Seminar *Quantum Compilation*

Introduction

Summer 2024; April 16, 2024

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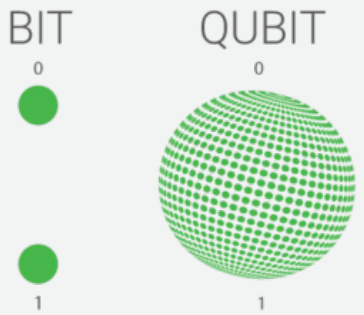
https://moves.rwth-aachen.de/teaching/ss-24/qc/

Software Modeling and Verification Chair | RWTH AACHEN UNIVERSITY

Outline

Quantum Computer – Basic Idea



CLASSICAL COMPUTER

BIT

0

...00010111010...

1

QUANTUM COMPUTER

QUBIT

0

$\cdots \begin{pmatrix}1\\0\end{pmatrix}\begin{pmatrix}1\\0\end{pmatrix}\begin{pmatrix}1\\0\end{pmatrix}\begin{pmatrix}0\\1\end{pmatrix}\begin{pmatrix}1\\0\end{pmatrix}\begin{pmatrix}0\\1\end{pmatrix}\begin{pmatrix}0\\1\end{pmatrix}\begin{pmatrix}0\\1\end{pmatrix}\begin{pmatrix}1\\0\end{pmatrix}\begin{pmatrix}0\\1\end{pmatrix}\begin{pmatrix}1\\0\end{pmatrix}\cdots$

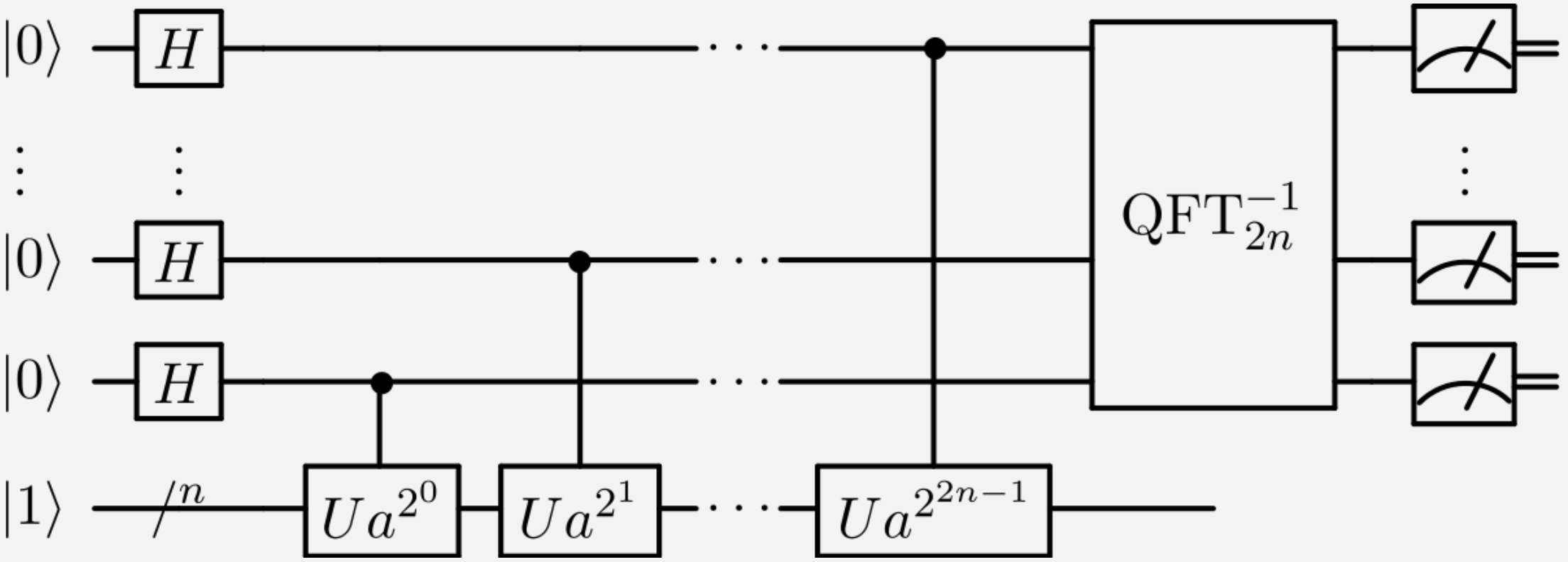
... 0 0 0 1 0 1 1 1 0 1 0 ...

