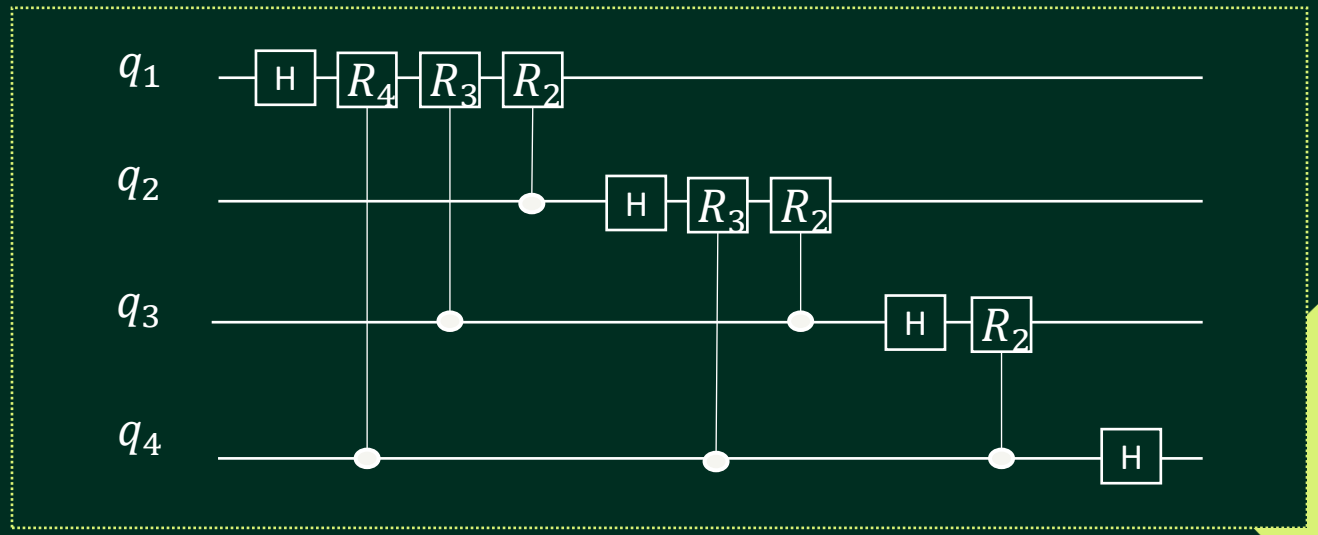


- Given a network of N-QPUs, exploit entanglement to implement a natively Distributed Quantum Algorithm (Approx.) $\mathcal{A}_{Nn_q}$

Example: Distributed QFT

Quantum Fourier Transform (QFT): Fundamental building block for many algorithms (QPE / Shor, signal processing, comb. opt, QML ….)

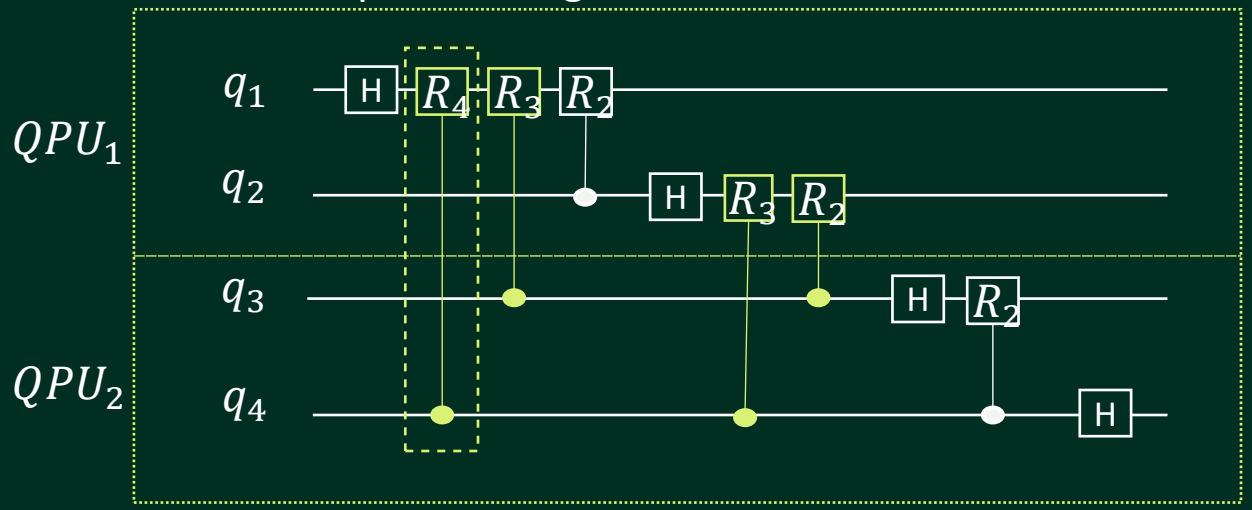
$$|j\rangle \rightarrow \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} e^{\frac{2\pi i}{N} j \cdot k} \; |k\rangle \quad \text{with} \quad N = 2^n \,, \qquad R_n = \begin{pmatrix} 1 & 0 \\ 0 & e^{\frac{2\pi i}{N}} \end{pmatrix}$$



