Efficient Bipartite Distributed Quantum Computing

Tim Forrer (Murao Group)

Japanese-French Quantum Information Workshop 2023

13th December 2023

Collaborators

Entanglement-efficient bipartite-distributed quantum computing

Jun-Yi Wu[1,2], Kosuke Matsui[3], Tim Forrer[3], Akihito Soeda[3,4,5], Pablo Andrés-Martínez[6], Daniel Mills[6], Luciana Henaut[6], and Mio Murao[3]

[1]Department of Physics and Center for Advanced Quantum Computing, Tamkang University, 151 Yingzhuan Rd., New Taipei City 25137, Taiwan, ROC

[2]Physics Division, National Center for Theoretical Sciences, Taipei 10617, Taiwan, ROC

[3]The University of Tokyo, Hongo 7-3-1, Bunkyo-ku, Tokyo 113-0033, Japan

[4]Principles of Informatics Research Division, National Institute of Informatics, 2-1-2 Hitotsubashi, Chiyoda-ku, Tokyo 101-8430, Japan

[5]Department of Informatics, School of Multidisciplinary Sciences, SOKENDAI (The Graduate University for Advanced Studies), 2-1-2 Hitotsubashi, Chiyoda-ku, Tokyo 101-8430, Japan

[6]Quantinuum, Terrington House, 13-15 Hills Road, Cambridge CB2 1NL, UK

Contents

Contents

Efficient bipartite distributed quantum computing

- Notation & Terminology

Contents

Efficient bipartite distributed quantum computing

- Notation & Terminology
- Classical inspiration
- Quantum twist
- EJPP protocol

Contents

Efficient bipartite distributed quantum computing

- Notation & Terminology
- Classical inspiration
- Quantum twist
- EJPP protocol
- Our proposal

Contents

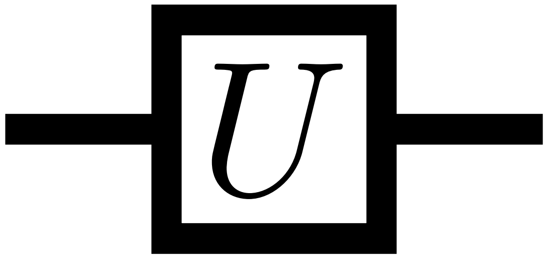
Contents

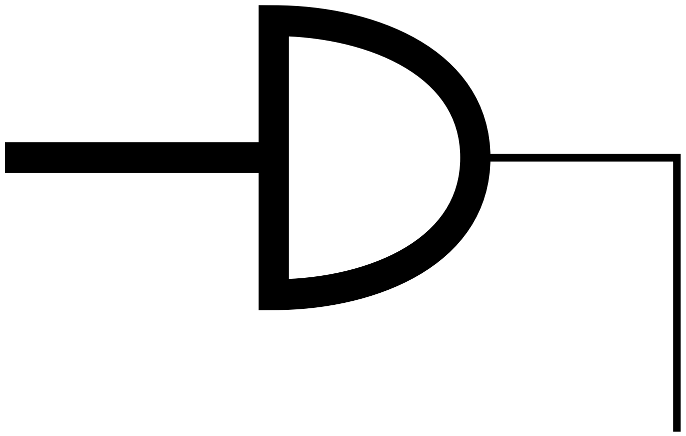
Notation and Terminology

Quantum computations described by quantum circuits acting on qubits

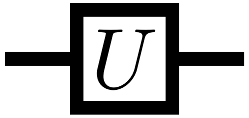
Quantum circuits are built from:

- Unitary quantum gates (inc. classical control)
- Projective measurements (in computational basis)

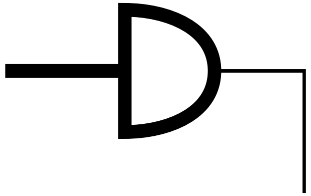




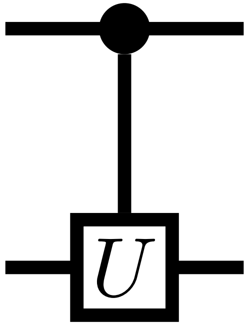
Terminology and Notation



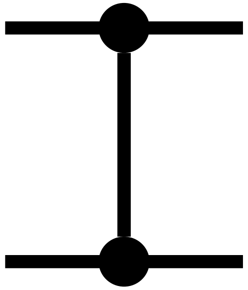
:= Single qubit unitary



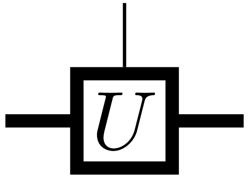
:= Computational basis measurement



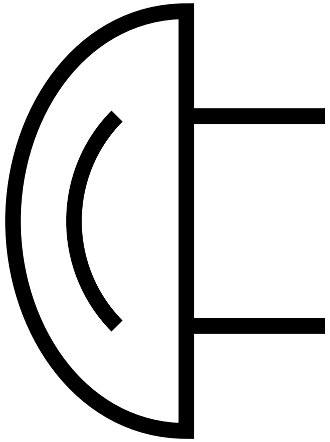
:= Quantum control unitary



:= CZ unitary



:= Classical control unitary



:= Bell State

Motivation

"Useful" quantum circuits need lots of qubits…

…but scaling quantum computers is difficult

How can we still run these large circuits?