$|0\rangle\ |0\rangle\ |0\rangle\ |1\rangle\ |0\rangle\ |1\rangle\ |1\rangle\ |1\rangle\ |0\rangle\ |1\rangle\ |0\rangle$

1

Dirac Notation

A Quantum Program



[Shor's Algorithm, Wikipedia]

Quantum Compilation

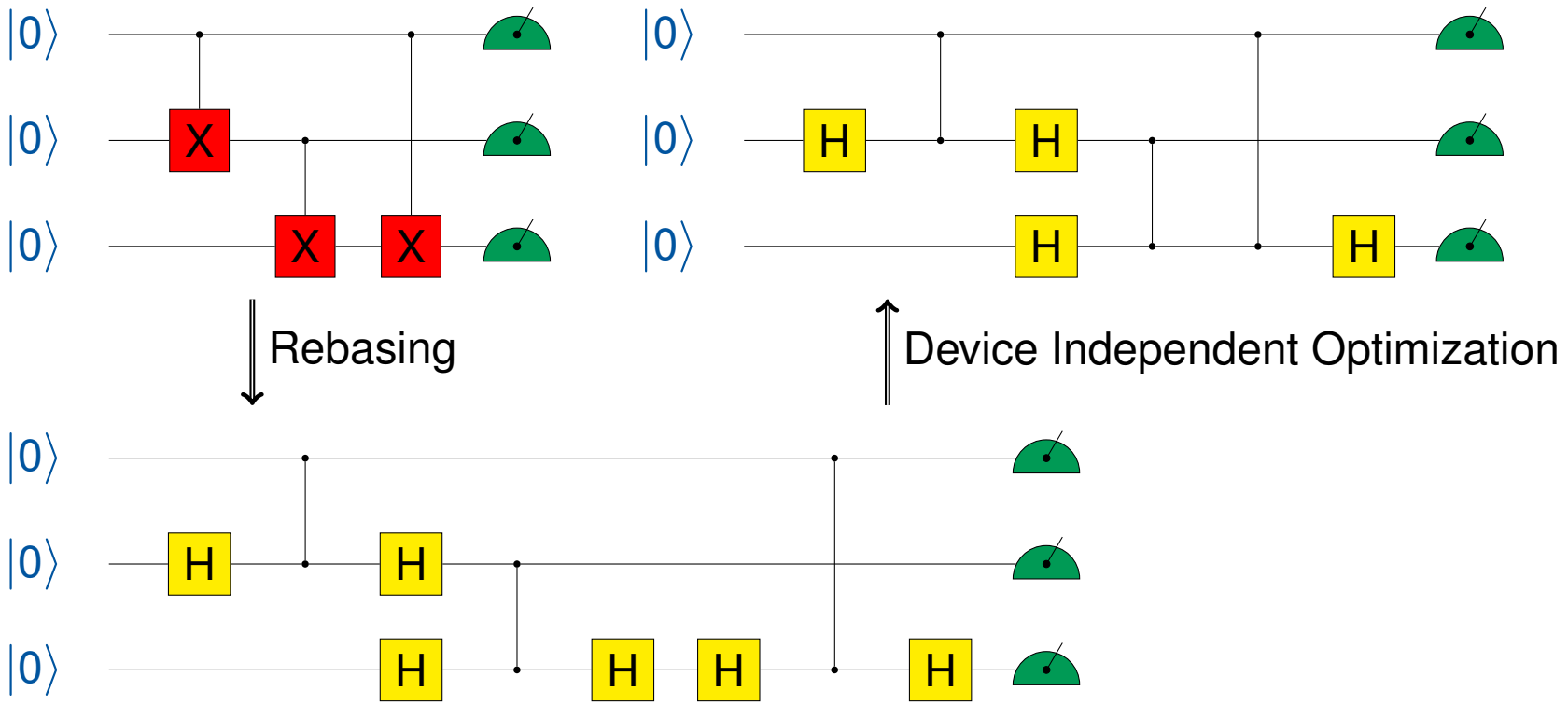
Mapping quantum circuit $\rightarrow$ quantum computer

