DIPARTIMENTO INTERATENEO DI FISICA

Dynamical cluster-based optimization of tensor network algorithms for simulating quantum circuits with finite fidelity

Andrea De Girolamo

Bari Theory Group XMas Workshop

Bari, December 17th 2024

In collaboration with:

WMI

MCQST

Leibniz Supercomputing Centre of the Bavarian Academy of Sciences and Humanities

Acknowledgments:

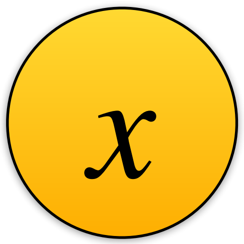
Quasimodo – Quantum sensing for one-health

ICSC – Centro Nazionale di Ricerca in HPC, Big Data and Quantum Computing

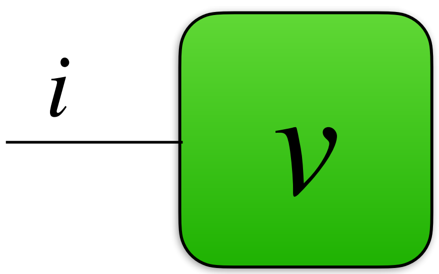
INFN

CINECA

Tensor diagrams

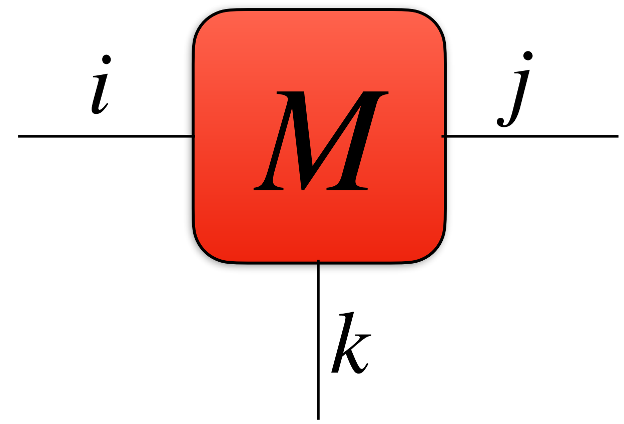


number

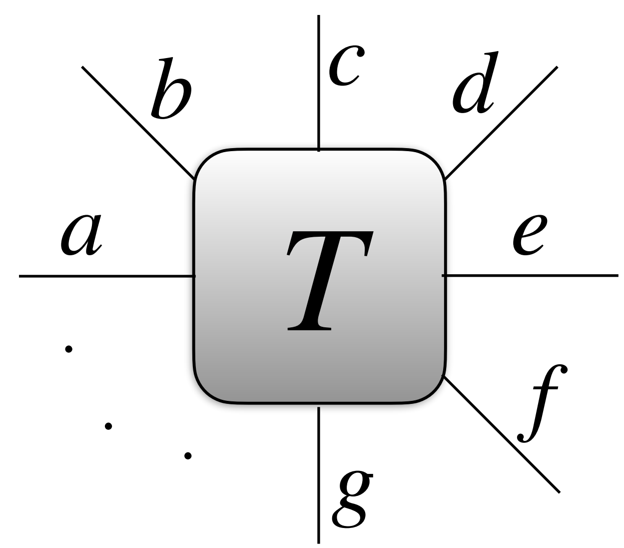


vector

matrix



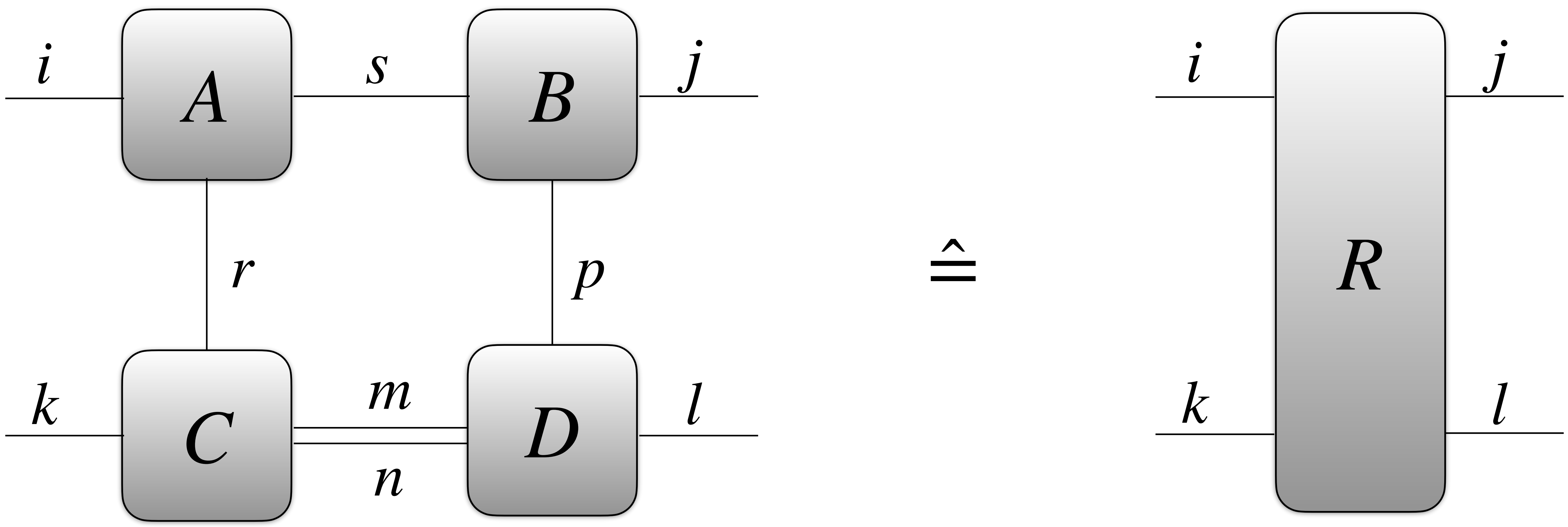
rank-3 tensor



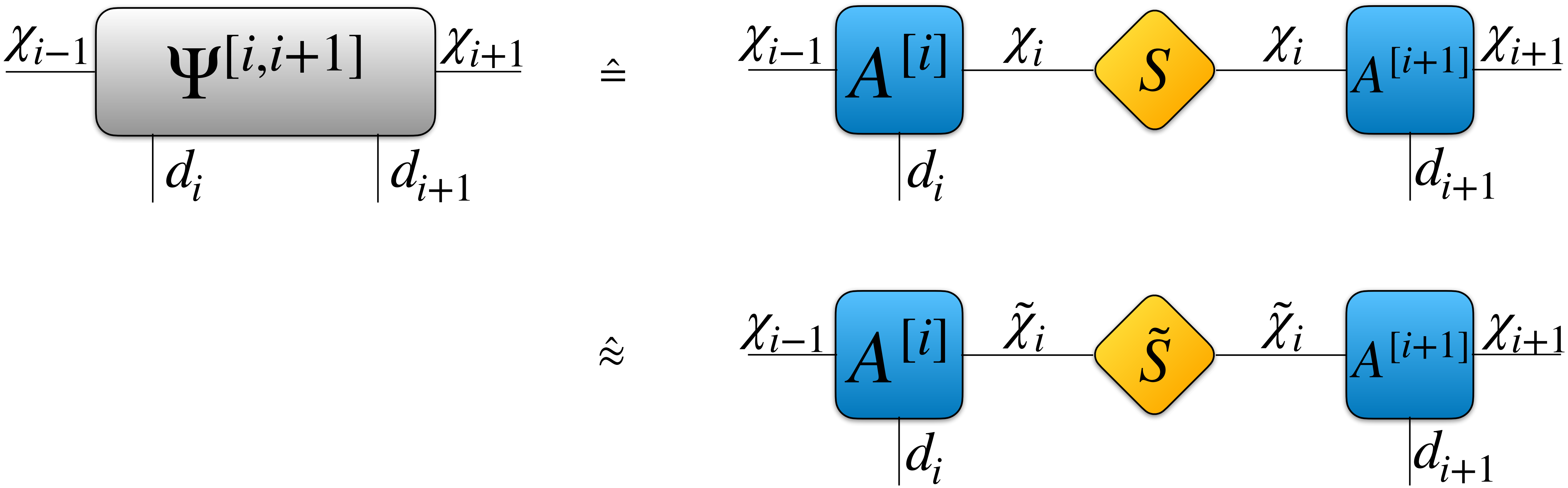
rank-n tensor

DIPARTIMENTO
INTERATENEO
DI FISICA

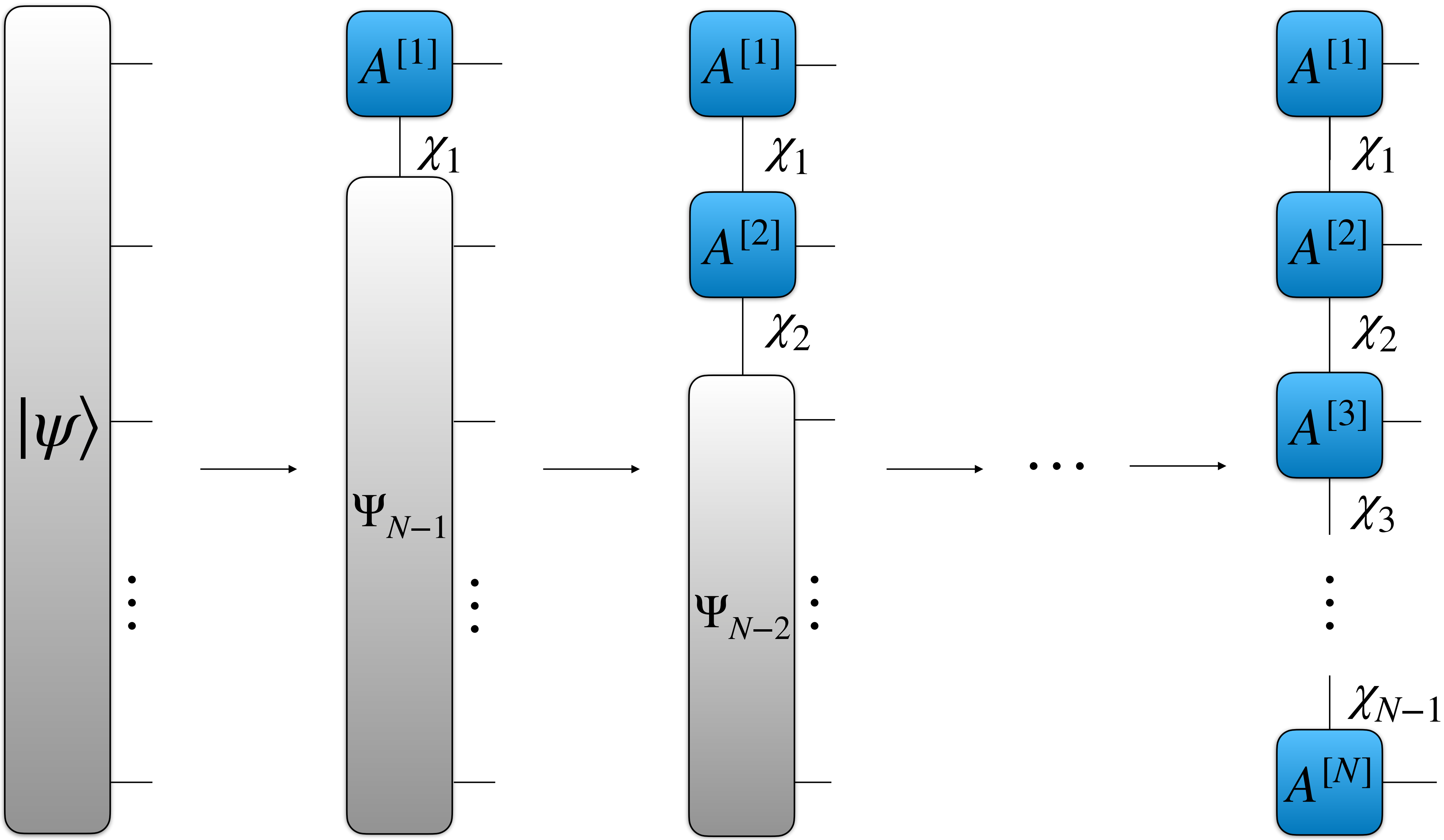
Tensor network



Singular Value Decomposition (SVD) [3,4]