QFT Monolithic Circuit for 4 qubits

Example: Distributed QFT via TeleGate

Bi-partitioning of the monolithic circuit



Each non-local control gate operation can be distributed via **TeleGate**

Example: Distributed QFT via TeleGate

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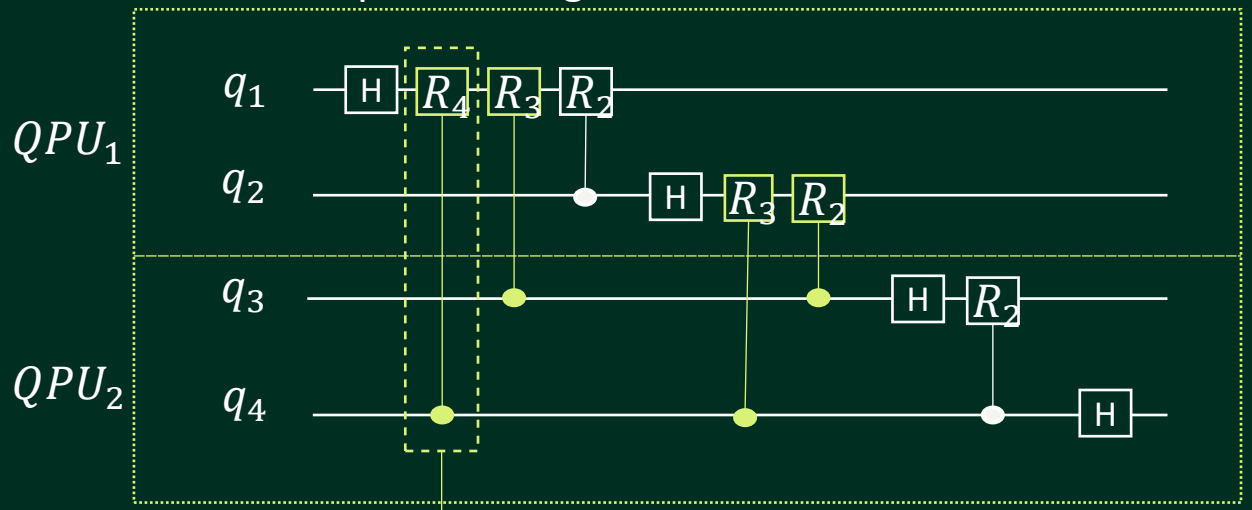

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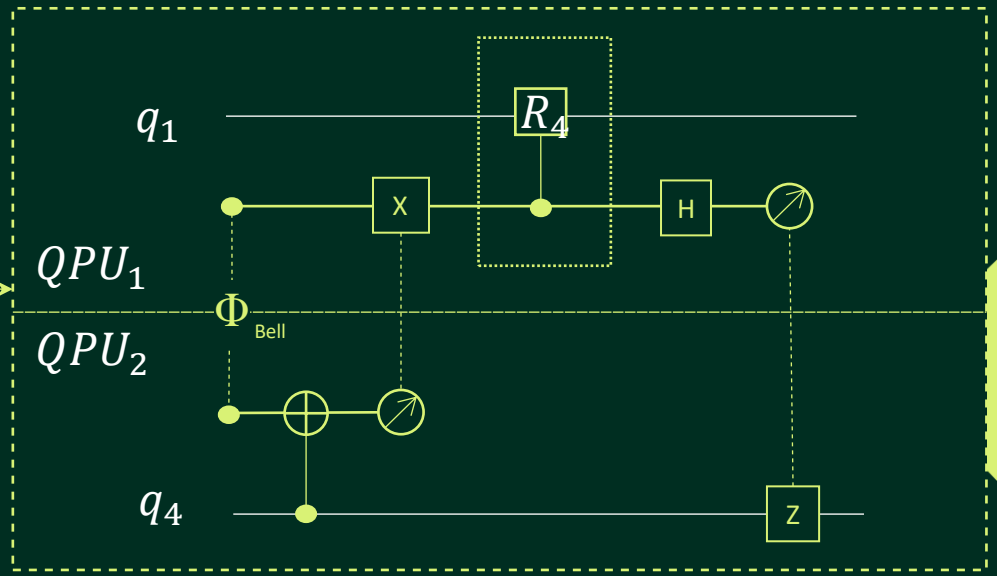