1. Rebasing
2. Device-independent optimisations
3. Mapping logical $\rightarrow$ physical qubits
4. Routing and re-mapping (swapping/shuttling operations)
5. Scheduling of gate operations

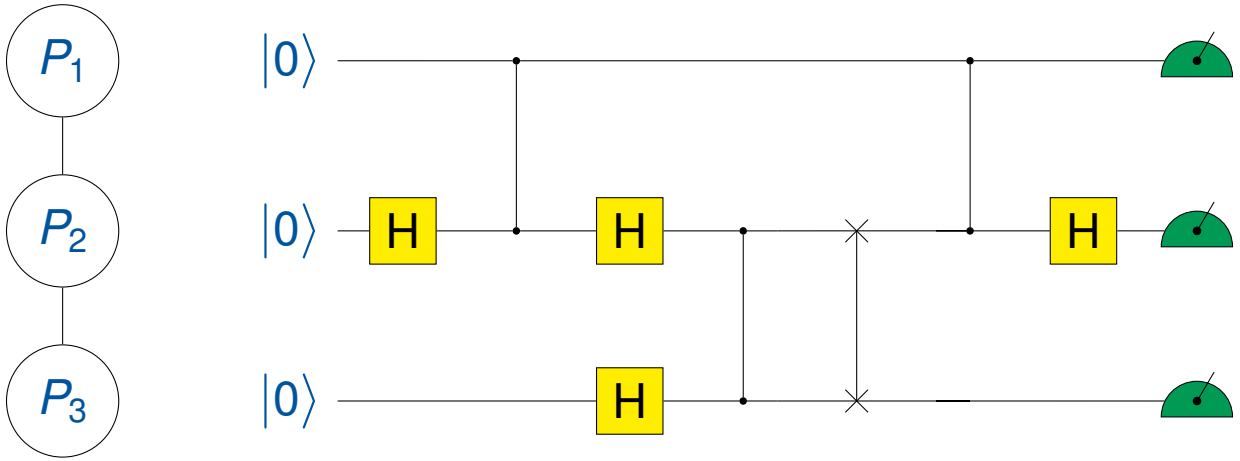
(while minimising errors)

Quantum Circuit Compilation

Traditional Compilation



Traditional Compilation



- Architecture:
  - Physical Qubits
  - Allowed 2-Qubit Gates
- Mapping of Qubits: Logical $\Leftrightarrow$ Physical
- Exemplary Initial Mapping: $Q_i \Leftrightarrow P_i$ for $i \in \{1, 2, 3\}$

- Remapping Required
- $Q_1 \leftrightarrow P_1, Q_2 \leftrightarrow P_3, Q_3 \leftrightarrow P_3$
- Established via SWAP-Gates

Areas Covered by the Seminars

Topic areas

- Overview topics
- The Routing Problem in General
- Compilation for Neutral-Atom Quantum Computers
- Compilation for Trapped-Ion Quantum Computers
- Compilation for Spin Quantum Computers
- Software Frameworks

Outline

Goals

Aims of this seminar

- Independent understanding of a scientific topic
- Acquiring, reading and understanding scientific literature
  - given references sufficient in most cases
- Writing of your own report on this topic
  - far more that just a translation/rewording
  - usually an “extended subset” of original literature
    - “subset”: present core ideas and omit too specific details (e.g., related work or optimisations)
    - “extended”: more extensive explanations, examples, ...
    - discuss contents with supervisor!
- Oral presentation of your results
  - can be “proper subset” of report
  - generally: less (detailed) definitions/proofs and more examples