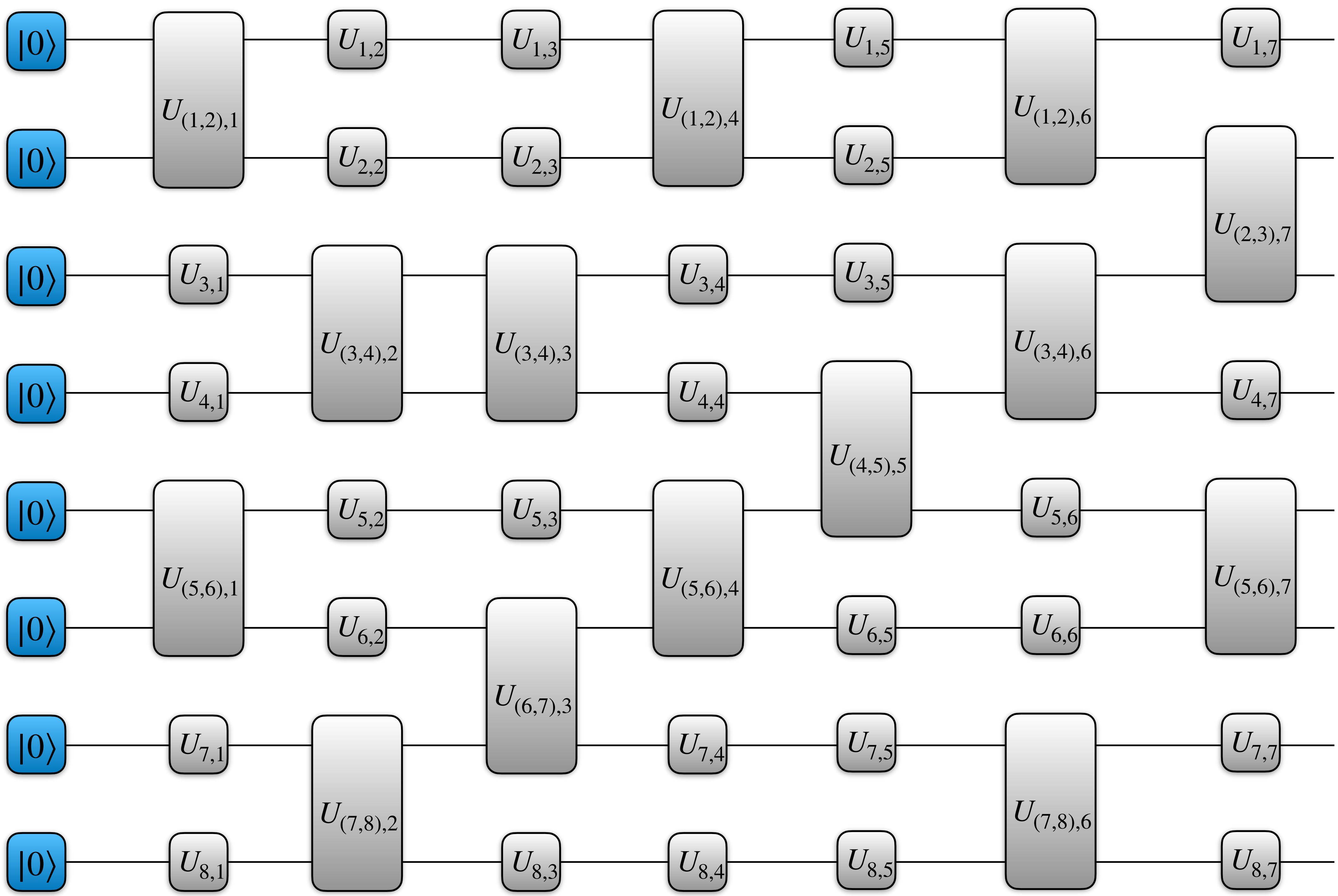


Matrix-Product State (MPS) [3,4]



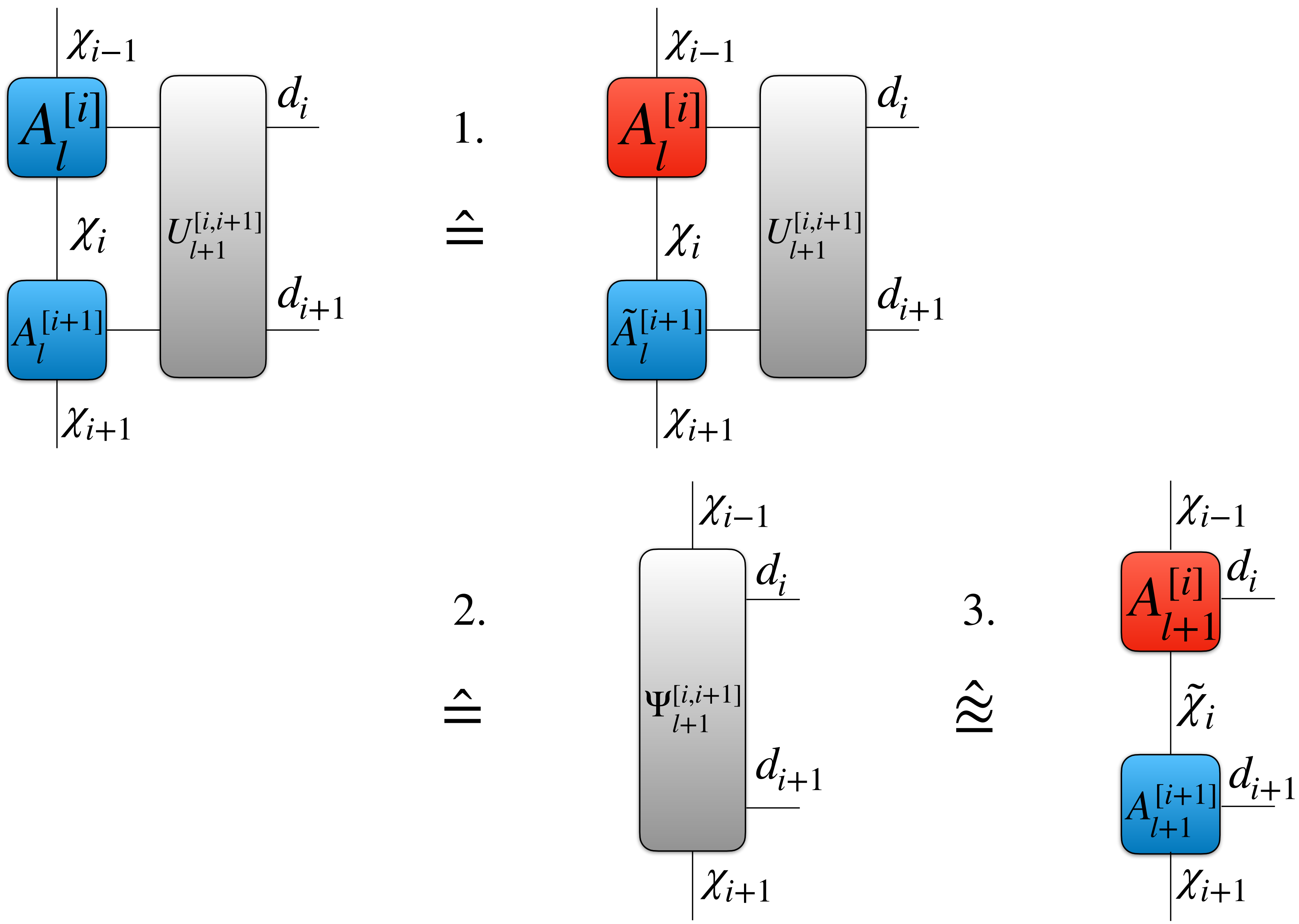
DIPARTIMENTO
INTERATENEO
DI FISICA

Quantum circuit modelled as a tensor network [1]



[1] A. De Girolamo, P. Facchi, P. Rabl, S. Pascazio, C. Lupo, G. Magnifico, *TBA*

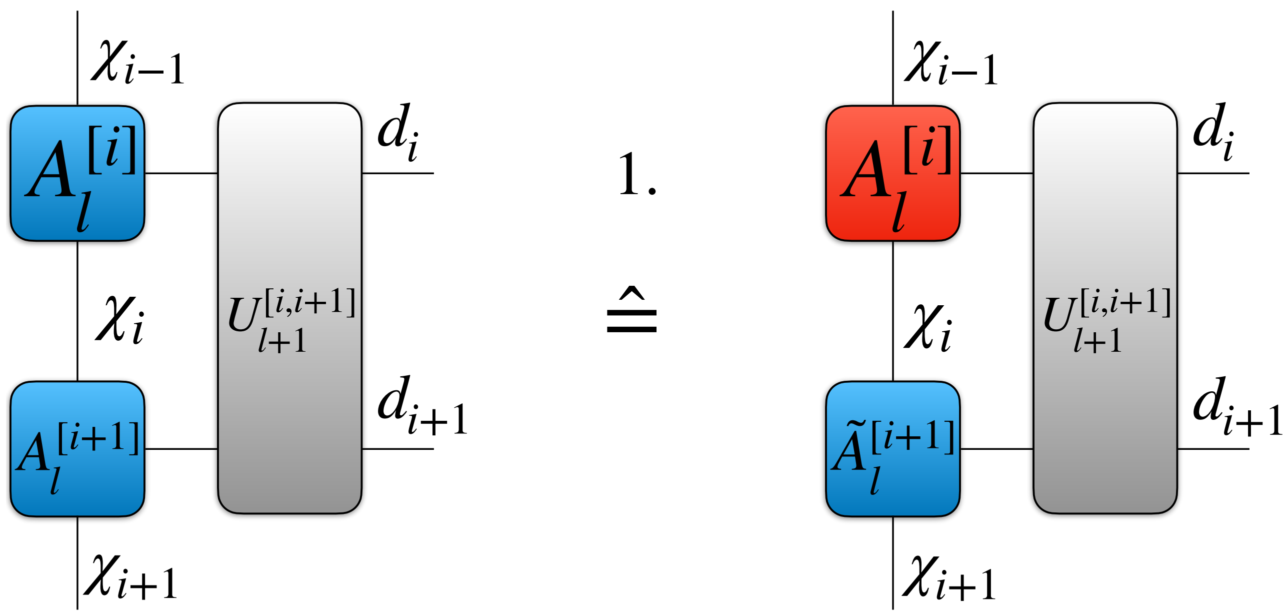
Time-Evolving Block Decimation (TEBD) algorithm [2]



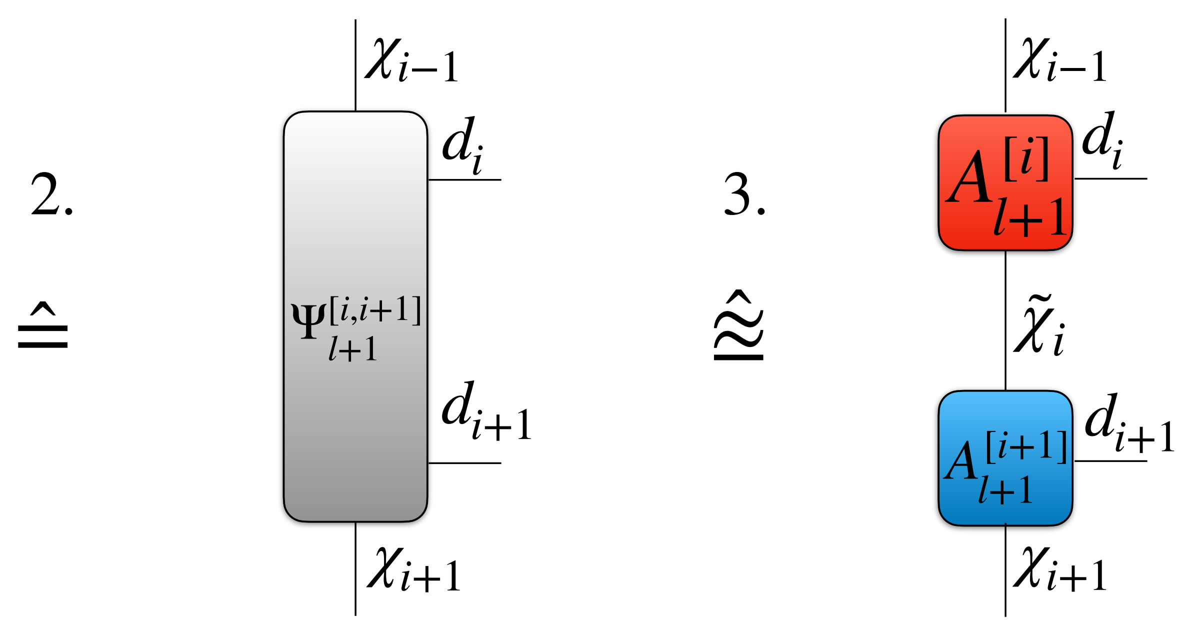
[2] Y. Zhou, E. M. Stoudenmire, and X. Waintal, *Phys. Rev. X 10, 041038 (2020).*

DIPARTIMENTO
INTERATENEO
DI FISICA

Time-Evolving Block Decimation (TEBD) algorithm [2]