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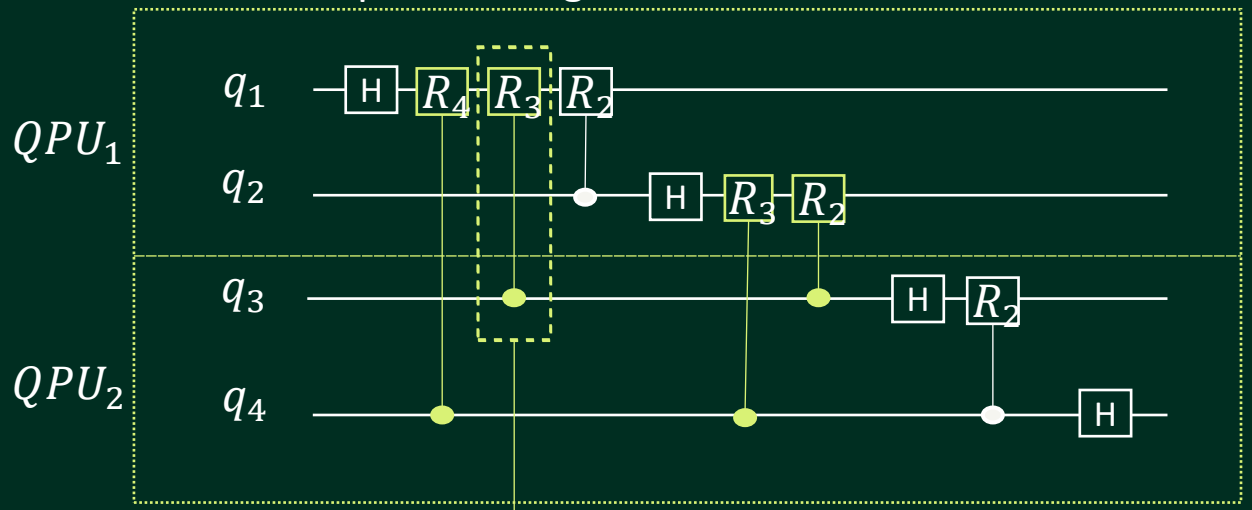

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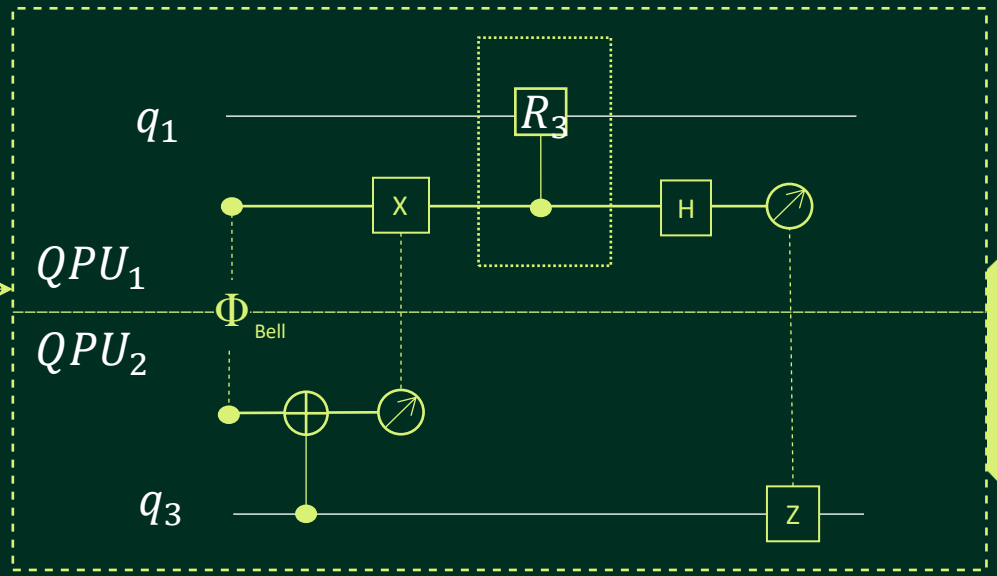