This is **not a uniquely quantum** problem

Distributed Quantum Computing

Classical computers also have computational bottlenecks

Solution: Distributed computing

Distributed Quantum Computing

E.g. protein folding

FOLDING
@HOME

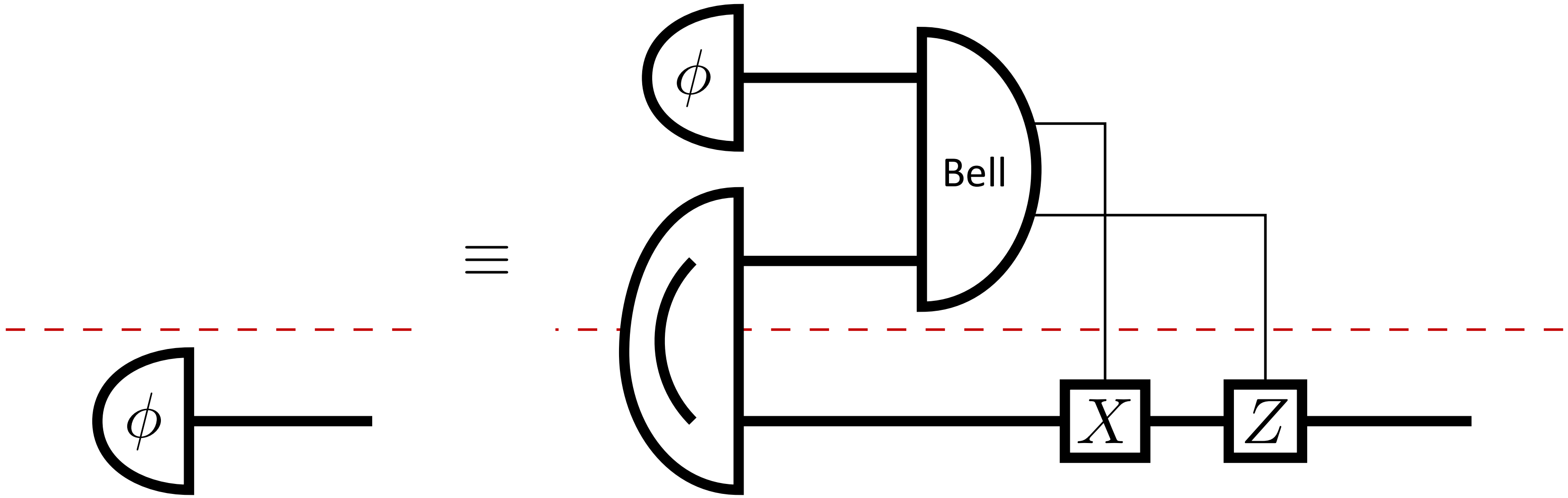
Distributed Quantum Computing

Question: How can we build distributed computing systems for quantum computers?

Two steps:

1. Break up computation
2. Connect computers to pass information as needed

Distributed Quantum Computing

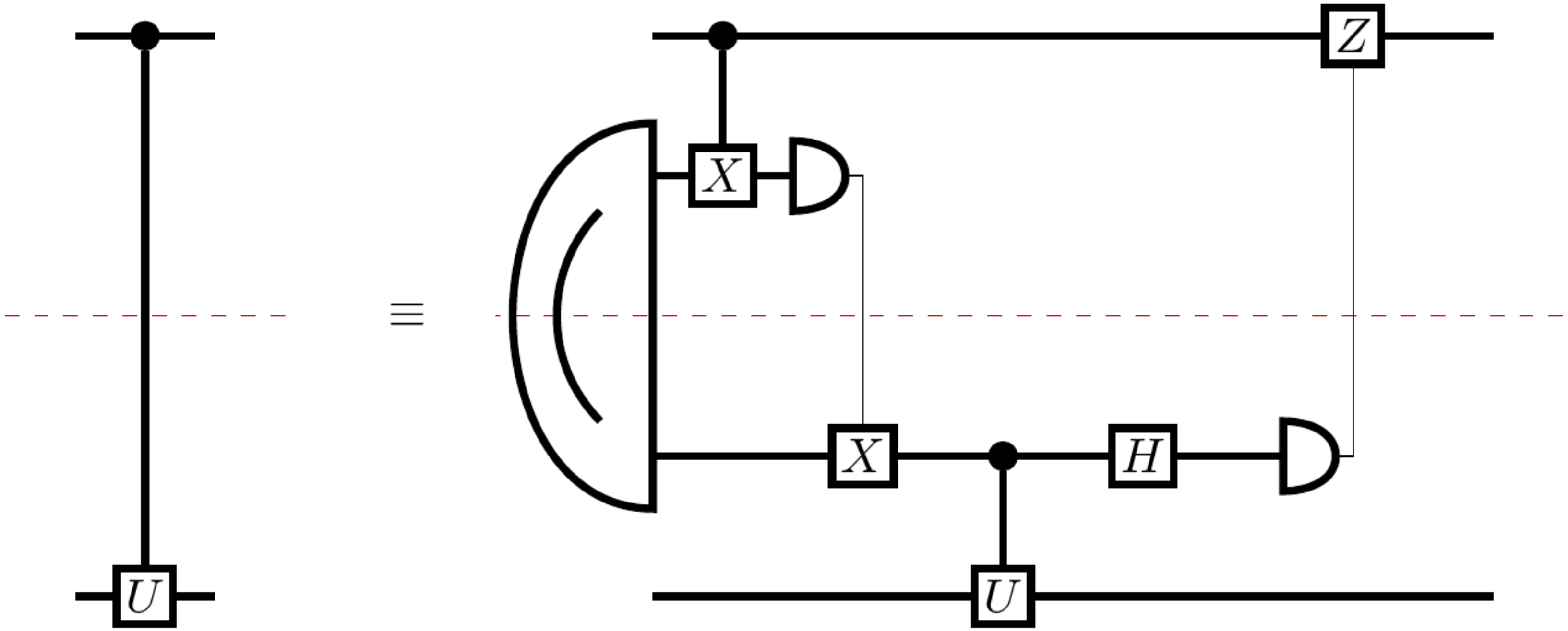


But can we do better?

≫Yes!