Requirements on Report

Your report

- Independent writing of a report of 12–15 pages
- First milestone: detailed outline
  - not: “1. Introduction/2. Main part/3. Conclusions”
  - rather: overview of structure (section headers, main definitions/theorems) and initial part of main section (one page)
- Complete set of references to all consulted literature
- Correct citation of important literature
- Plagiarism: taking text blocks (from literature or web) without source indication causes immediate exclusion from this seminar
- Font size 12pt with “standard” page layout
  - LaTeX template will be made available on seminar web page
- Language: German or English
- We expect the correct usage of spelling and grammar
  - $\geq$ 10 errors per page $\Longrightarrow$ abortion of correction

Requirements on Talk

Your talk

- Talk of 30 minutes
- Available: projector, presenter, [laptop]
- Focus your talk on the audience
- Descriptive slides:
  - $\leq$ 15 lines of text
  - use (base) colors in a useful manner
  - number your slides
  - LaTeX/beamer template will be made available on seminar web page
- Language: German or English
- No spelling mistakes please!
- Finish in time. Overtime is bad
- Ask for questions
- Have backup slides ready for expected questions

Outline

Important Dates

Deadlines

- April 19: Topic preferences due
- May 13: Detailed outline due
- June 10: Full report due
- June 24: Presentation slides due
- July 8/9/10 (?): Seminar talks

Important

- Missing a deadline causes immediate exclusion from the seminar
- Please notify us if you decide to quit

Selecting Your Topic

Procedure

- You obtain(ed) a list of topics of this seminar.
- Indicate the preference of your topics (first, second, third).
- Return sheet here or via e-mail (noll@cs.rwth-aachen.de) by Friday (April 19).
- We do our best to find an adequate topic-student assignment.
  - disclaimer: no guarantee for an optimal solution
- Assignment will be published on web site next week.
- Then also your supervisor will be indicated.
- Please give language preference (unsure $\Longrightarrow$ German).