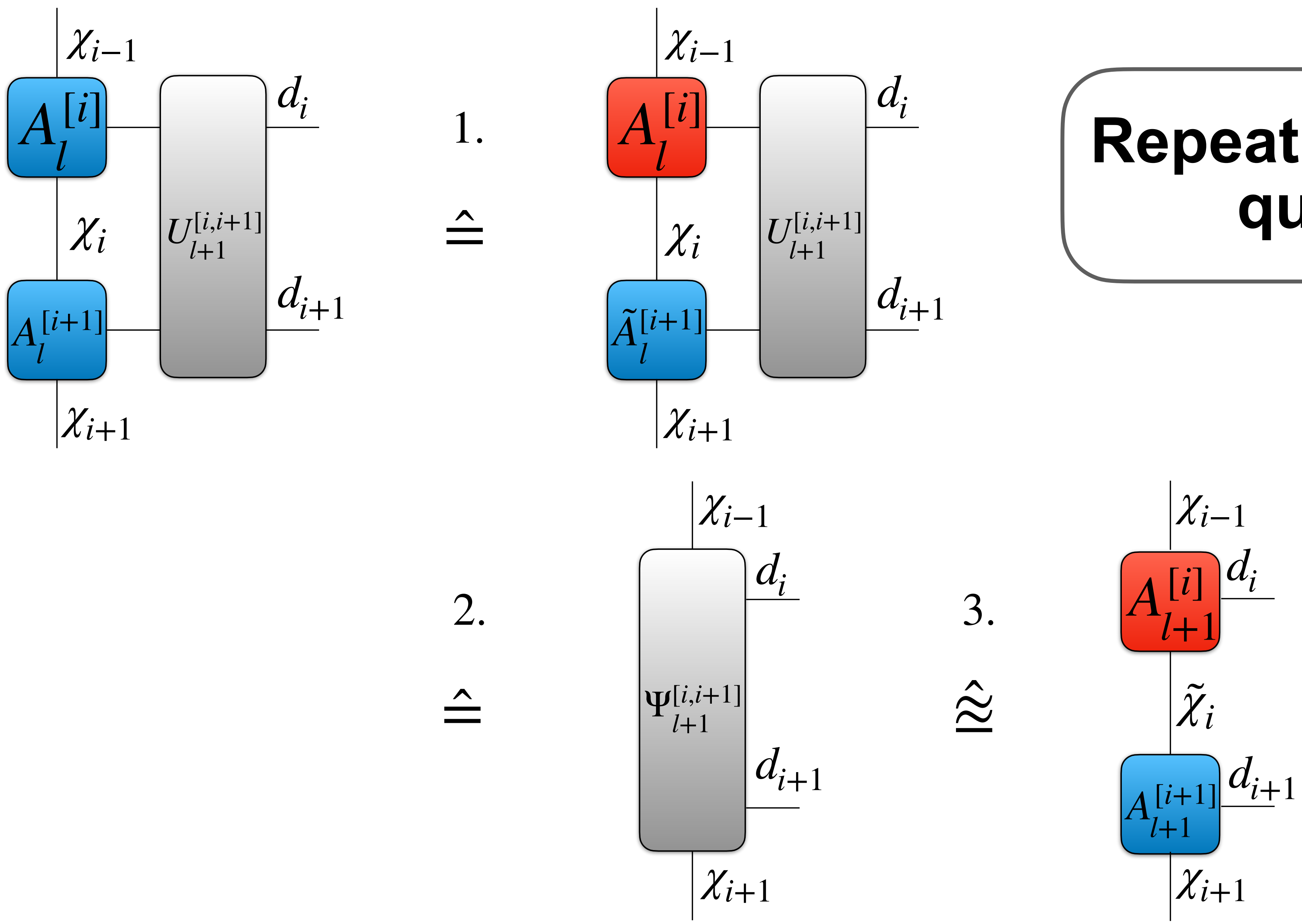


Repeat for all gates in the quantum circuit



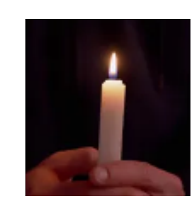
[2] Y. Zhou, E. M. Stoudenmire, and X. Waintal, *Phys. Rev. X 10, 041038 (2020).*

Time-Evolving Block Decimation (TEBD) algorithm [2]



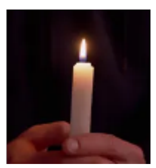
Repeat for all gates in the quantum circuit

Let's talk about philosophy!

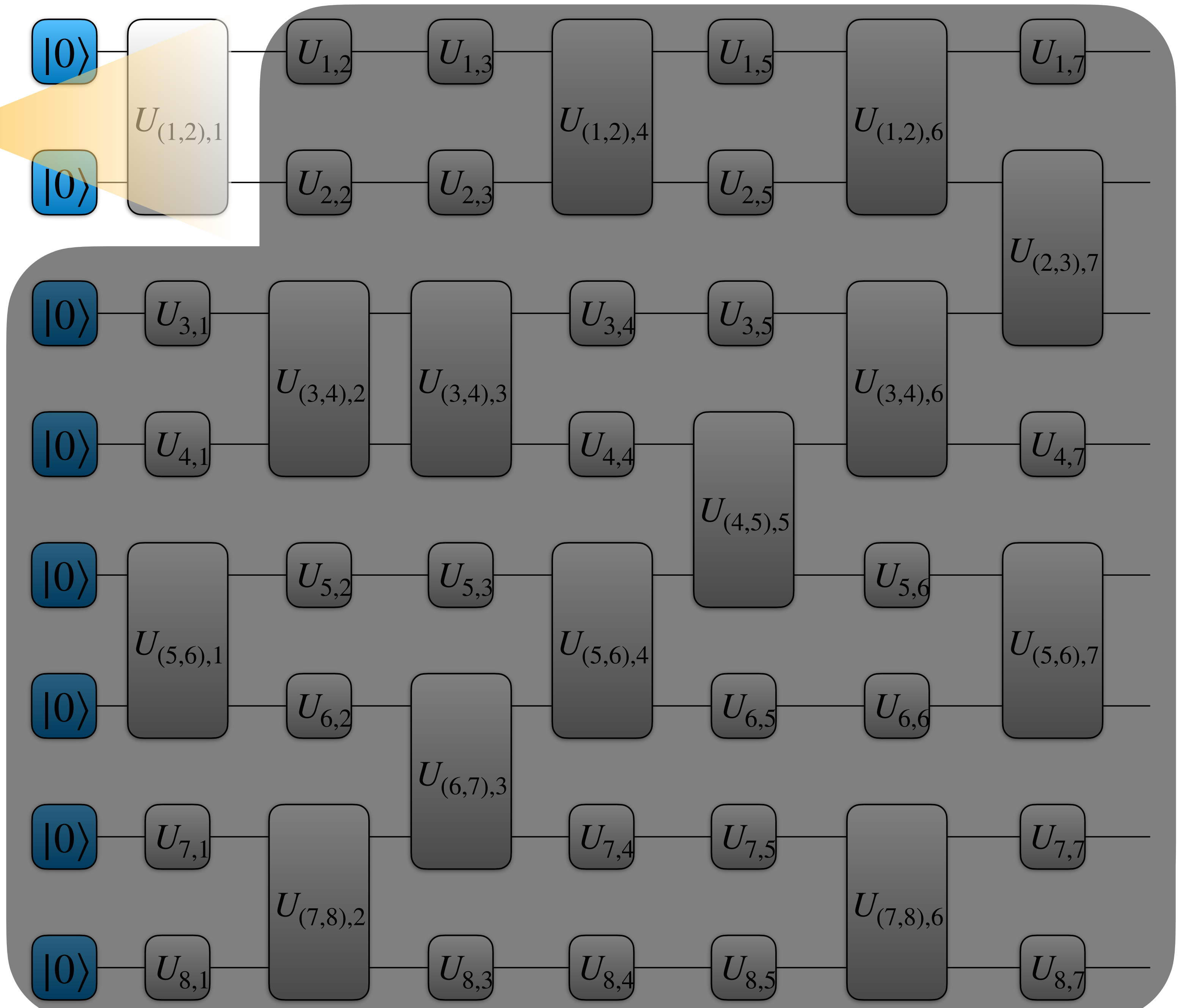


[2] Y. Zhou, E. M. Stoudenmire, and X. Waintal, *Phys. Rev. X 10, 041038 (2020).*

Time-Evolving Block Decimation (TEBD) algorithm [2]

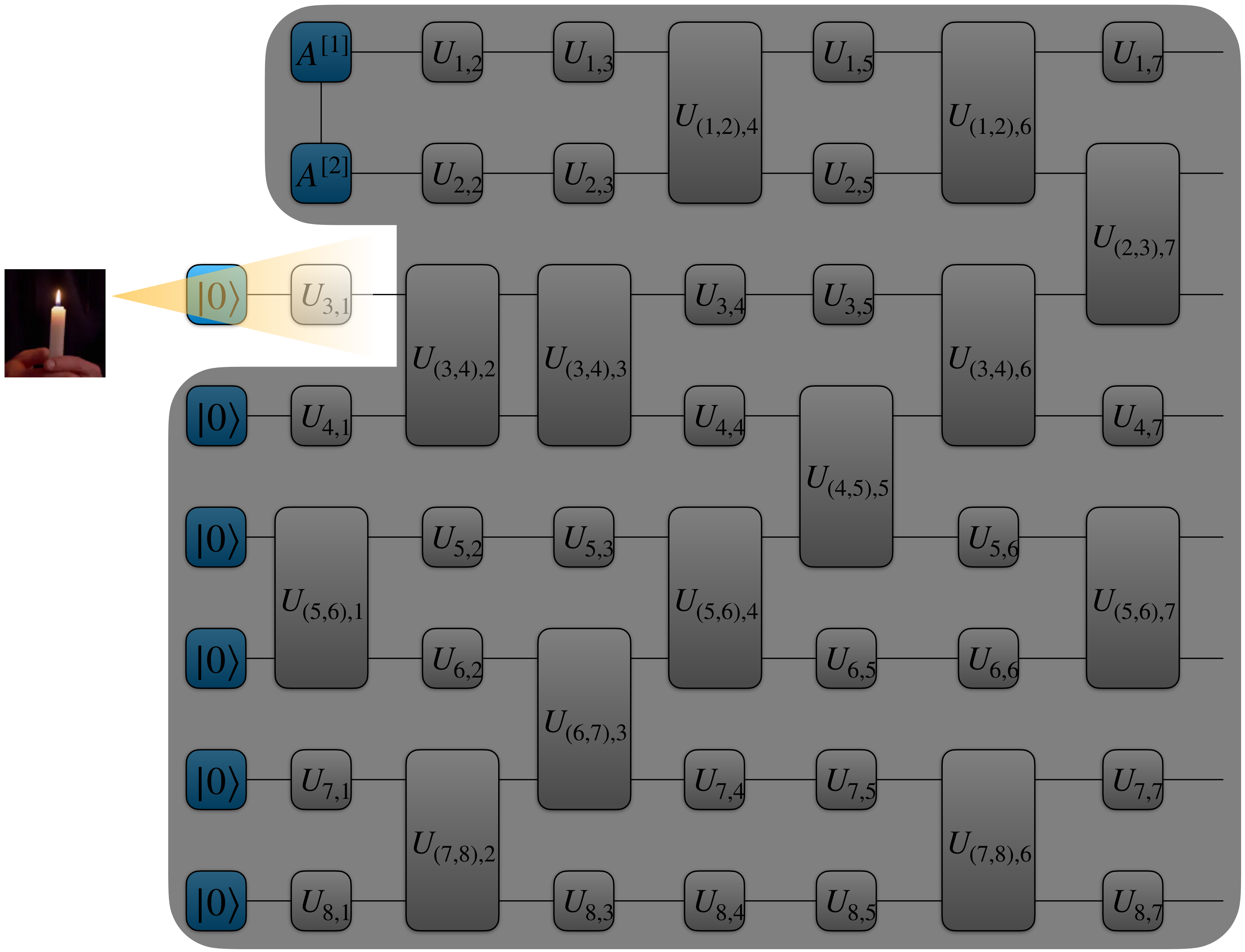


The western approach



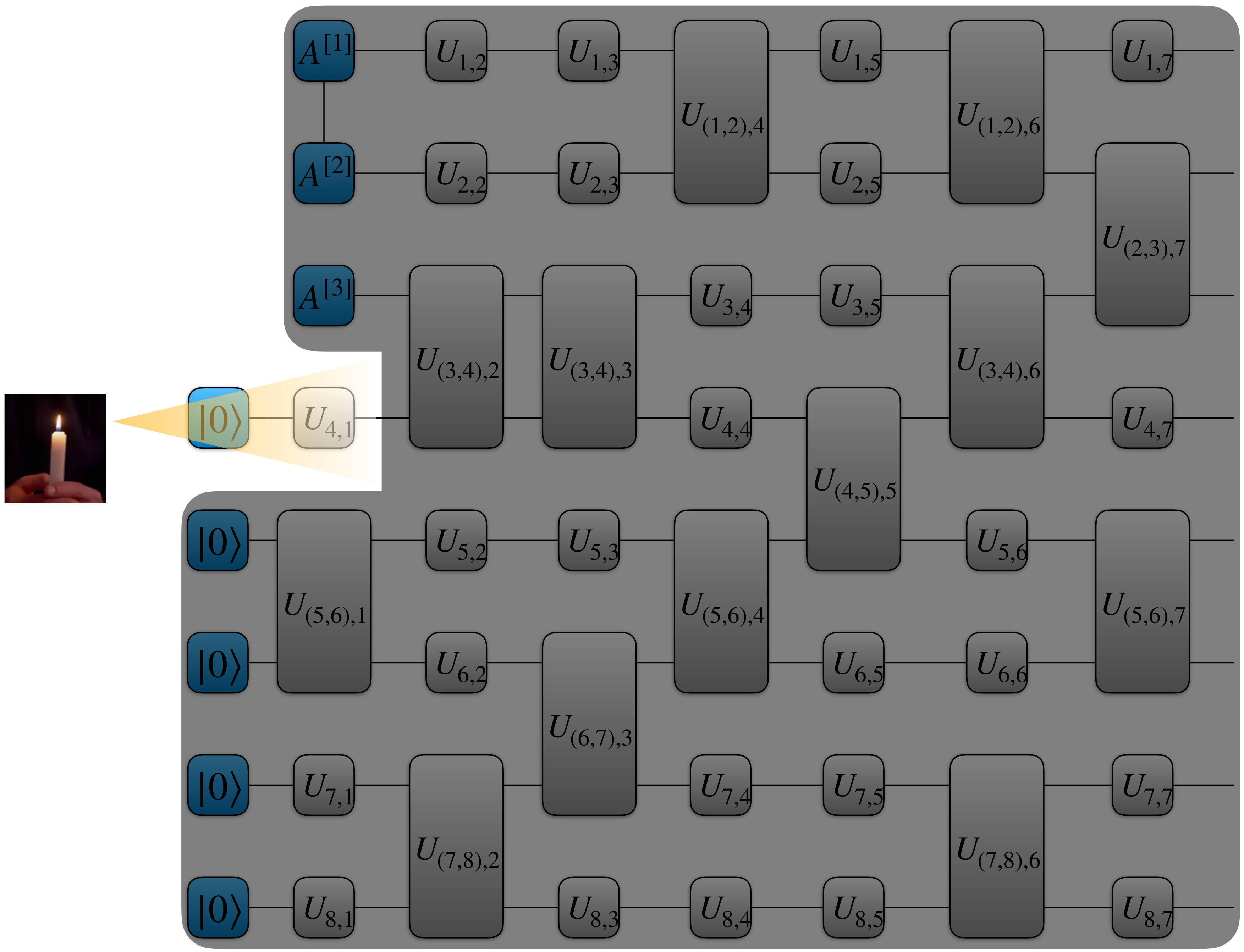
[2] Y. Zhou, E. M. Stoudenmire, and X. Waintal, *Phys. Rev. X 10, 041038 (2020).*