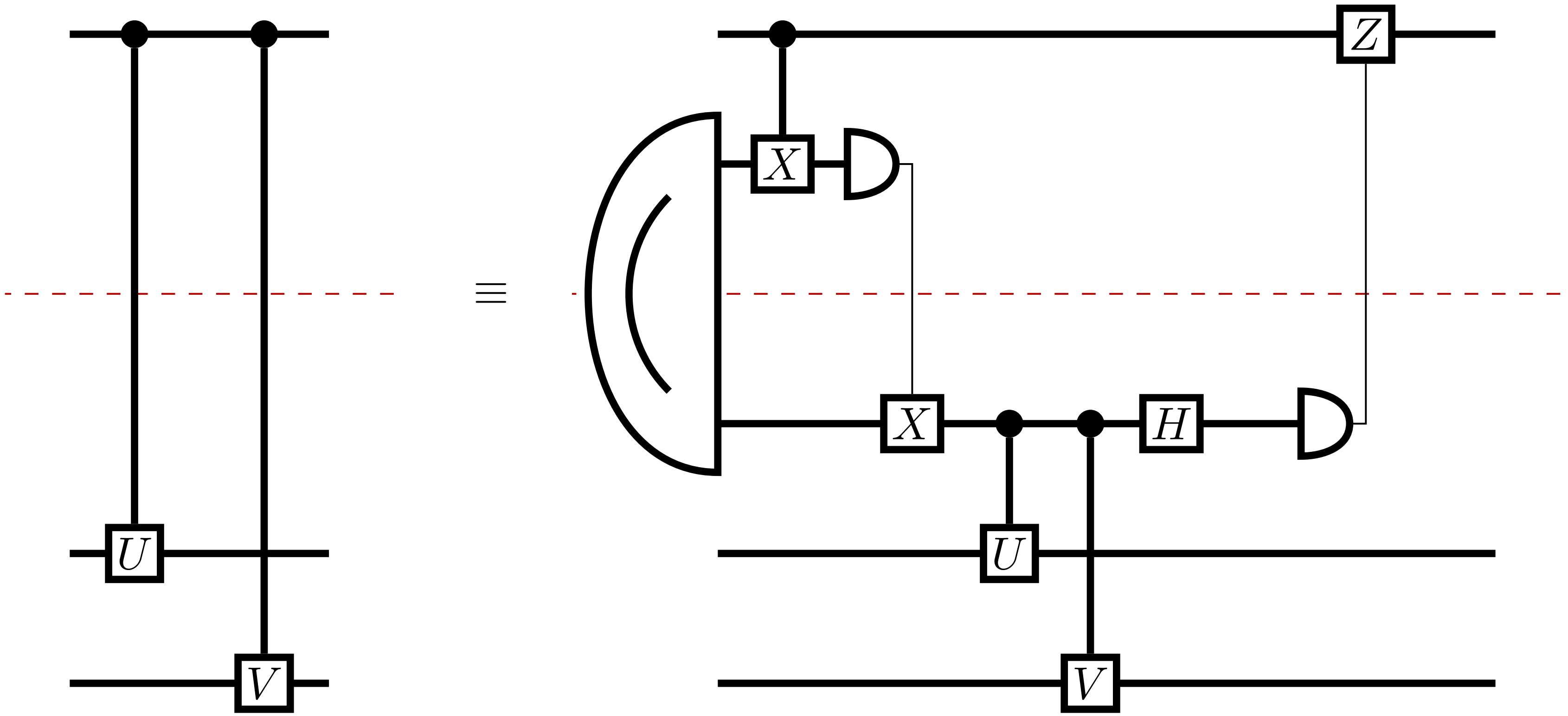
Distributed Quantum Computing

“EJPP” Protocol

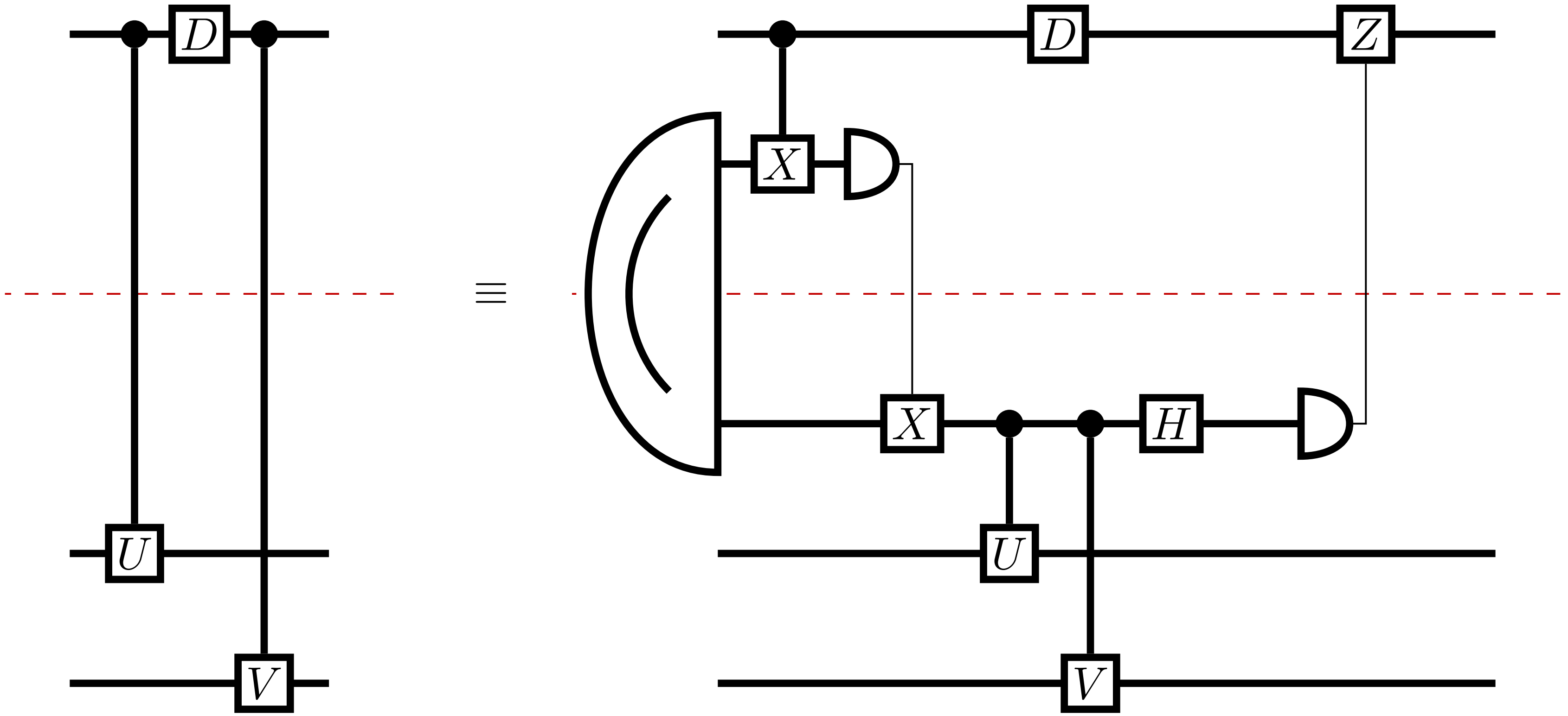


J. Eisert, K. Jacobs, P. Papadopoulos, and M. B. Plenio.
Optimal local implementation of nonlocal quantum gates. Physical Review A, 2000 62: 052317