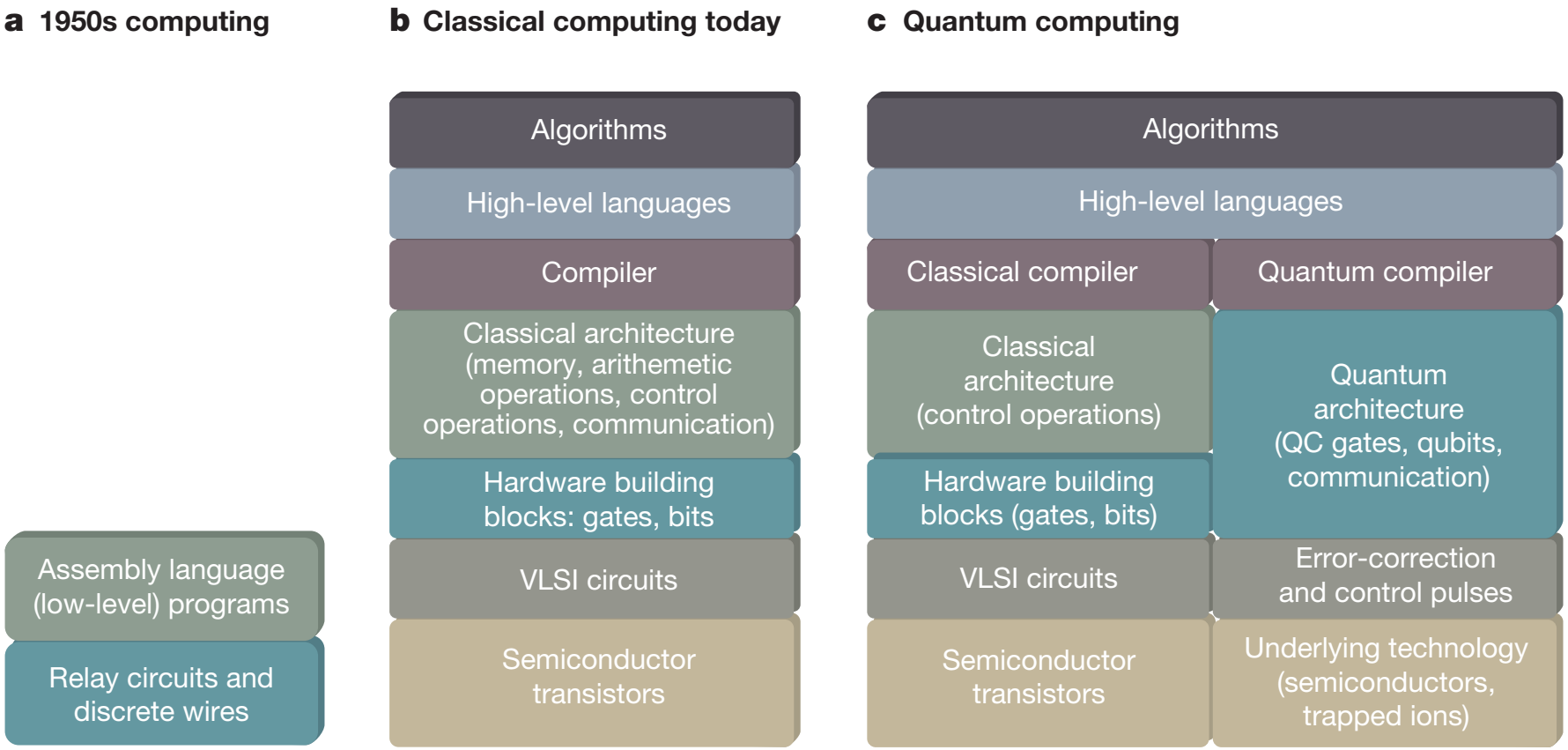
Withdrawal

- You have up to three weeks to refrain from participating in this seminar.
- Later cancellation (by you or by us) causes a not passed for this seminar and reduces your (three) possibilities by one.

Outline

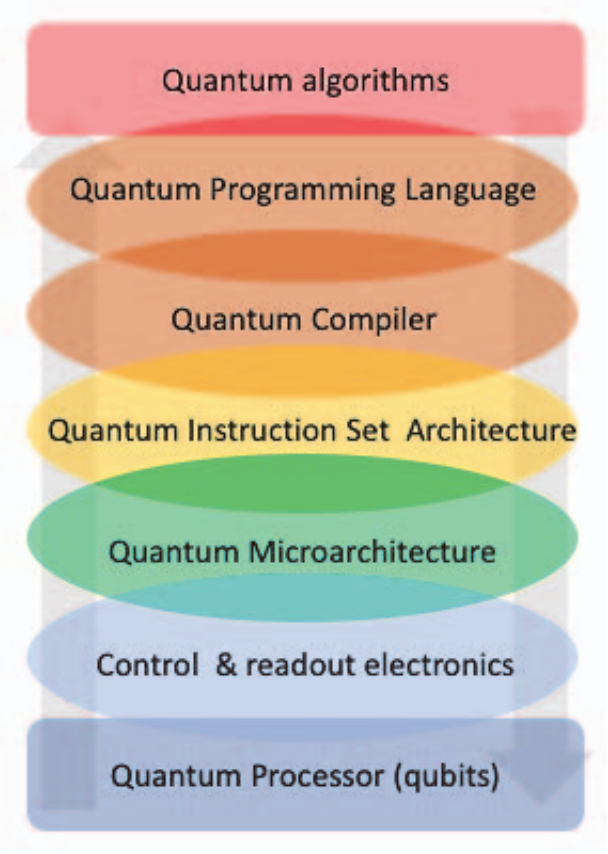
1. Programming languages and compiler design for realistic quantum hardware

Frederic T. Chong, Diana Franklin, Margaret Martonosi: *Programming languages and compiler design for realistic quantum hardware*. Nature 549, 2017