Time-Evolving Block Decimation (TEBD) algorithm [2]



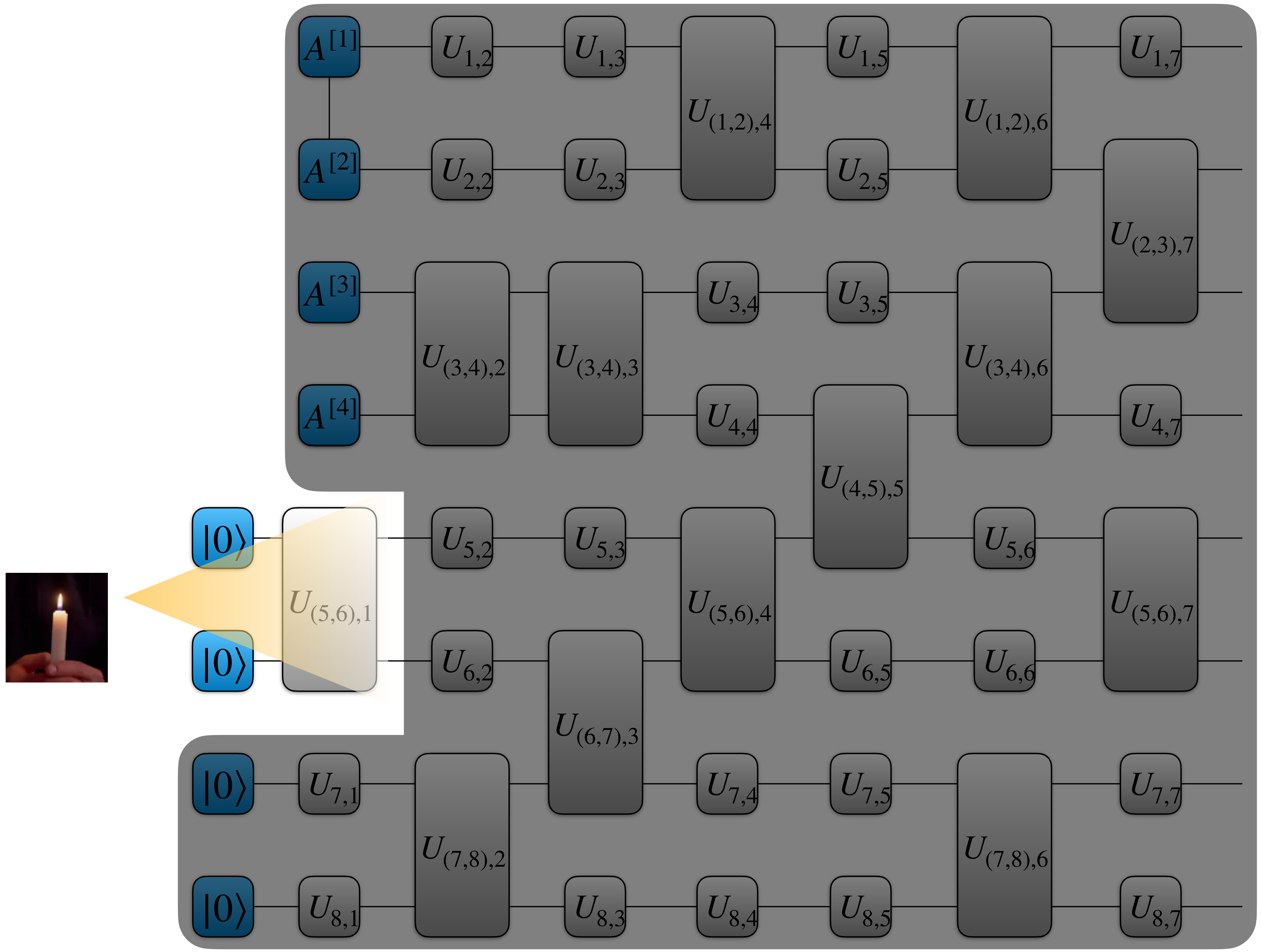
[2] Y. Zhou, E. M. Stoudenmire, and X. Waintal, *Phys. Rev. X 10, 041038 (2020).*

Time-Evolving Block Decimation (TEBD) algorithm [2]



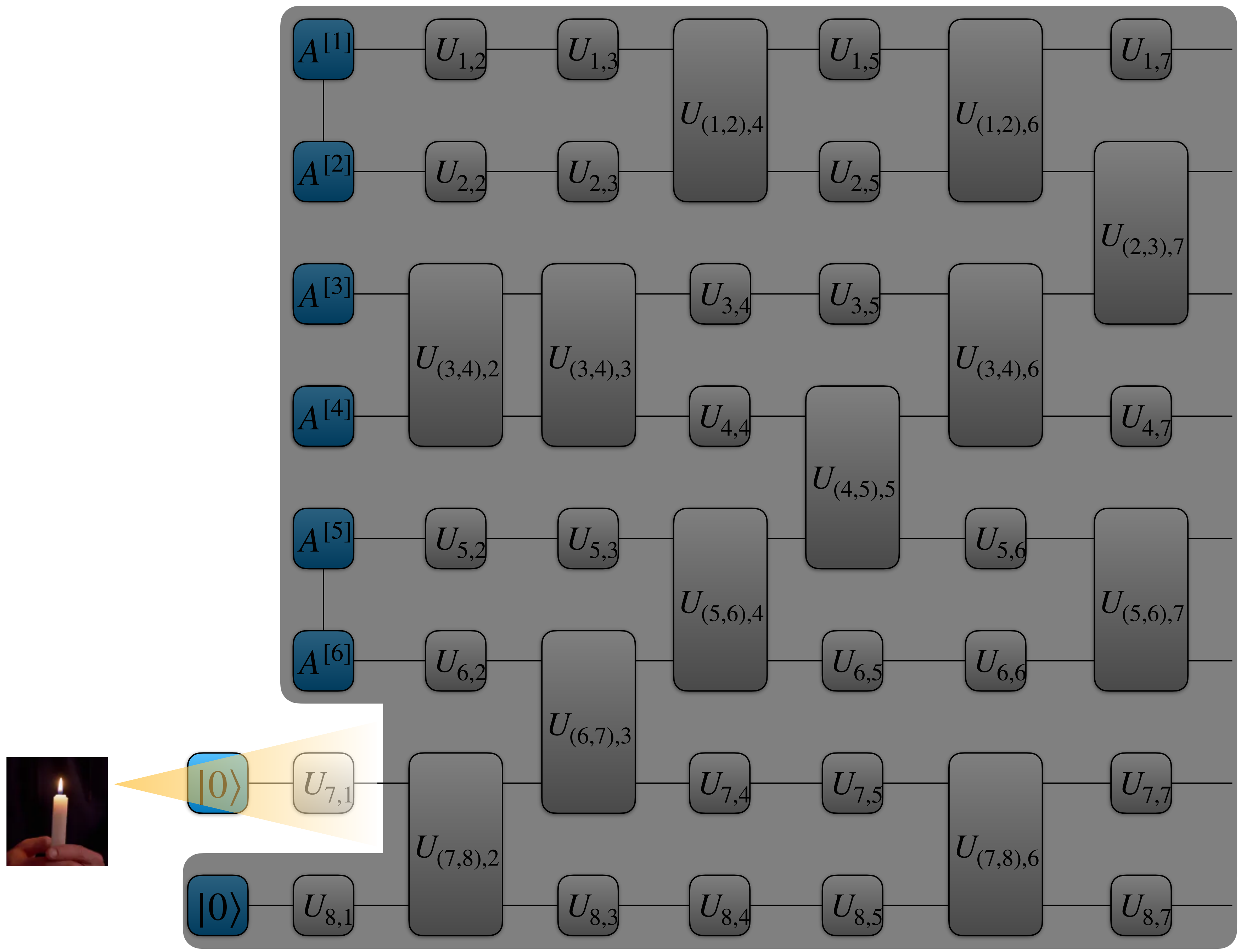
[2] Y. Zhou, E. M. Stoudenmire, and X. Waintal, *Phys. Rev. X 10, 041038 (2020).*

Time-Evolving Block Decimation (TEBD) algorithm [2]



[2] Y. Zhou, E. M. Stoudenmire, and X. Waintal, *Phys. Rev. X 10, 041038 (2020).*

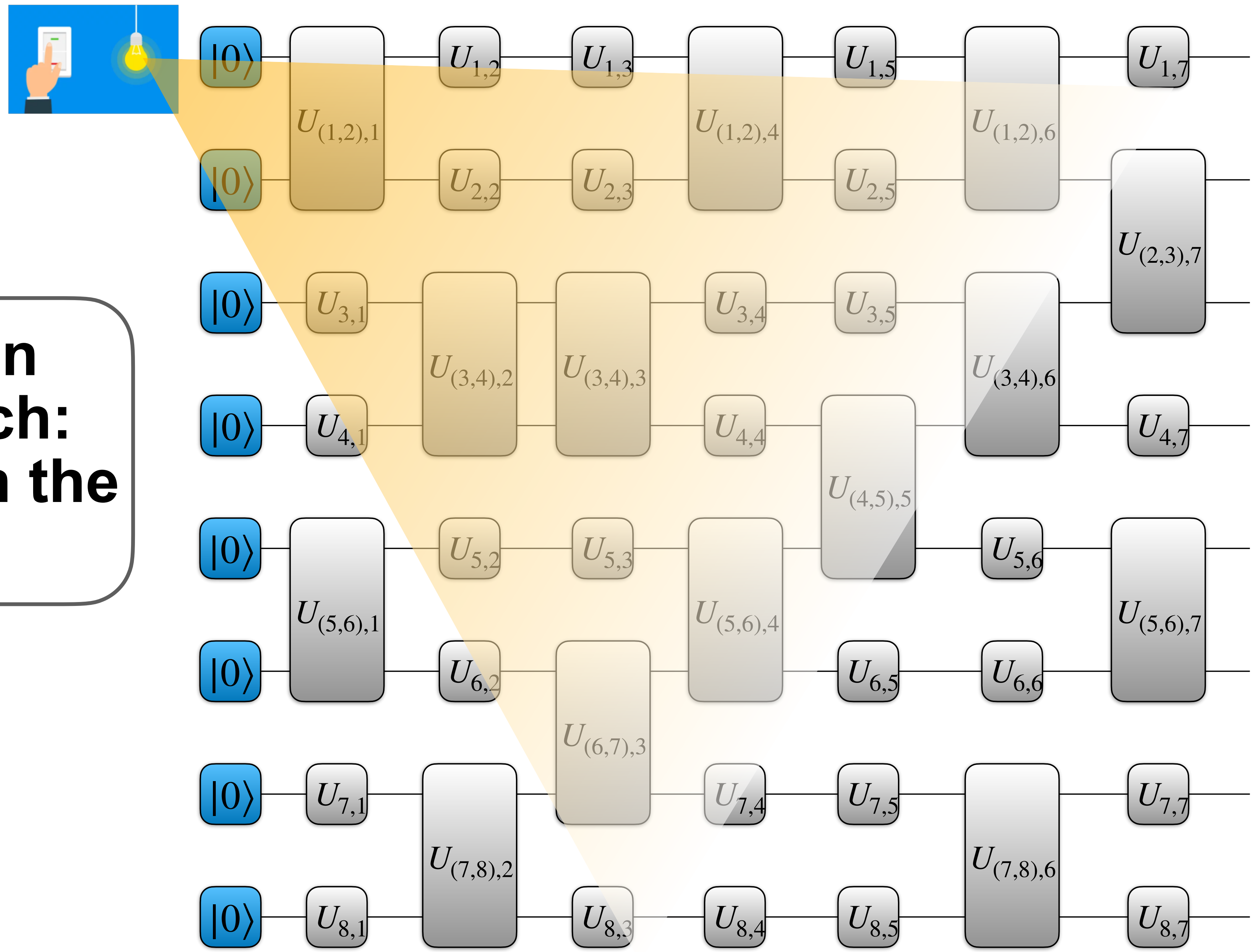
Time-Evolving Block Decimation (TEBD) algorithm [2]



[2] Y. Zhou, E. M. Stoudenmire, and X. Waintal, *Phys. Rev. X 10, 041038 (2020).*

DIPARTIMENTO
INTERATENEO
DI FISICA

Cluster-TEBD algorithm [1]



The zen approach: switch on the light!