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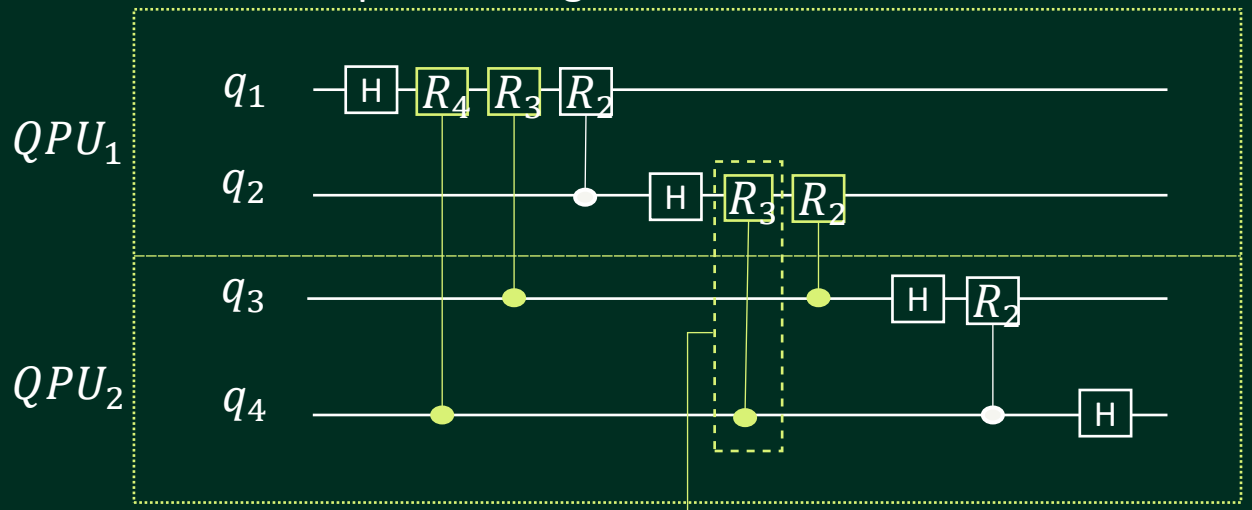

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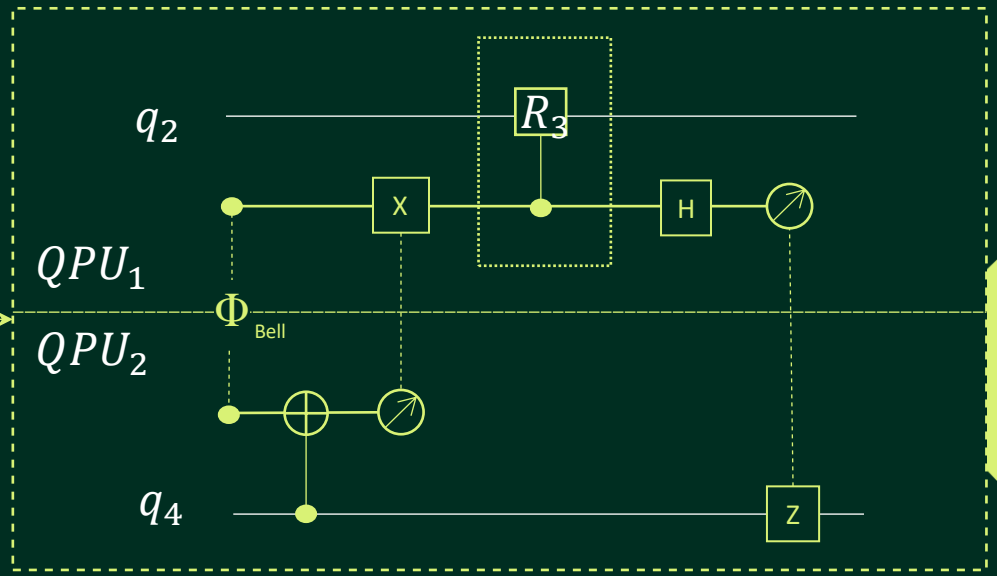

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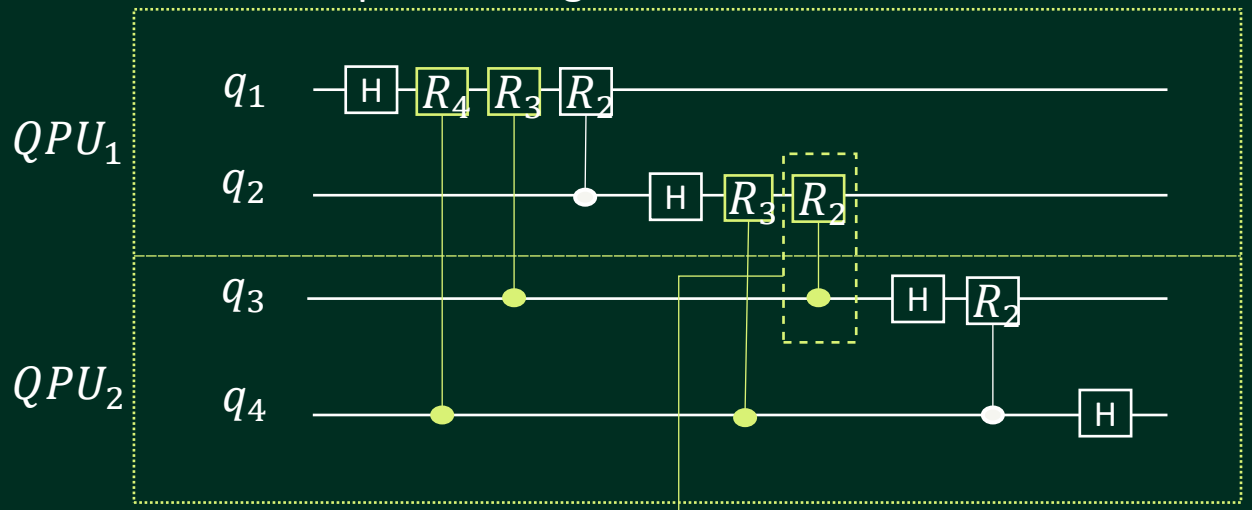