2. Full-stack quantum computing systems in the NISQ era

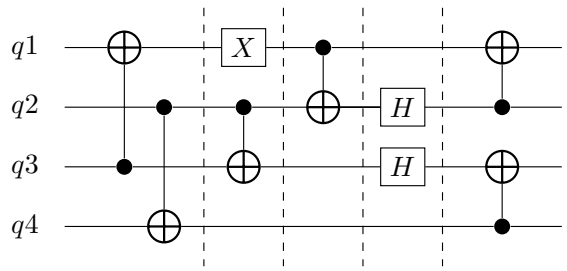
Medina Bandic, Sebastian Feld, Carmen G. Almudever: *Full-stack quantum computing systems in the NISQ era: algorithm-driven and hardware-aware compilation techniques*. DATE 2022

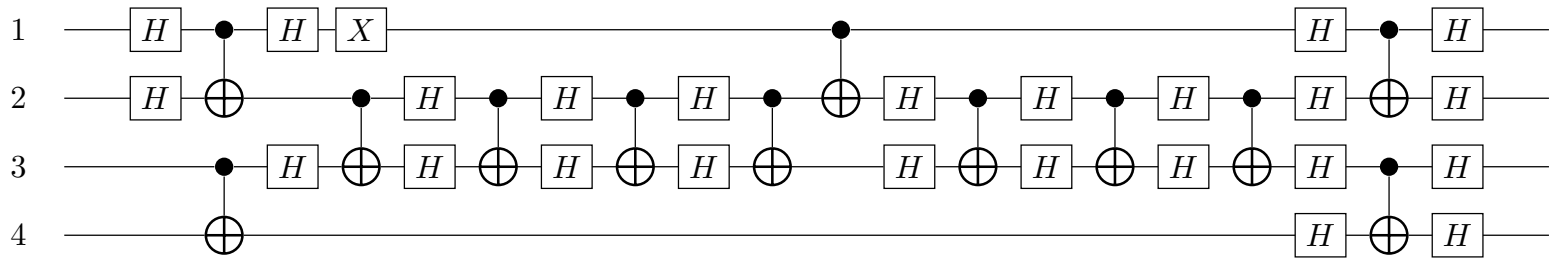


Outline

3. On the Qubit Routing Problem

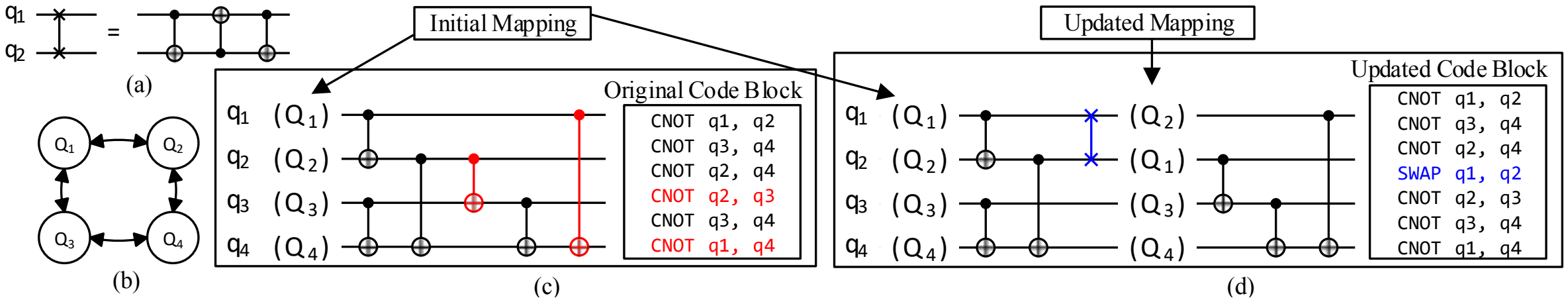
Alexander Cowtan et al.: *On the Qubit Routing Problem*. TQC 2019