[1] A. De Girolamo, P. Facchi, P. Rabl, S. Pascazio, C. Lupo, G. Magnifico, *TBA*

DIPARTIMENTO
INTERATENEO
DI FISICA

Cluster-TEBD algorithm [1]

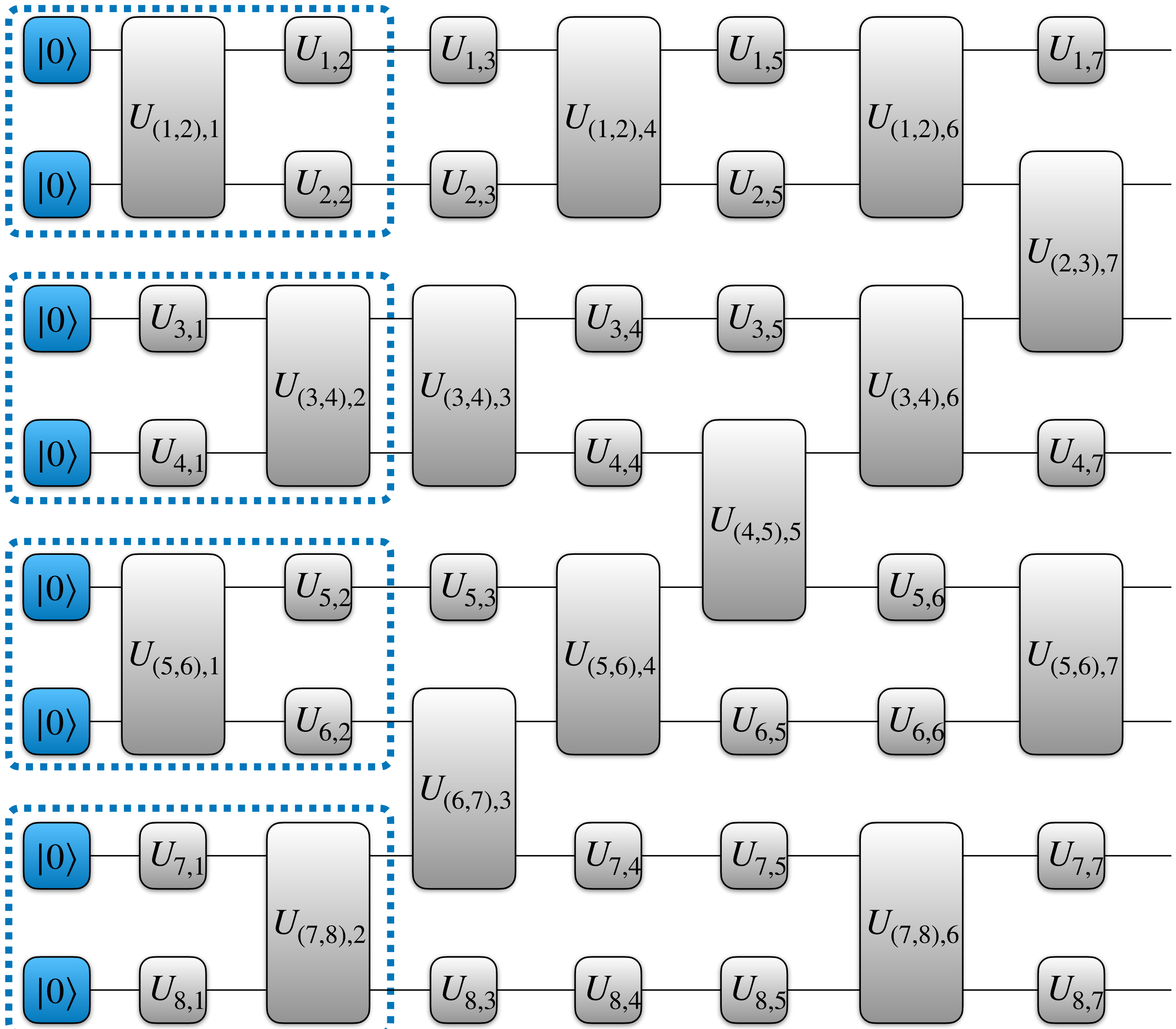
$Q_{max} = 5$

Cluster 1 $Q_2^{[1]} = 2$

Cluster 2 $Q_2^{[2]} = 2$

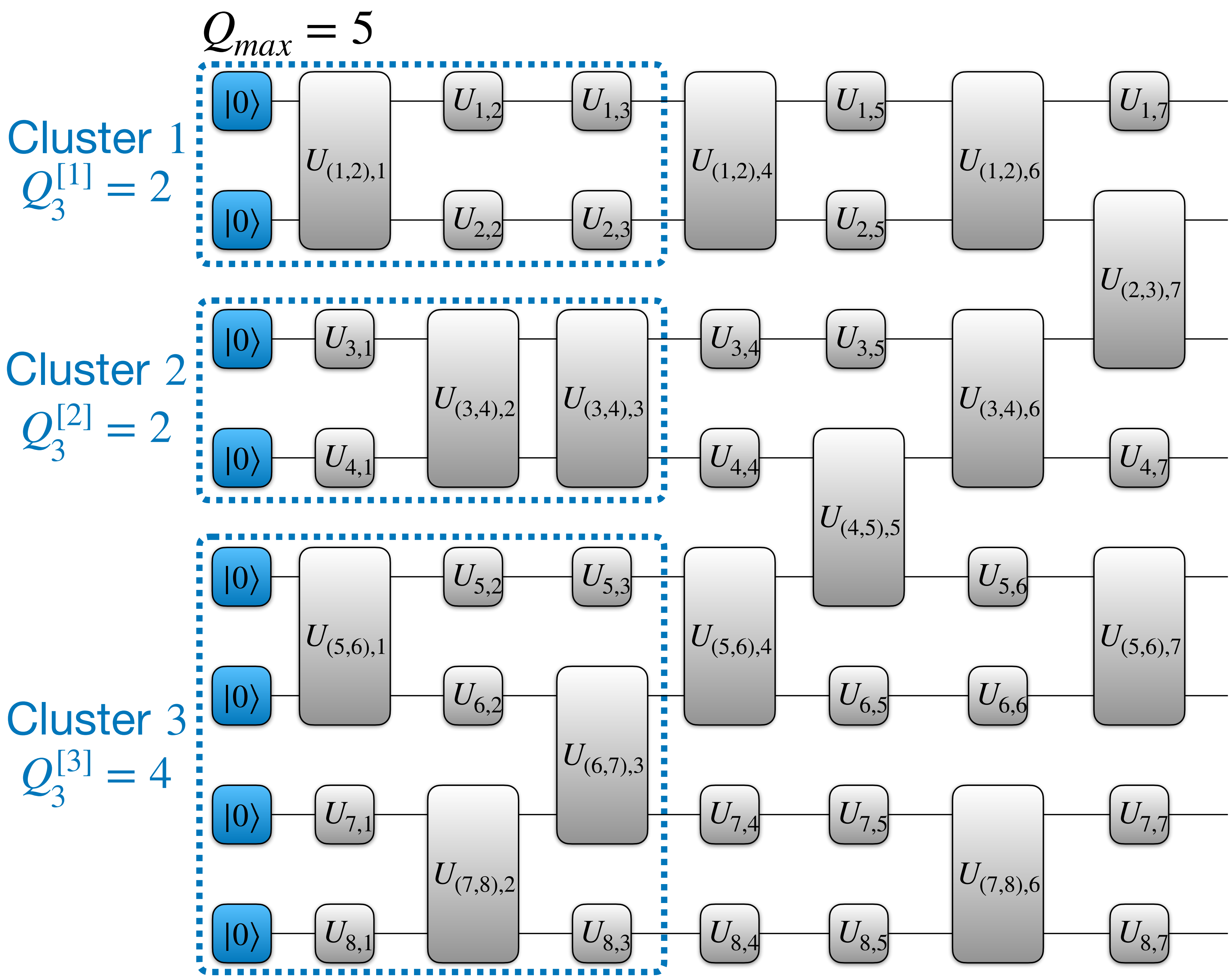
Cluster 3 $Q_2^{[3]} = 2$

Cluster 4 $Q_2^{[4]} = 2$



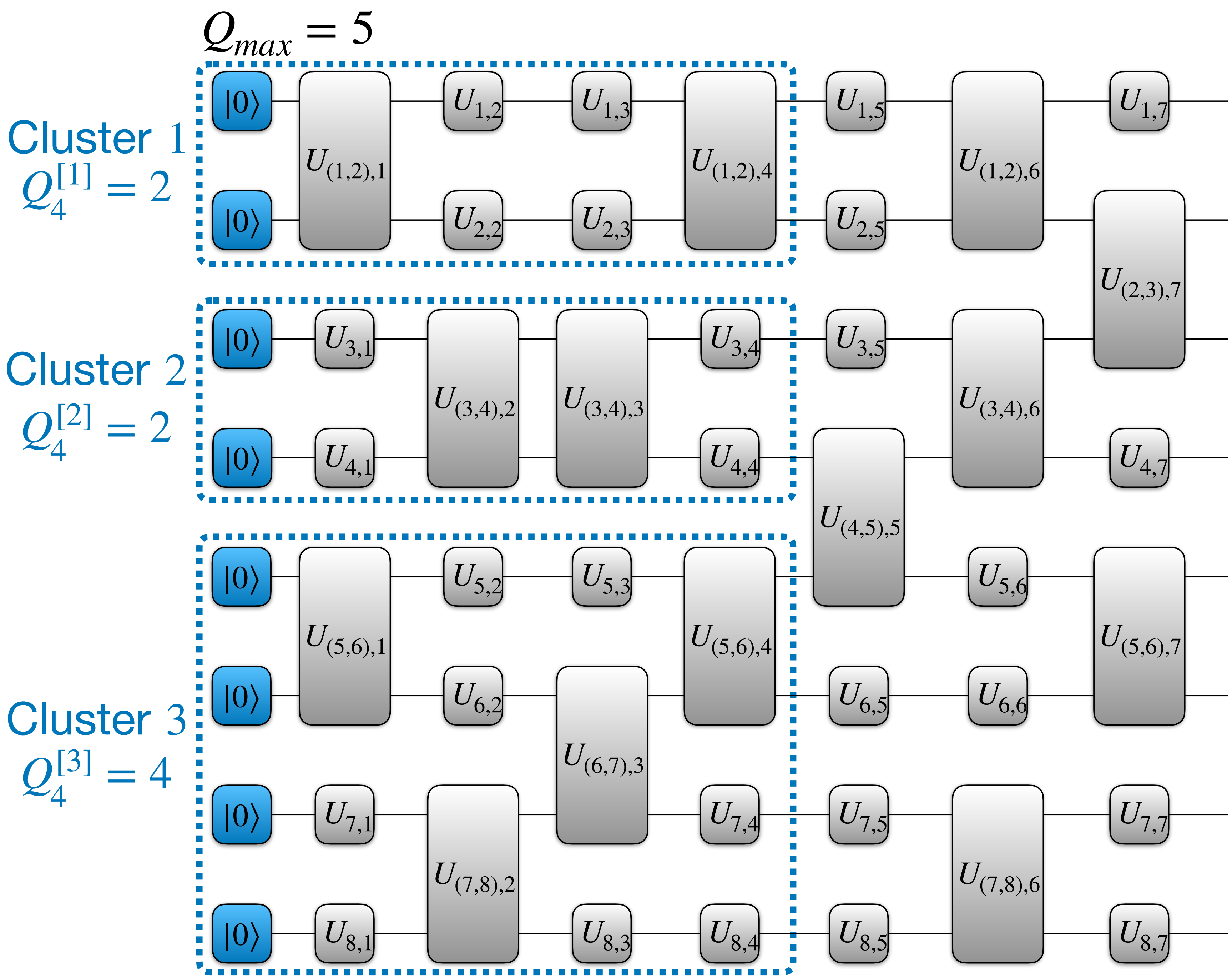
[1] A. De Girolamo, P. Facchi, P. Rabl, S. Pascazio, C. Lupo, G. Magnifico, *TBA*

Cluster-TEBD algorithm [1]



[1] A. De Girolamo, P. Facchi, P. Rabl, S. Pascazio, C. Lupo, G. Magnifico, *TBA*