Distributed Quantum Computing

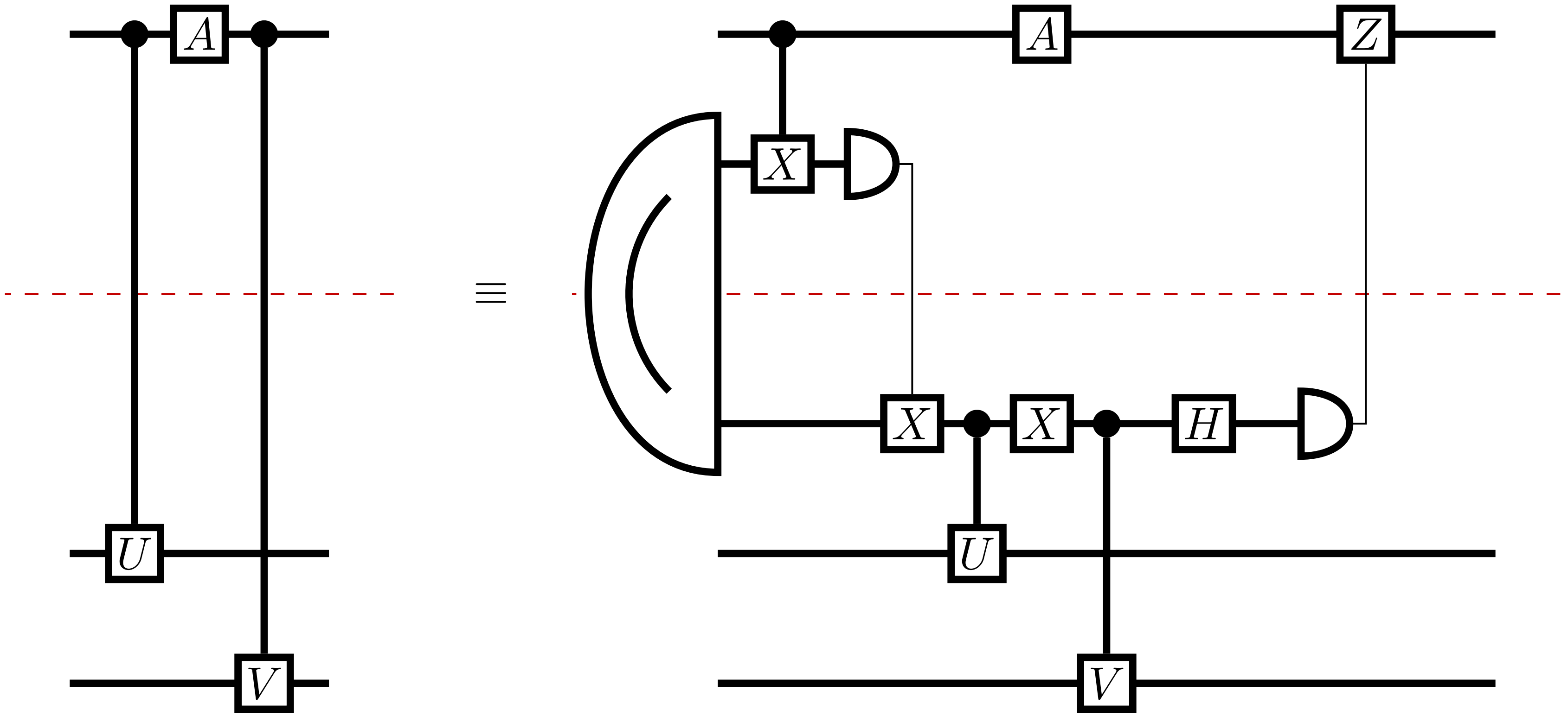


Distributed Quantum Computing



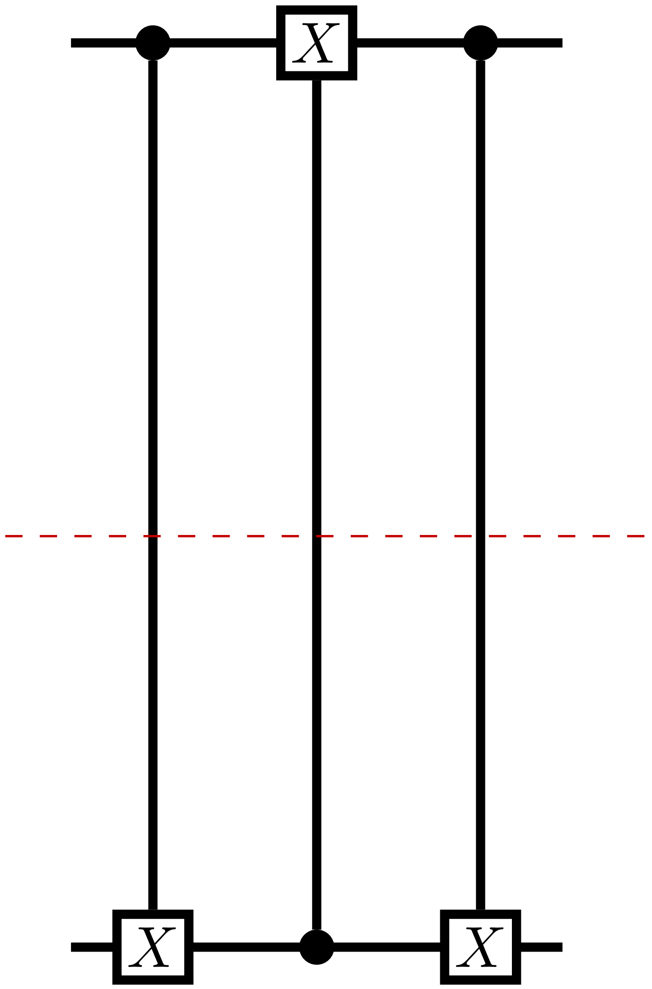
Diagonal gates don't matter

Distributed Quantum Computing

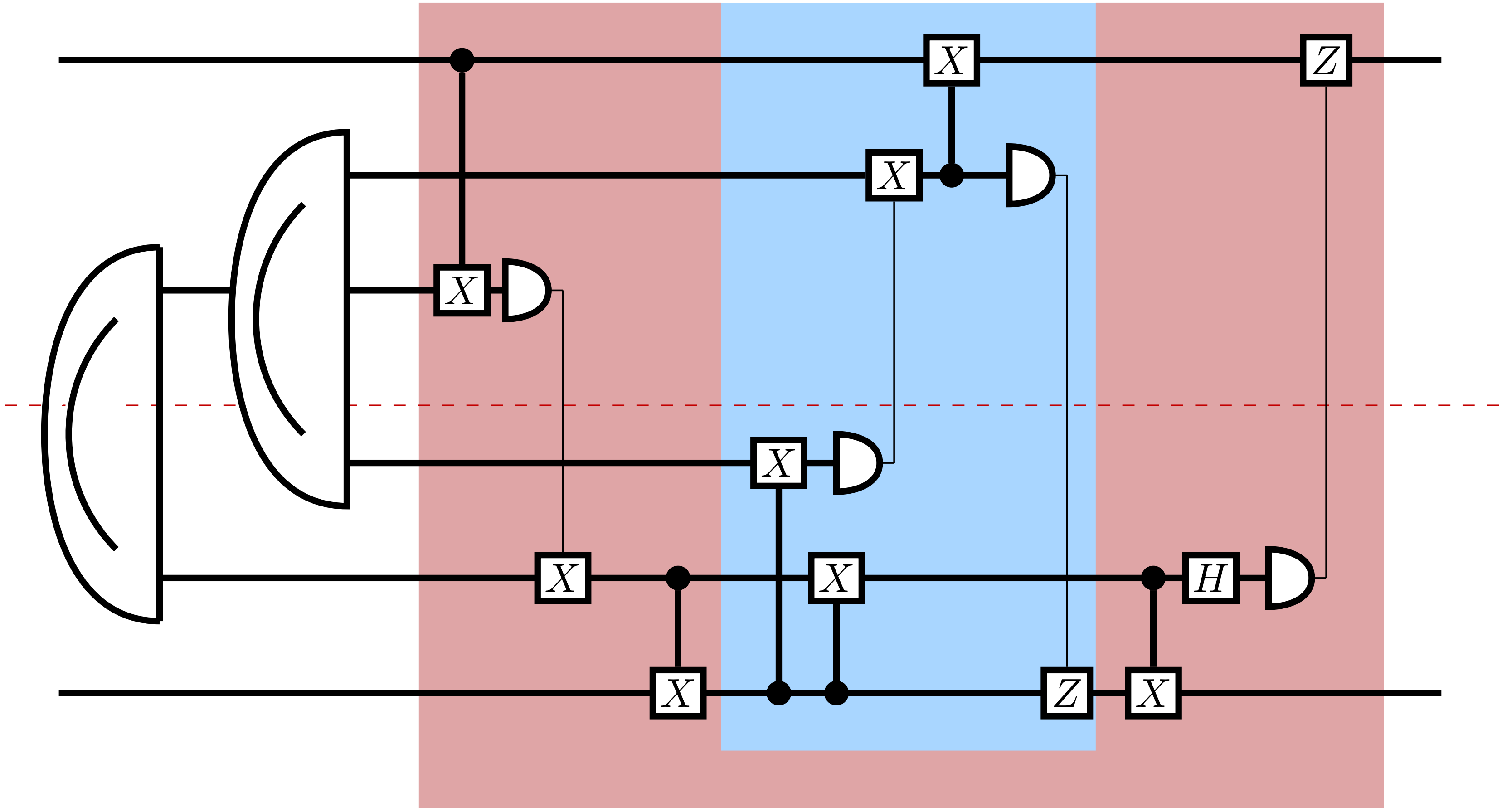


Anti-diagonal gates don't matter

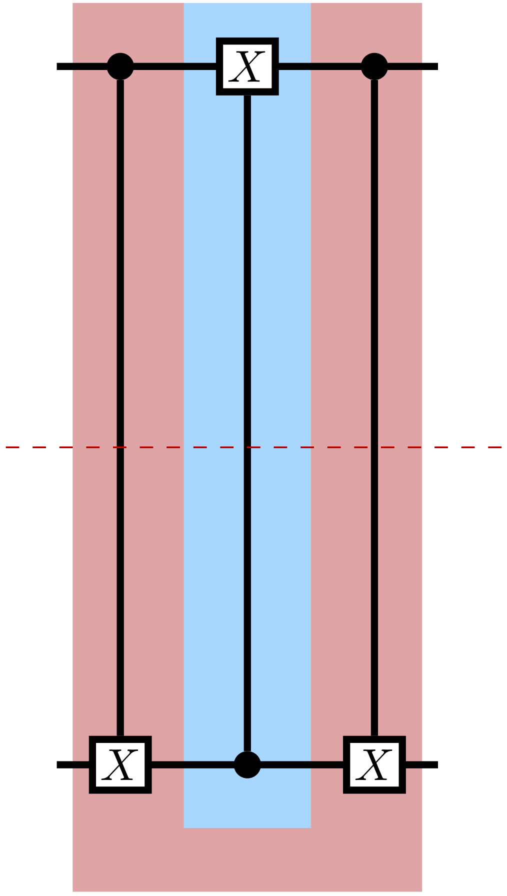
Distributed Quantum Computing