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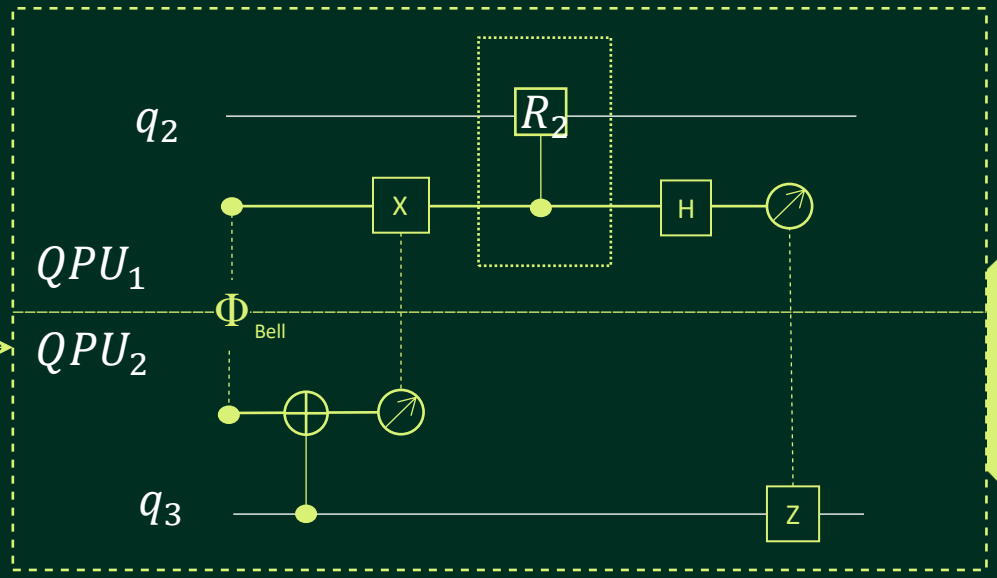
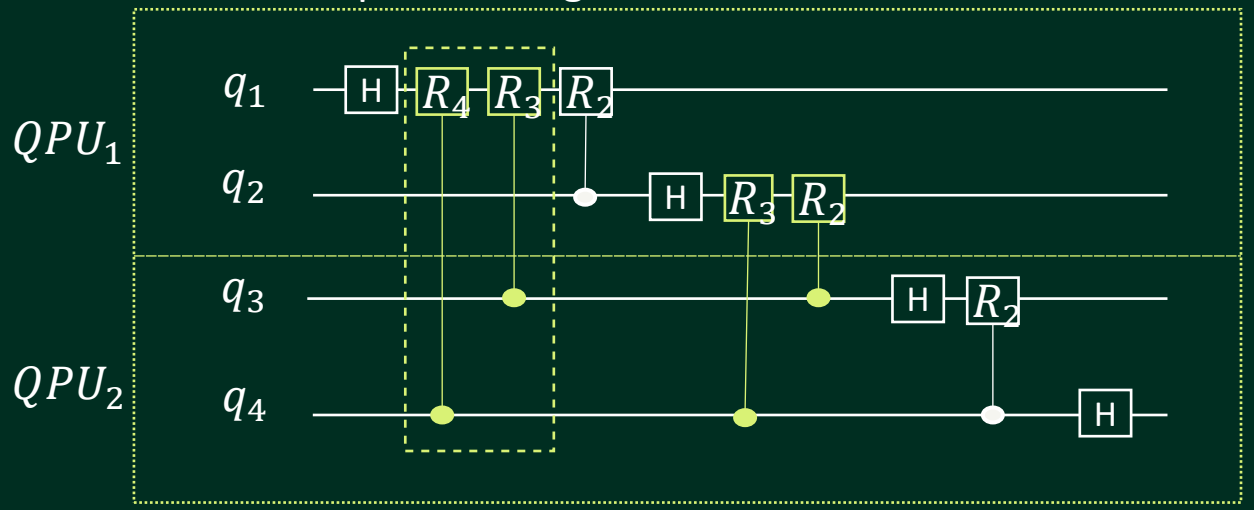