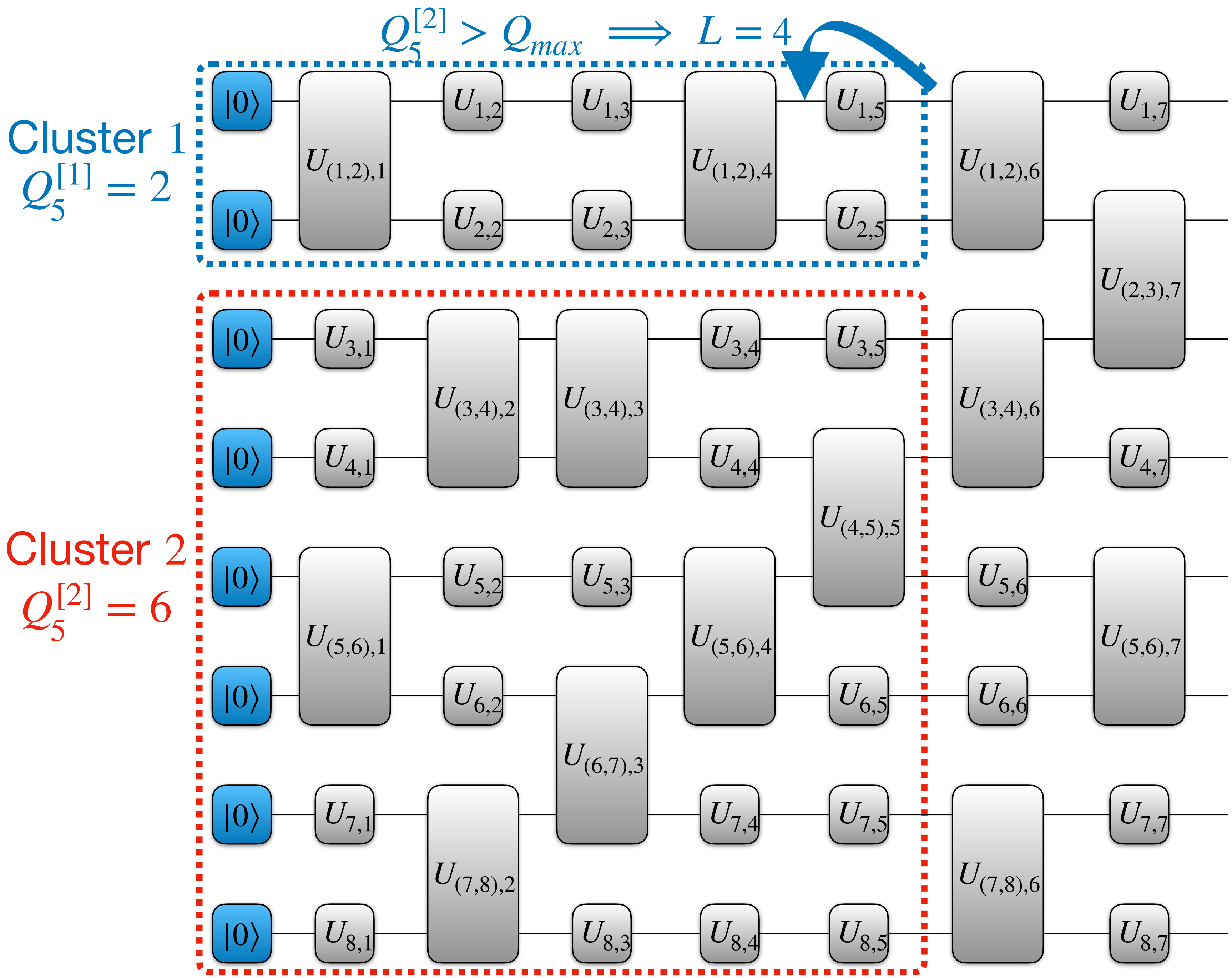
Cluster-TEBD algorithm [1]



[1] A. De Girolamo, P. Facchi, P. Rabl, S. Pascazio, C. Lupo, G. Magnifico, *TBA*

DIPARTIMENTO INTERATENEO DI FISICA

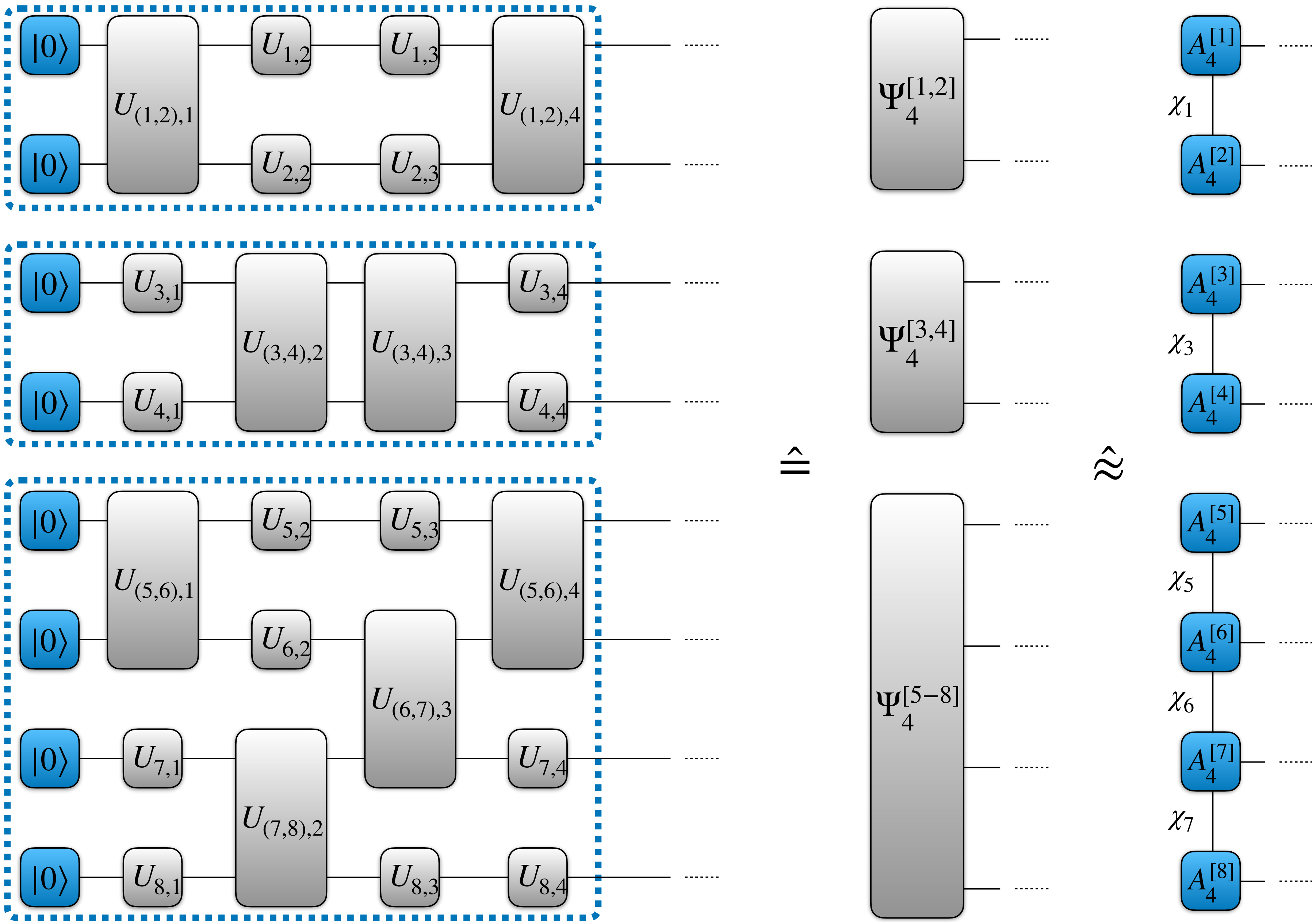
Cluster-TEBD algorithm [1]



[1] A. De Girolamo, P. Facchi, P. Rabl, S. Pascazio, C. Lupo, G. Magnifico, *TBA*

Cluster-TEBD algorithm [1]

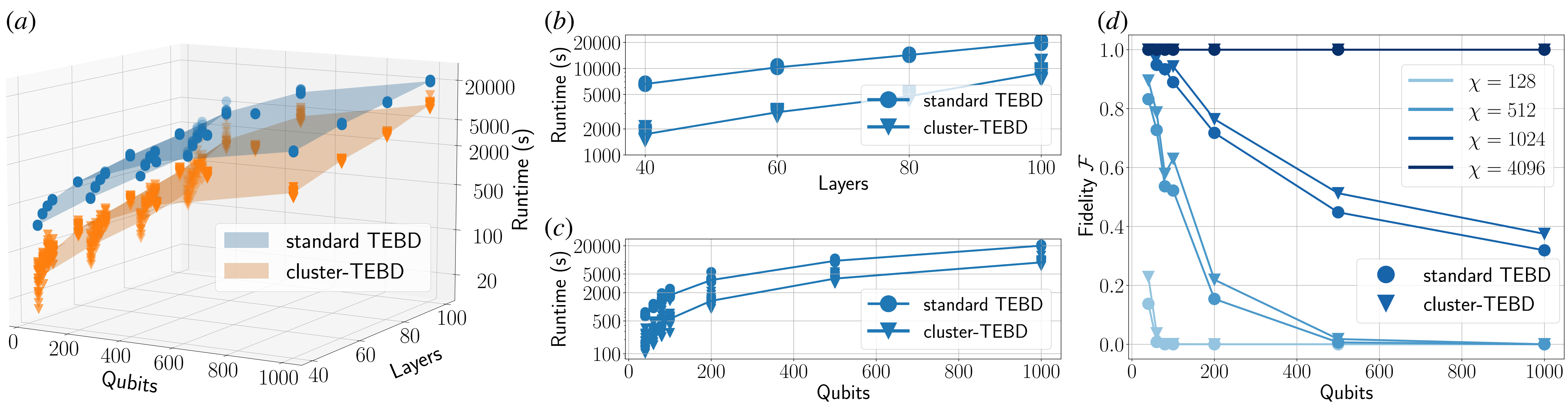
$Q_{max} = 5$



[1] A. De Girolamo, P. Facchi, P. Rabl, S. Pascazio, C. Lupo, G. Magnifico, *TBA*

Results - cluster-TEBD vs. standard TEBD [1]

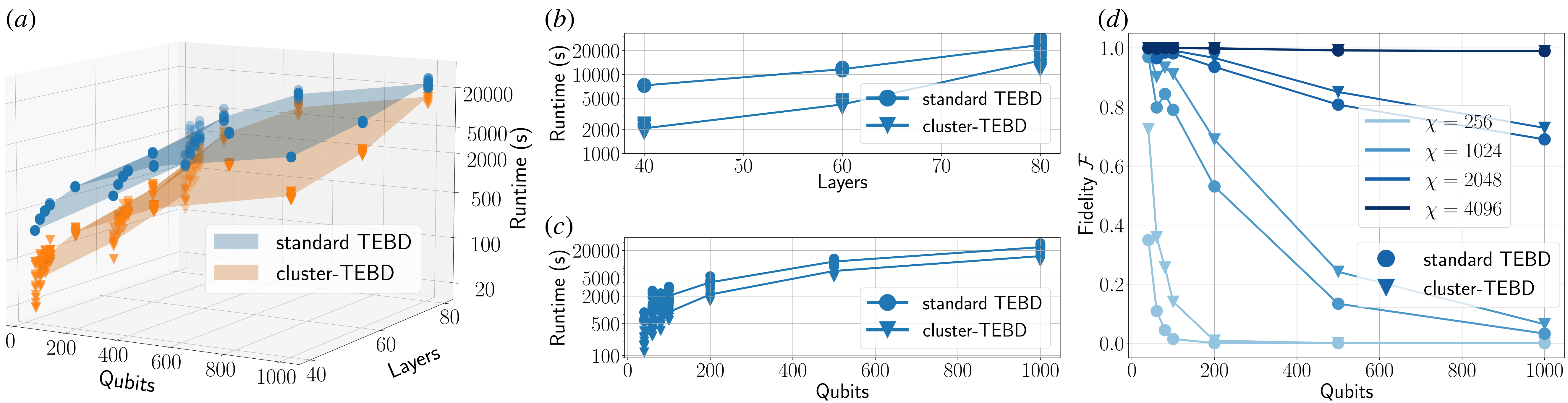
Clifford[4] random-structure quantum circuits:



[1] A. De Girolamo, P. Facchi, P. Rabl, S. Pascazio, C. Lupo, G. Magnifico, *TBA*
[4] D. Gottesman, *arXiv:quant-ph/9807006 [quant-ph], (1998)*.