Distributed Quantum Computing

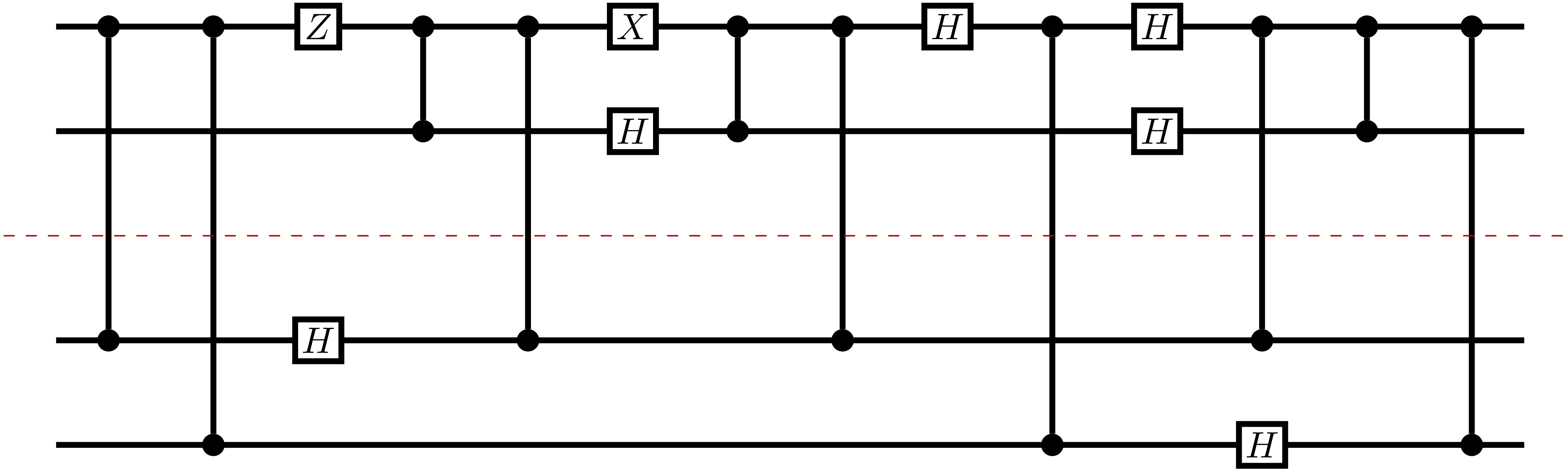


≡



Bipartite Distributed Quantum Computing

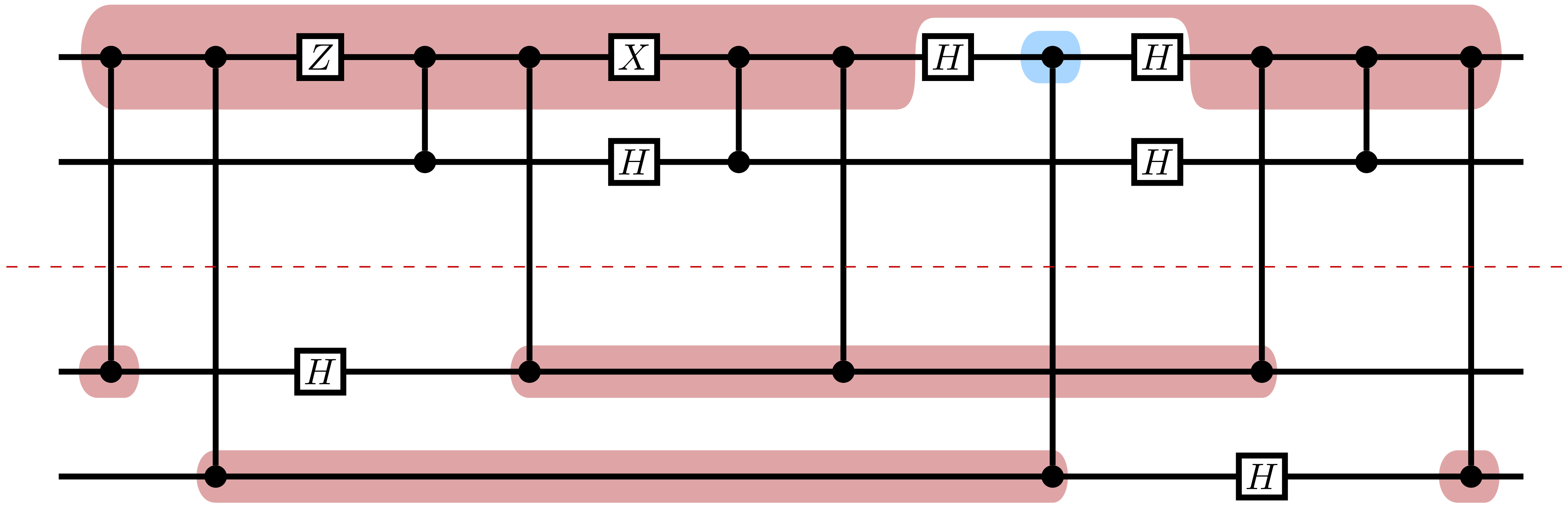
Given



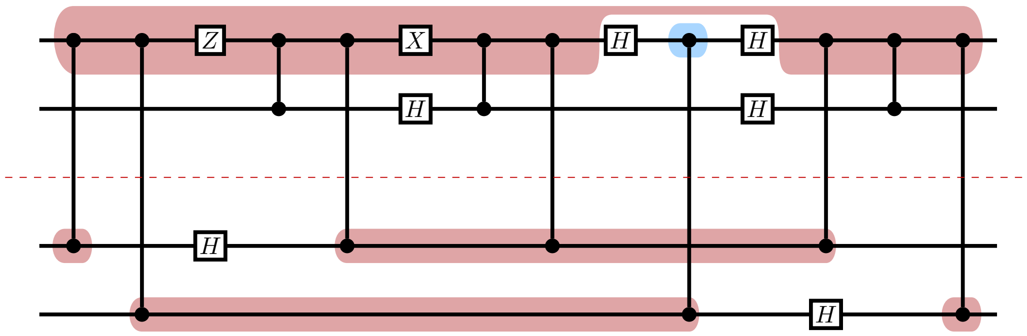
Find equivalent circuit with no non-local quantum gates

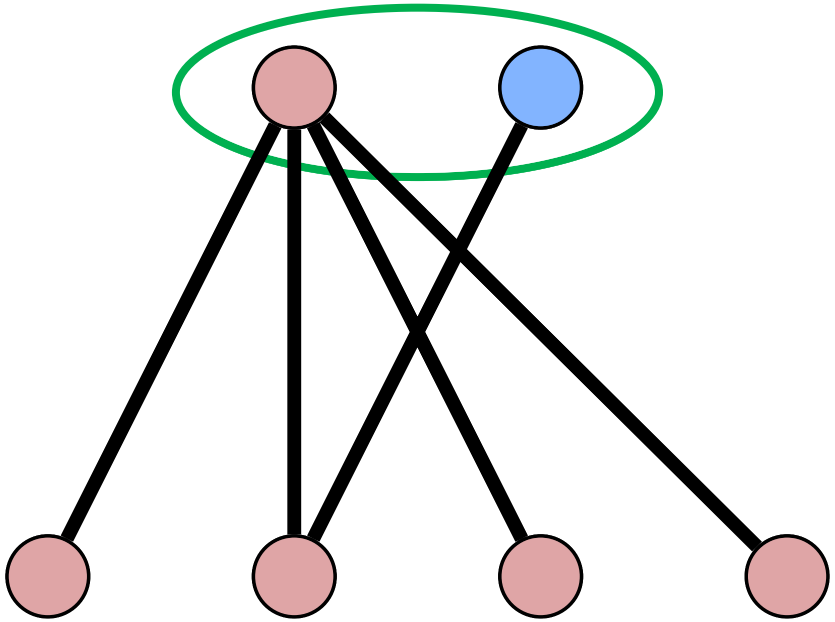
Subject to minimising ebit cost

Bipartite Distributed Quantum Computing



Bipartite Distributed Quantum Computing





*Colours are irrelevant

Efficient Bipartite Distributed Quantum Computing

Minimum vertex cover of a bipartite graph is efficiently computable!

Efficient Bipartite Distributed Quantum Computing

pytket-dqc

Automated entanglement-efficient distribution of quantum circuits.