Example: Distributed QFT via TeleData

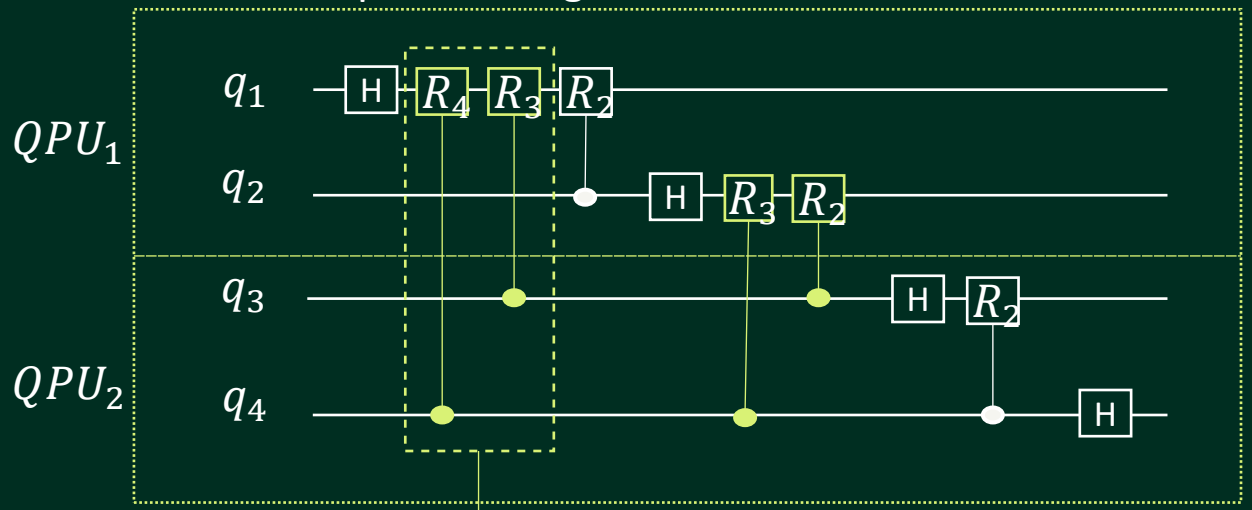
Bi-partitioning of the monolithic circuit



Each qubit involved in non-local gate operations can be teleported via **TeleData**, then the initial configuration is restored

Example: Distributed QFT via TeleData

Bi-partitioning of the monolithic circuit



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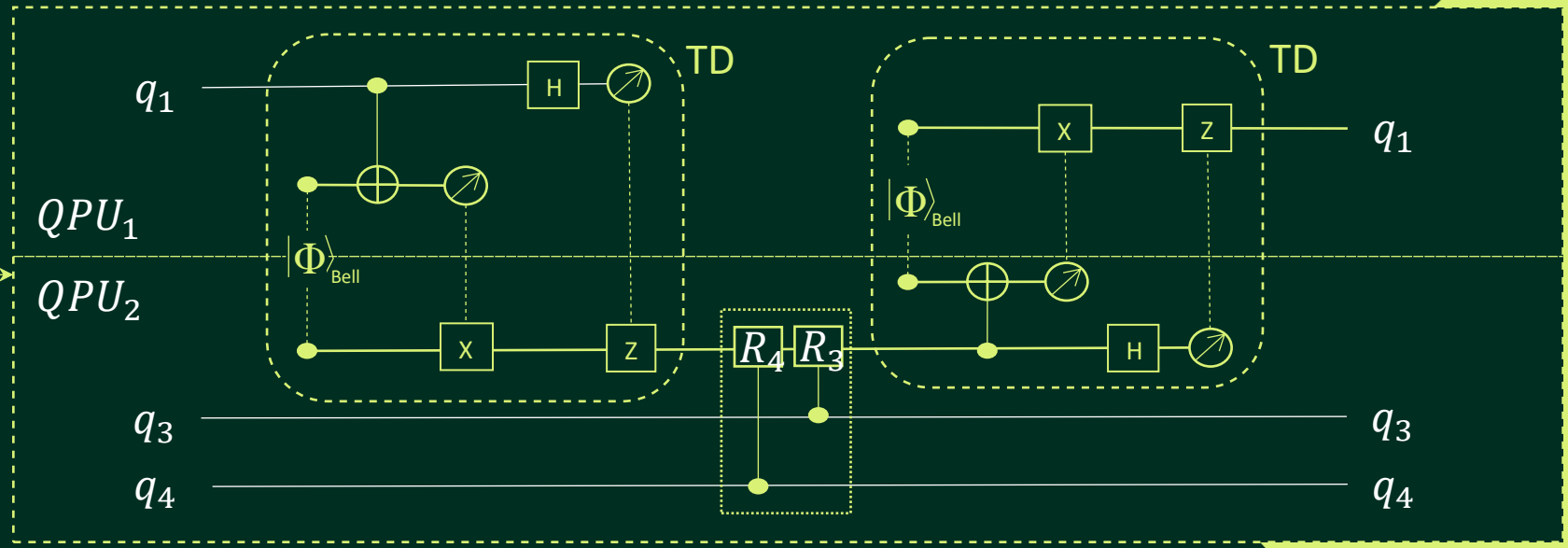