Results - cluster-TEBD vs. standard TEBD [1]

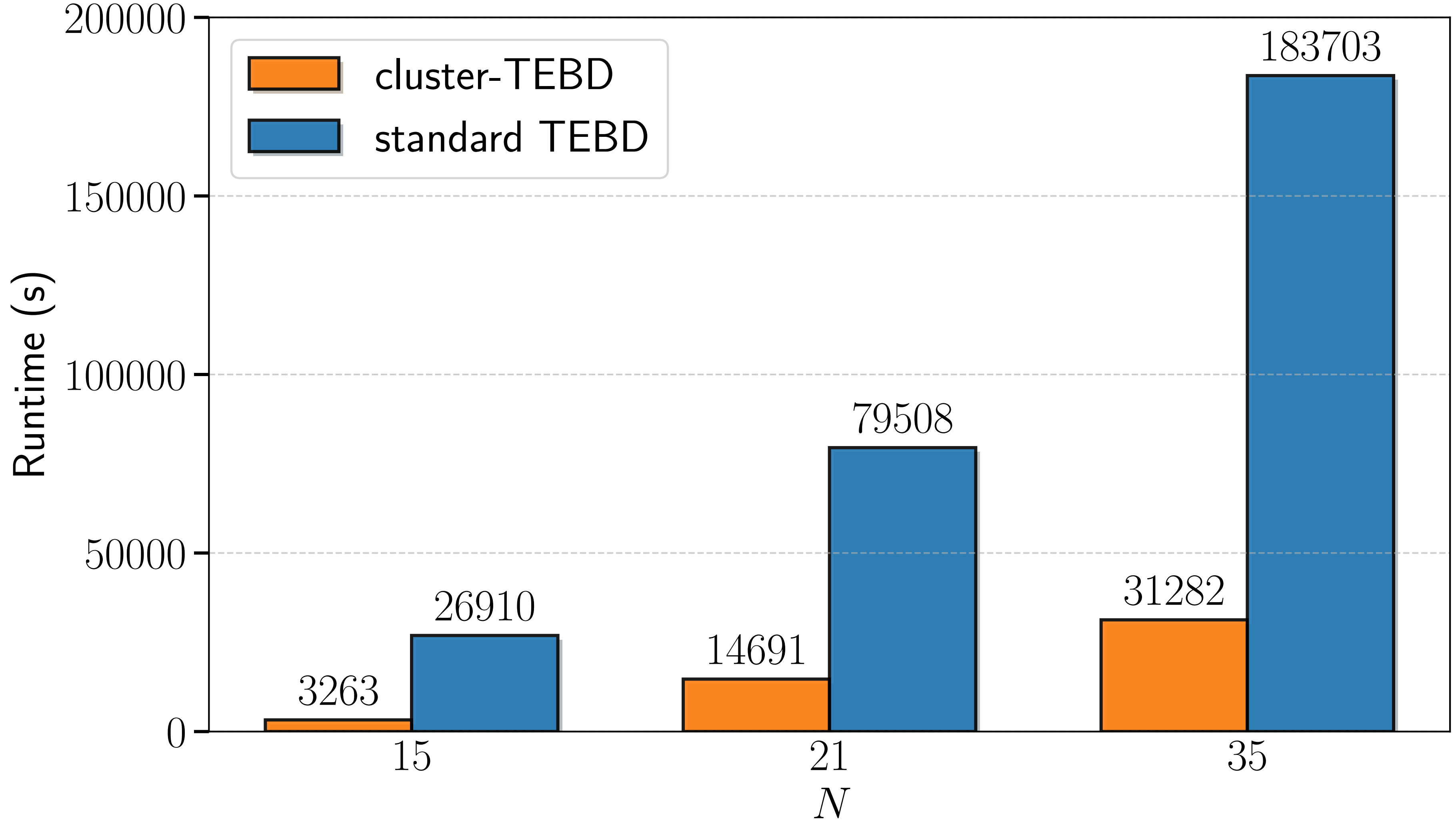
Non-Clifford[4] random-structure quantum circuits:



[1] A. De Girolamo, P. Facchi, P. Rabl, S. Pascazio, C. Lupo, G. Magnifico, *TBA*
[4] D. Gottesman, *arXiv:quant-ph/9807006 [quant-ph], (1998)*.

Results - cluster-TEBD vs. standard TEBD [1]

Shor's algorithm for factoring[5]:



[5] P. W. Shor, *SIAM Review 41, 303 (1999)*
[1] A. De Girolamo, P. Facchi, P. Rabl, S. Pascazio, C. Lupo, G. Magnifico, *TBA*

DIPARTIMENTO
INTERATENEO
DI FISICA

Conclusions

- Cluster-TEBD significantly outperforms standard TEBD in both runtime and fidelity

Next steps

- Apply framework for new ansätze (tree tensor networks) for 2D topologies
- Exploiting clustering techniques in quantum compilation
- Digital twin of realistic quantum computers

QuanTeN.jl

A Julia package for optimized simulations of quantum circuits with tensor networks

COMING SOON

THANK YOU!

Giuseppe Magnifico

Cosmo Lupo

Peter Rabl

Paolo Facchi

Saverio Pascazio

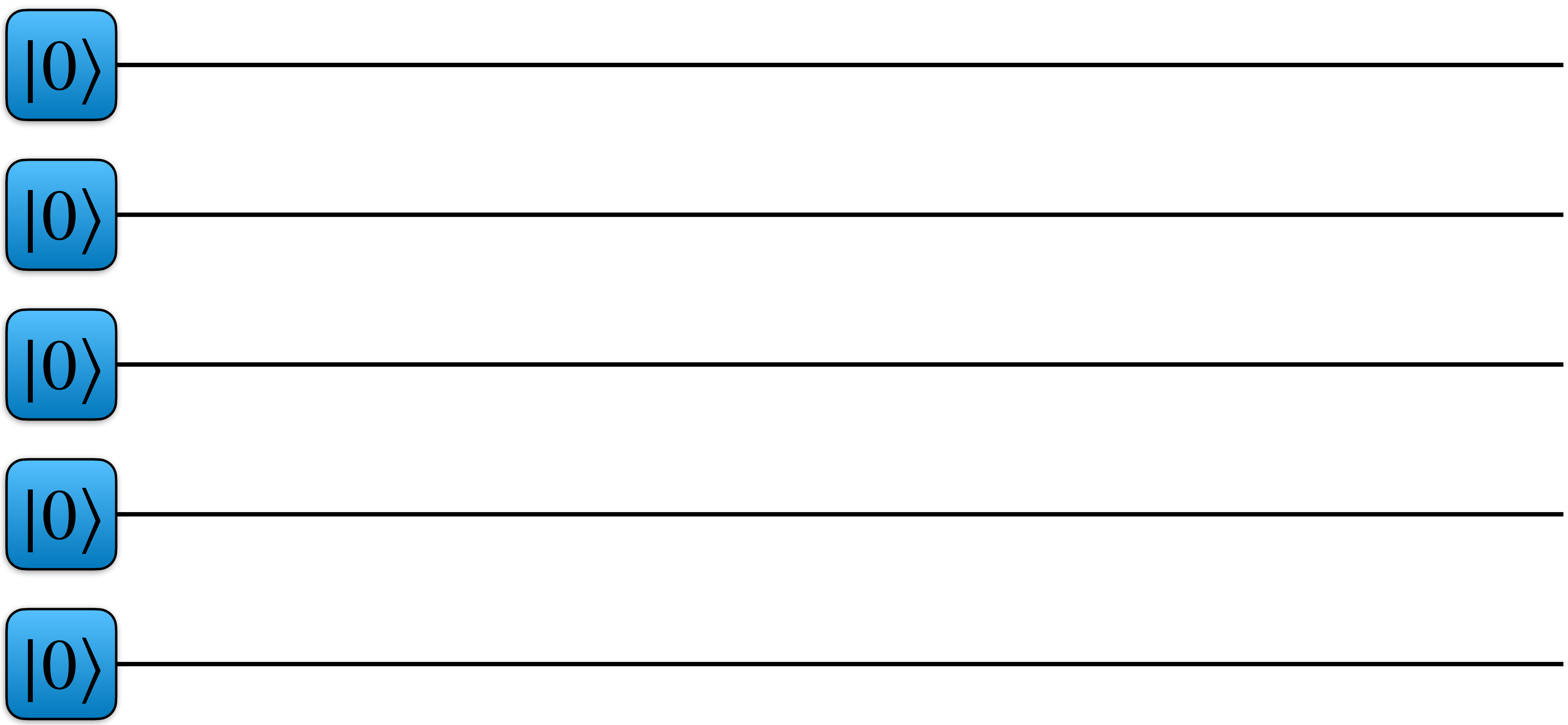
DIPARTIMENTO
INTERATENEO
DI FISICA

Dynamical cluster-based optimization of tensor network algorithms for simulating quantum circuits with finite fidelity

SUPPLEMENTARY MATERIAL

Generating random-structure quantum circuits

Toss a coin and apply either a single or a two qubit gate with 50% probability



GATES	Clifford	Non-Clifford
Single-qubit	H, X, Y, Z	$T, P\,(3\pi/4), \sqrt[4]{X}, \sqrt{(X+Y)/2}$
Two-qubit	$CNOT, C\text{-}Y, C\text{-}Z, SWAP$	$C\text{-}H, C\text{-}S, C\text{-}T, \sqrt{SWAP}$

DIPARTIMENTO
INTERATENEO
DI FISICA

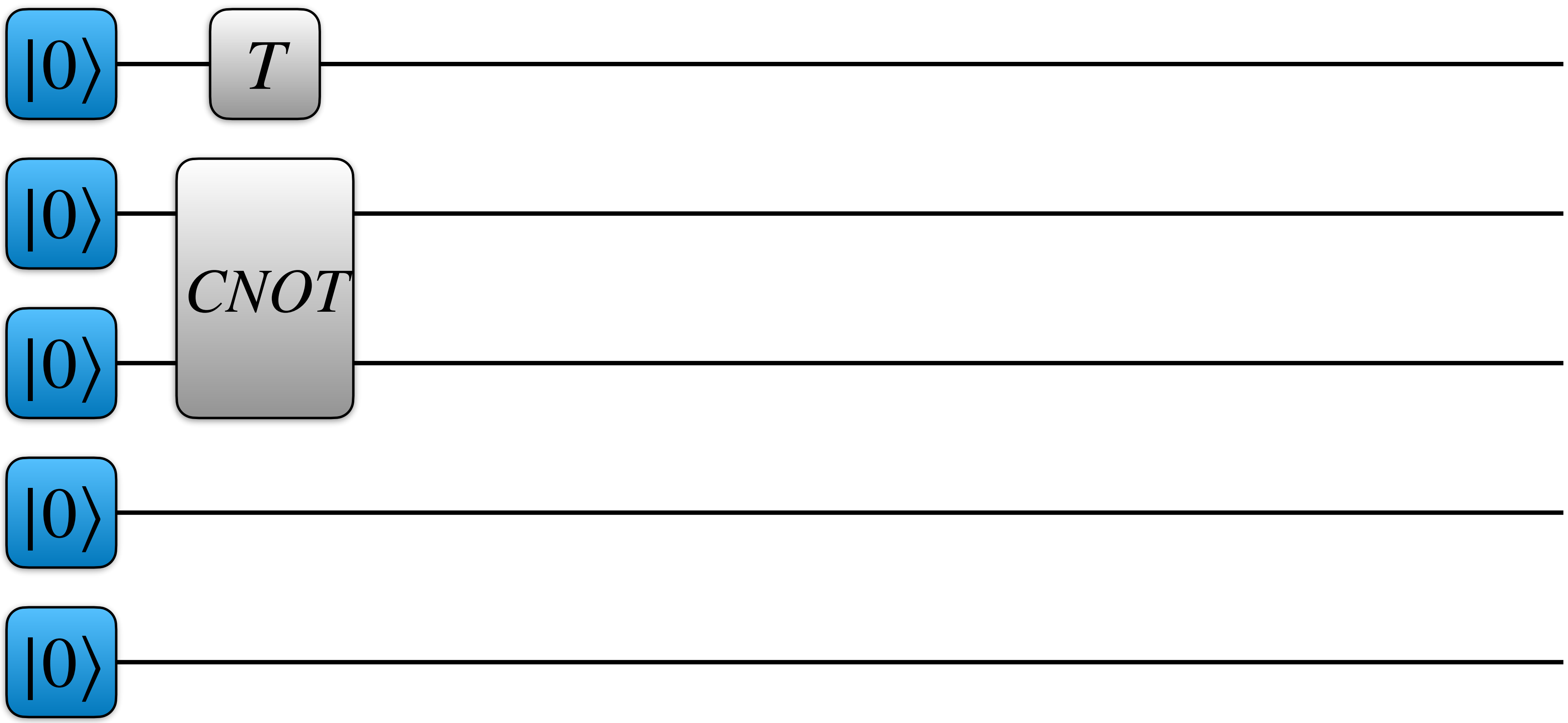
Generating random-structure quantum circuits

Toss a coin and apply either a single or a two qubit gate with 50% probability

GATES	Clifford	Non-Clifford
Single-qubit	H, X, Y, Z	$T, P(3\pi/4), \sqrt[4]{X}, \sqrt{(X+Y)/2}$
Two-qubit	$CNOT, C\text{-}Y, C\text{-}Z, SWAP$	$C\text{-}H, C\text{-}S, C\text{-}T, \sqrt{SWAP}$

Generating random-structure quantum circuits

Toss a coin and apply either a single or a two qubit gate with 50% probability



GATES	Clifford	Non-Clifford
Single-qubit	H, X, Y, Z	$T, P(3\pi/4), \sqrt[4]{X}, \sqrt{(X+Y)/2}$
Two-qubit	$CNOT, C\text{-}Y, C\text{-}Z, SWAP$	$C\text{-}H, C\text{-}S, C\text{-}T, \sqrt{SWAP}$