Table of Contents

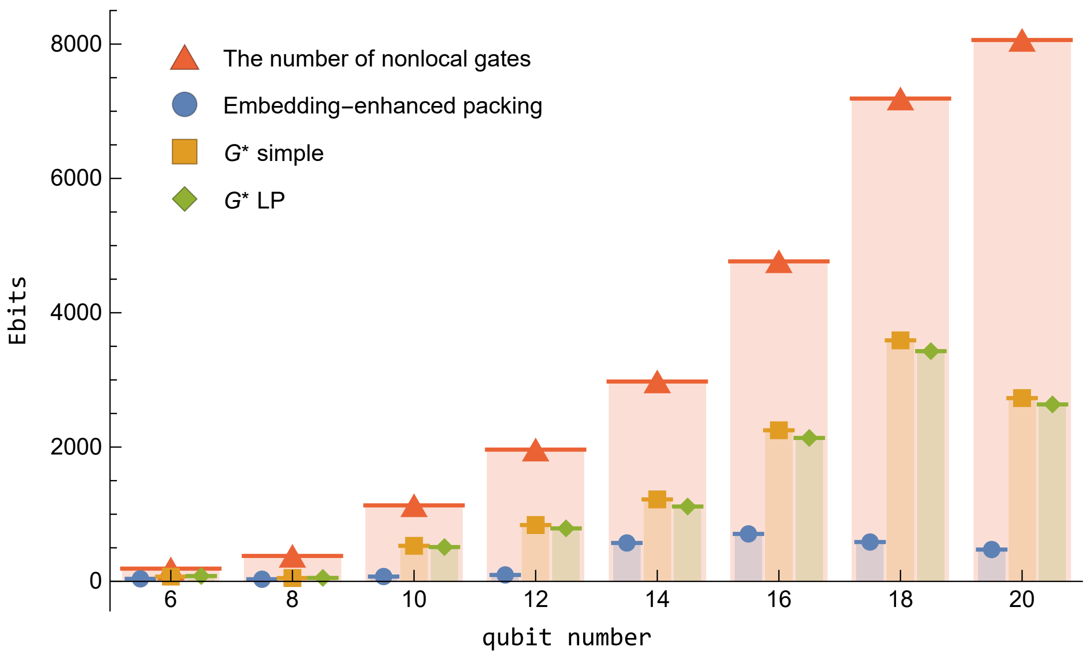
About

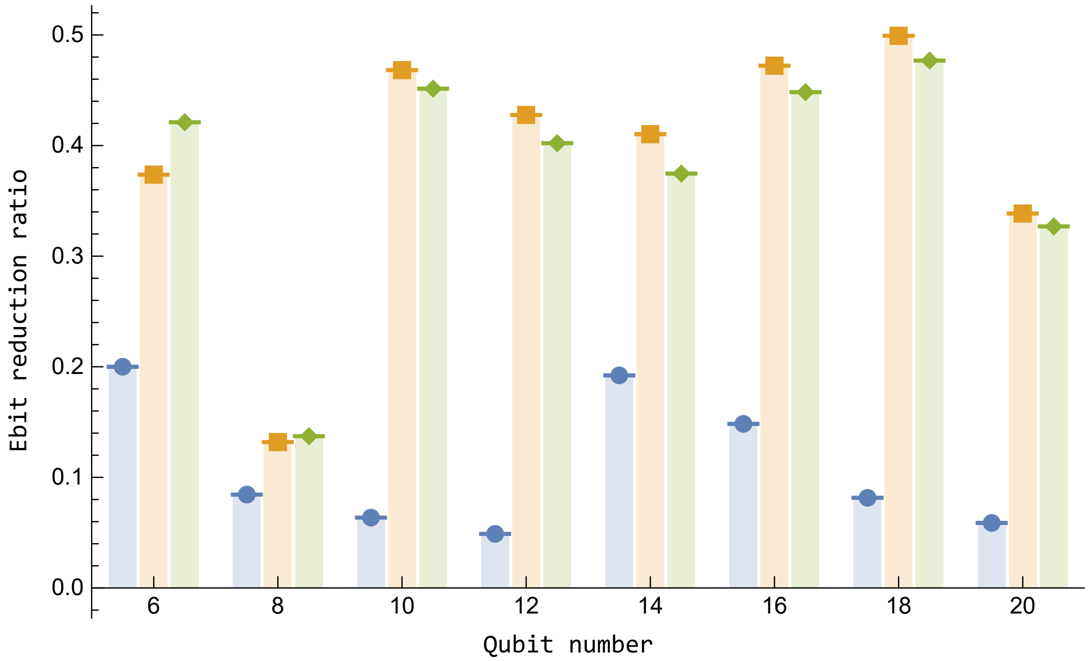
This package takes a quantum circuit and network description and produces a circuit distributed across the given network, using entanglement-assisted local operations and classical communication to implement non-local gates in the circuit, with the aim of reducing the amount of entanglement required for the circuit implementation. A more in-depth presentation of the methods implemented here can be found in the corresponding paper "Distributing circuits over heterogeneous, modular quantum computing network architectures".

Here we detail the steps required to install `pytket-dqc`. More thorough documentation of it use can be found here You may also find the example Jupyter notebooks in `examples/` instructive.

https://github.com/CQCL/pytket-dqc

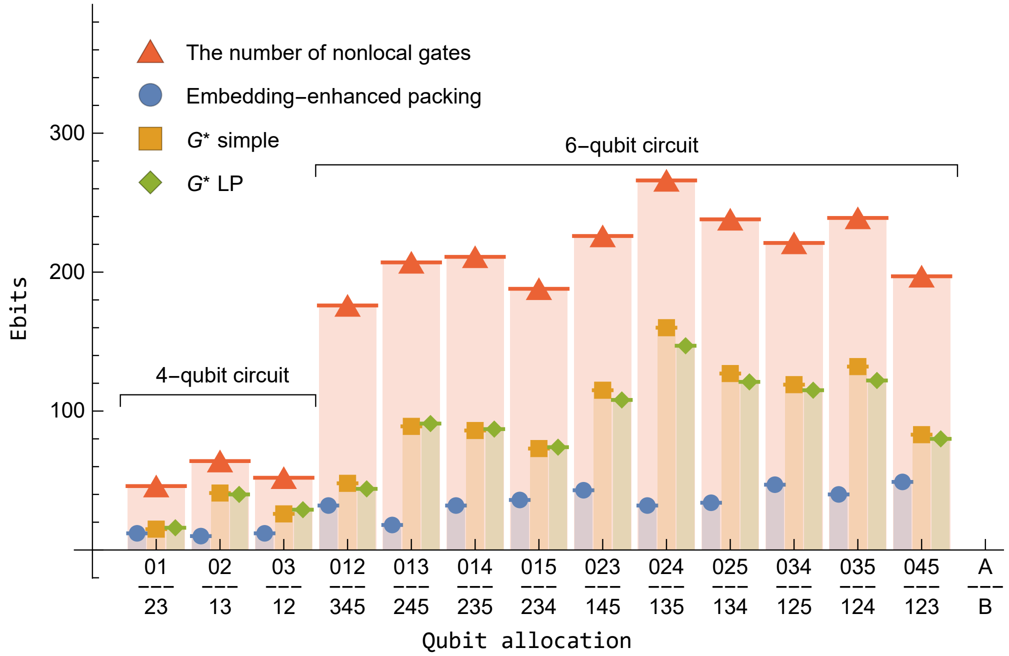
Efficient Bipartite Distributed Quantum Computing