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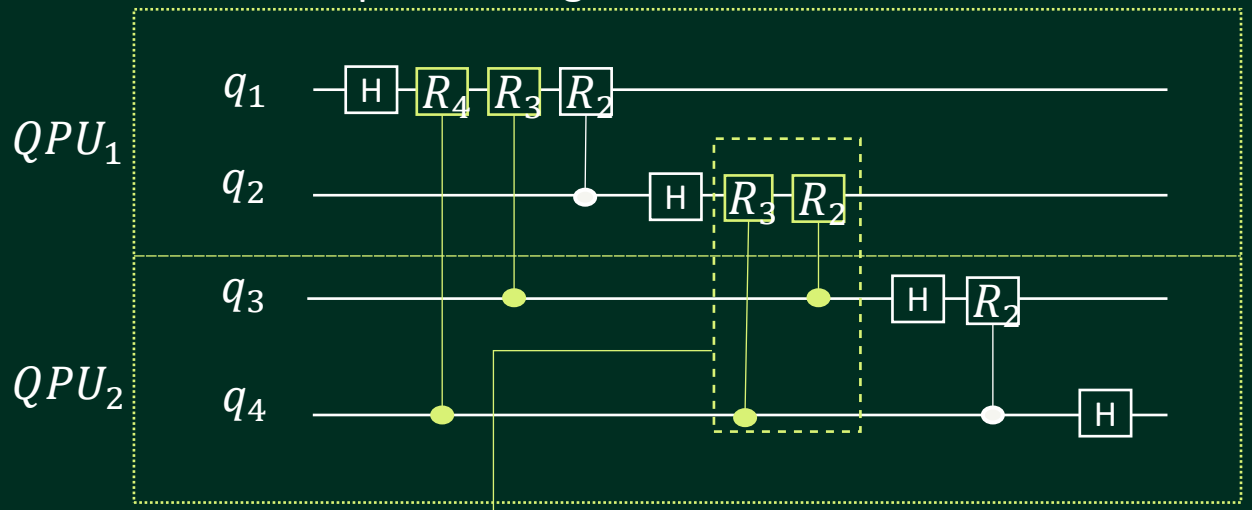