Generating random-structure quantum circuits

Toss a coin and apply either a single or a two qubit gate with 50% probability

GATES	Clifford	Non-Clifford
Single-qubit	H, X, Y, Z	$T, P(3\pi/4), \sqrt[4]{X}, \sqrt{(X+Y)/2}$
Two-qubit	$CNOT, C\text{-}Y, C\text{-}Z, SWAP$	$C\text{-}H, C\text{-}S, C\text{-}T, \sqrt{SWAP}$

DIPARTIMENTO
INTERATENEO
DI FISICA

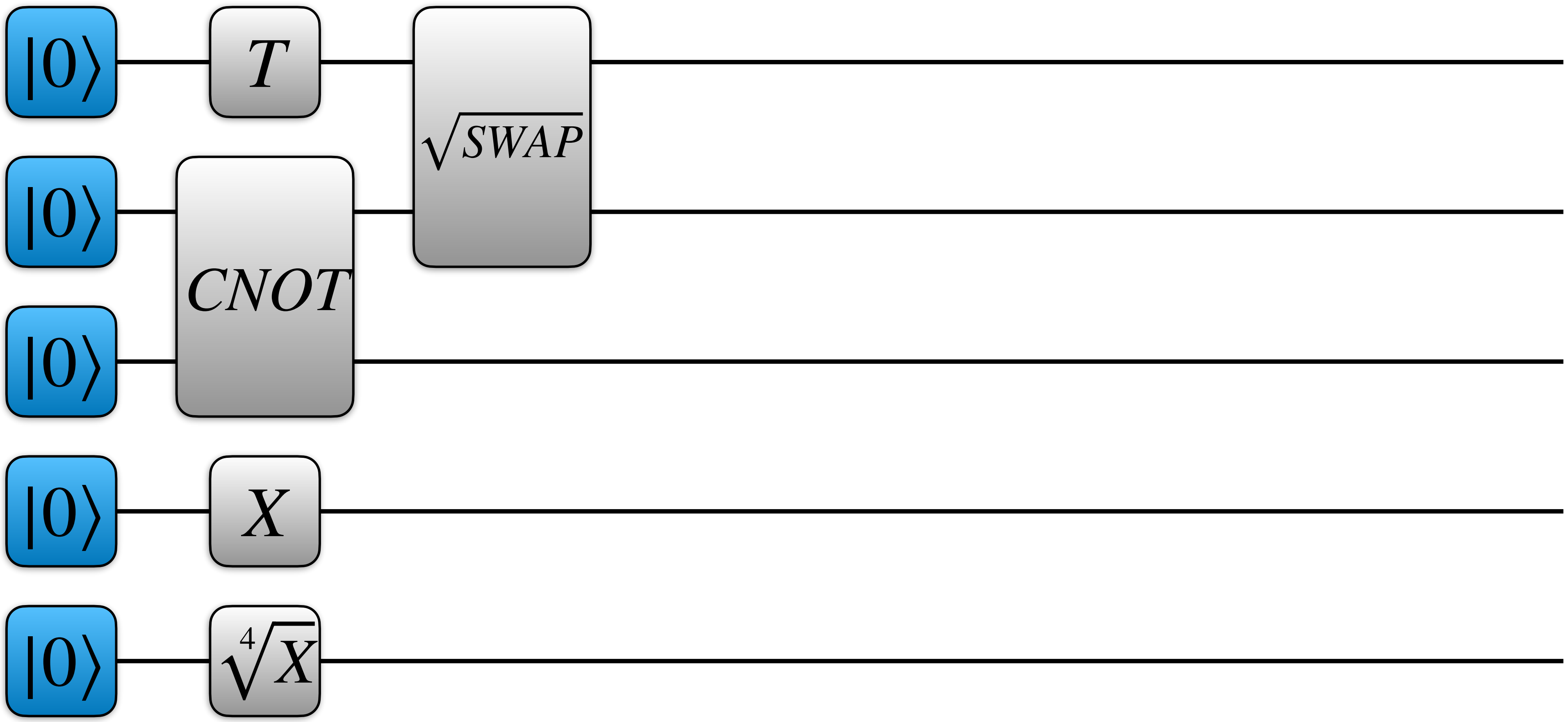
Generating random-structure quantum circuits

Toss a coin and apply either a single or a two qubit gate with 50% probability

GATES	Clifford	Non-Clifford
Single-qubit	H, X, Y, Z	$T, P\,(3\pi/4), \sqrt[4]{X}, \sqrt{(X+Y)/2}$
Two-qubit	$CNOT, C\text{-}Y, C\text{-}Z, SWAP$	$C\text{-}H, C\text{-}S, C\text{-}T, \sqrt{SWAP}$

Generating random-structure quantum circuits

Toss a coin and apply either a single or a two qubit gate with 50% probability

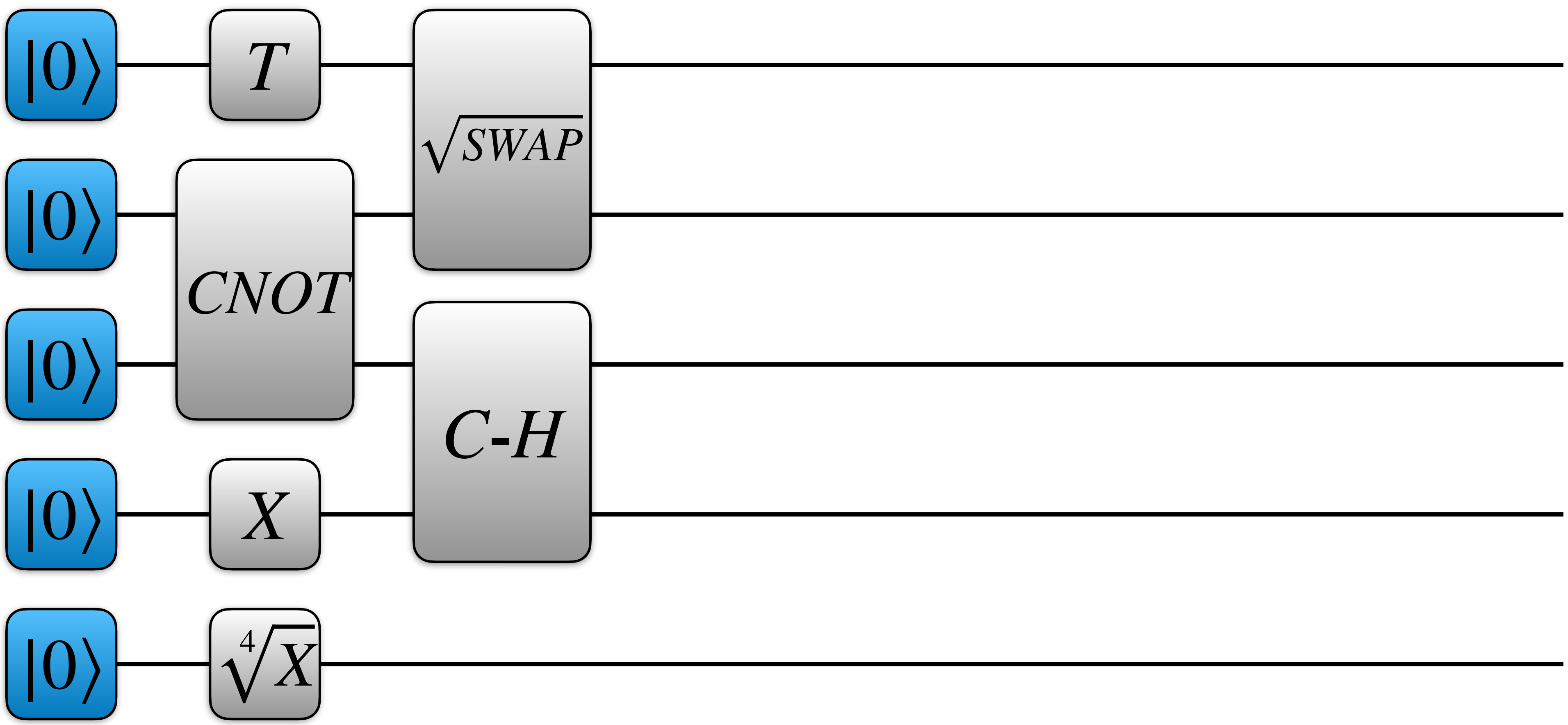


GATES	Clifford	Non-Clifford
Single-qubit	H, X, Y, Z	$T, P\,(3\pi/4), \sqrt[4]{X}, \sqrt{(X+Y)/2}$
Two-qubit	$CNOT, C\text{-}Y, C\text{-}Z, SWAP$	$C\text{-}H, C\text{-}S, C\text{-}T, \sqrt{SWAP}$

DIPARTIMENTO INTERATENEO DI FISICA

Generating random-structure quantum circuits

Toss a coin and apply either a single or a two qubit gate with 50% probability

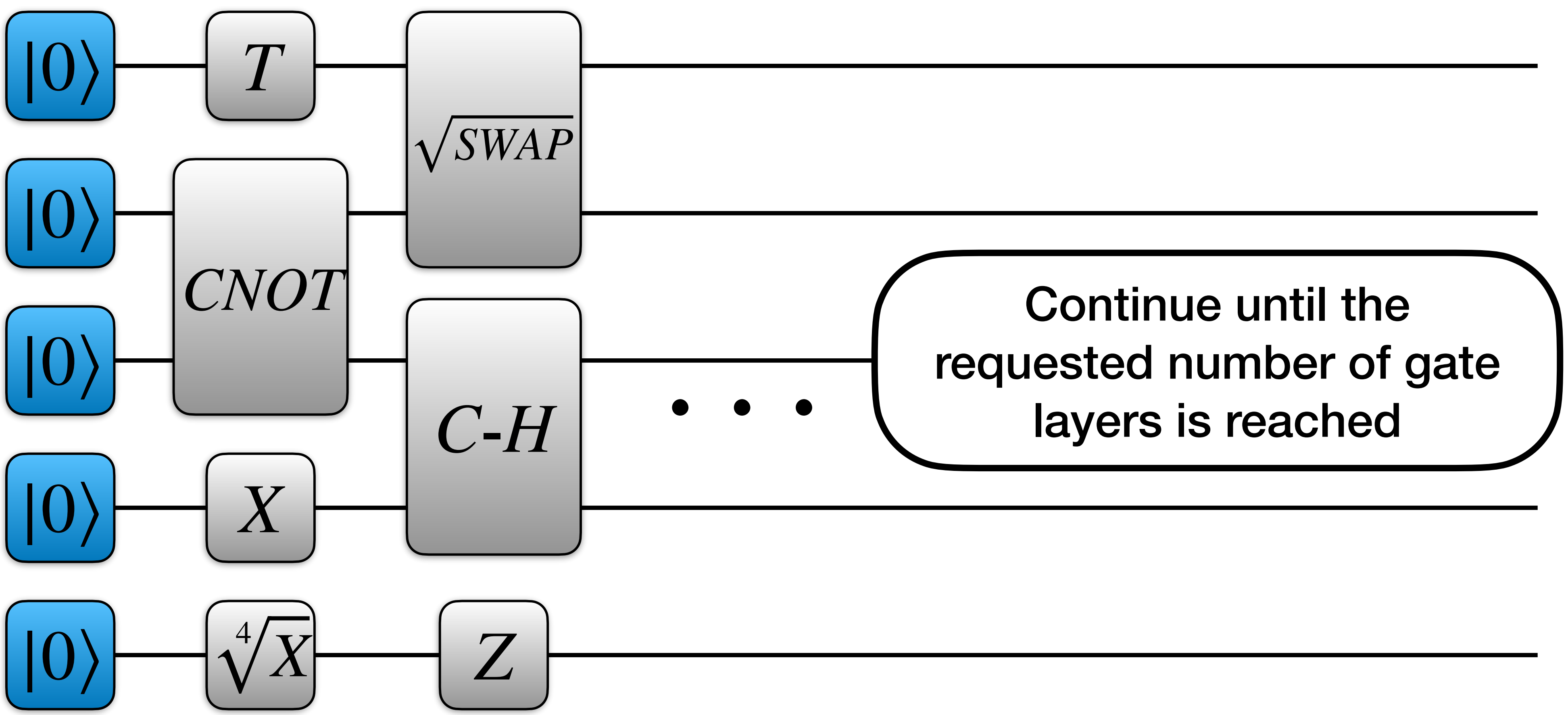


GATES	Clifford	Non-Clifford
Single-qubit	H, X, Y, Z	$T, P(3\pi/4), \sqrt[4]{X}, \sqrt{(X+Y)/2}$
Two-qubit	$CNOT, C\text{-}Y, C\text{-}Z, SWAP$	$C\text{-}H, C\text{-}S, C\text{-}T, \sqrt{SWAP}$

DIPARTIMENTO
INTERATENEO
DI FISICA

Generating random-structure quantum circuits

Toss a coin and apply either a single or a two qubit gate with 50% probability



GATES	Clifford	Non-Clifford
Single-qubit	H, X, Y, Z	$T, P\,(3\pi/4), \sqrt[4]{X}, \sqrt{(X+Y)/2}$
Two-qubit	$CNOT, C\text{-}Y, C\text{-}Z, SWAP$	$C\text{-}H, C\text{-}S, C\text{-}T, \sqrt{SWAP}$