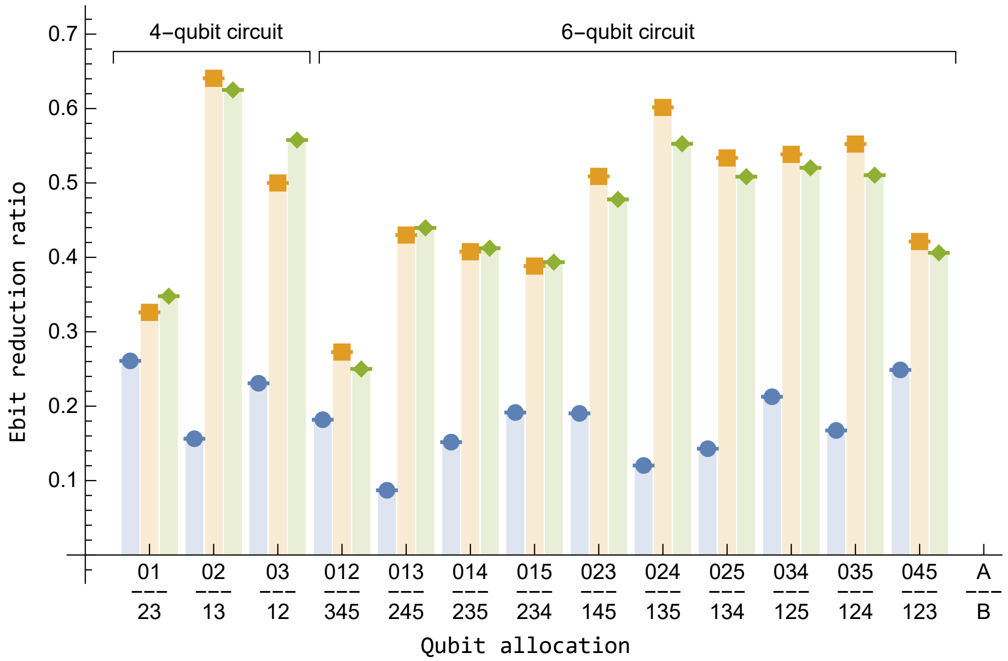




R. G. Sundaram, H. Gupta, and C. R. Ramakrishnan. Distribution of quantum circuits over general quantum networks.

Efficient Bipartite Distributed Quantum Computing



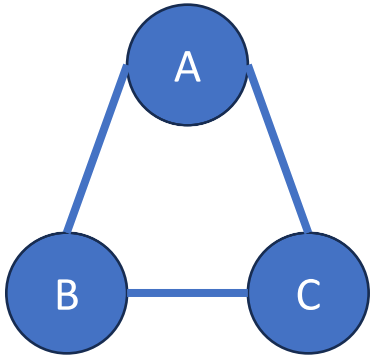


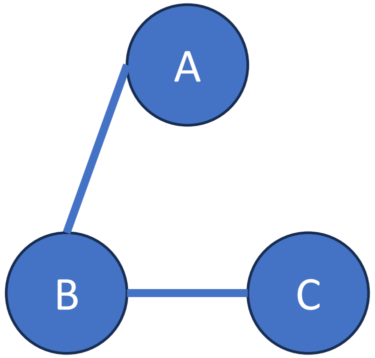
What next?

Look at the multipartite case

- Multipartite minimum vertex cover not efficient in general to compute
- Can find a vertex cover with size at most 2x size of minimum vertex cover

No unique network topology!





What next?

Distributing circuits over heterogeneous, modular quantum computing network architectures

Pablo Andres-Martinez[1,7], Tim Forrer[2,7], Daniel Mills[1,7], Jun-Yi Wu[3], Luciana Henaut[1], Kentaro Yamamoto[1], Mio Murao[2,5], and Ross Duncan[1,4,6]

[1]Quantinuum, Terrington House, 13-15 Hills Road, Cambridge CB2 1NL, UK
[2]Department of Physics, Graduate School of Science, The University of Tokyo, Hongo 7-3-1, Bunkyo-ku, Tokyo 113-0033, Japan
[3]Department of Physics, Tamkang University, 151 Yingzhuan Rd
[4]Department of Physics and Astronomy, University College London, Gower Street, London, WC1E 6BT, UK
[5]Trans-scale Quantum Science Institute, The University of Tokyo, Bunkyo-ku, Tokyo 113-0033, Japan
[6]Department of Computer and Information Sciences, University of Strathclyde, 26 Richmond Street, Glasgow G1 1XH, UK
[7]These authors contributed equally. Corresponding authors: {daniel.mills, pablo.andresmartinez}@quantinuum.com

What’s next?

Alternatives to EJPP?

Better gates other than CZ?

Summary

Why distributed quantum computing?

- Can run larger circuits without scaling individual quantum computers

How to distribute?

- Use EJPP

How to distributed efficiently?

- Take minimum vertex cover approach

Future challenges

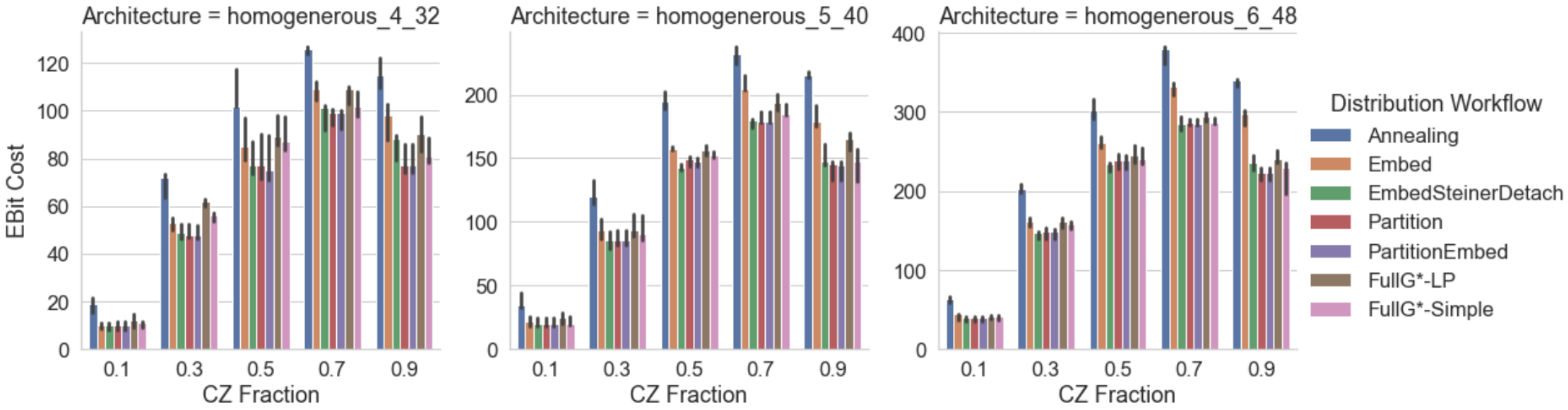
- Multipartite case

以上です - Fin

Bipartite (this talk)

Multipartite

Github repository with all code


Architecture = homogenerous_4_32
Architecture = homogenerous_5_40
Architecture = homogenerous_6_48
EBit Cost
CZ Fraction
0.1
0.3
0.5
0.7
0.9
0
20
40
60
80
100
120
50
150
200
300
400
Distribution Workflow
Annealing
Embed
EmbedSteinerDetach
Partition
PartitionEmbed
FullG*-LP
FullG*-Simple