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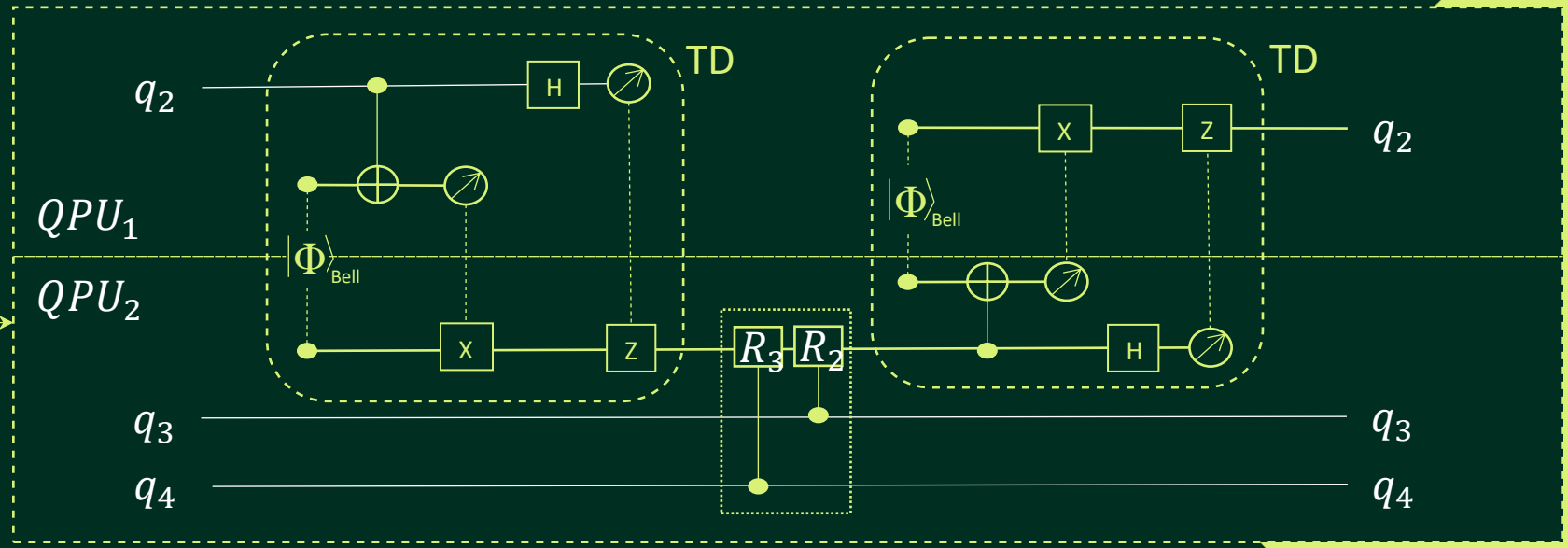
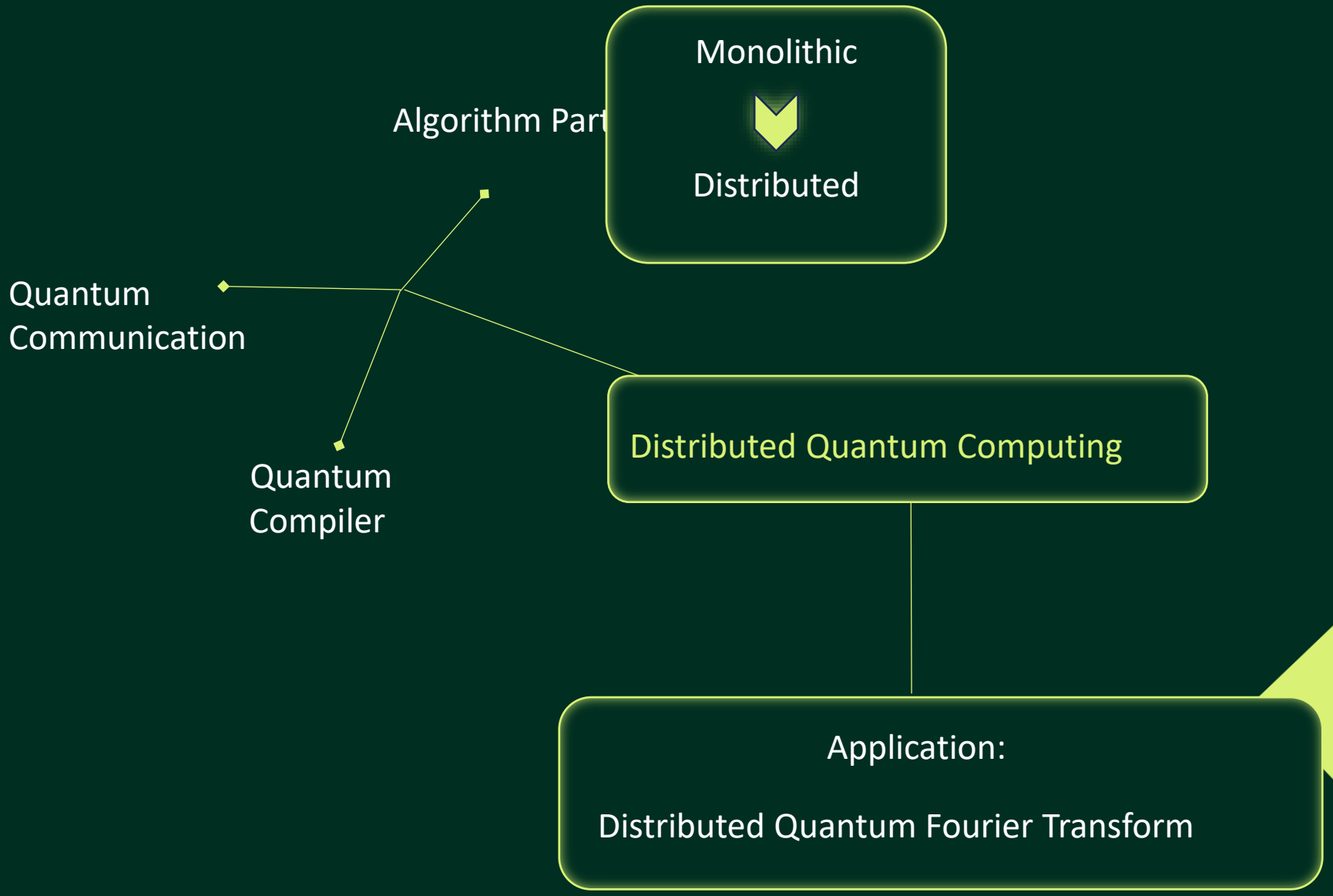


Summary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φύσις κρύπτεσθαι φιλεῖ

Nature tends to remain concealed

Heraclitus, Fragment B123 DK

Thank you for your attention!

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