4. Tackling the Qubit Mapping Problem for NISQ-Era Quantum Devices

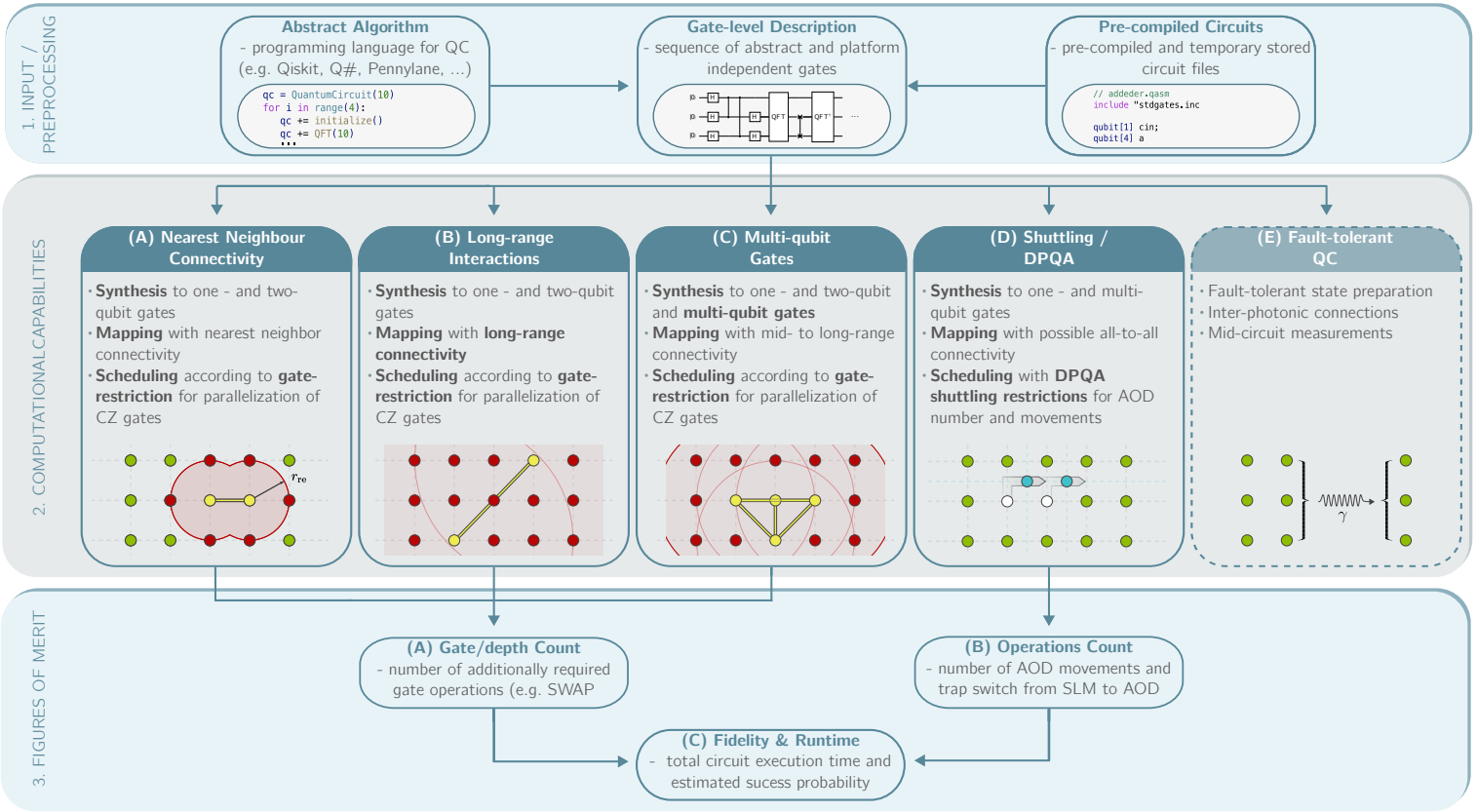
Gushu Li, Yufei Ding, Yuan Xie: *Tackling the Qubit Mapping Problem for NISQ-Era Quantum Devices*. ASPLOS 2019



Outline

5. Computational Capabilities and Compiler Development for Neutral Atom Quantum Processors

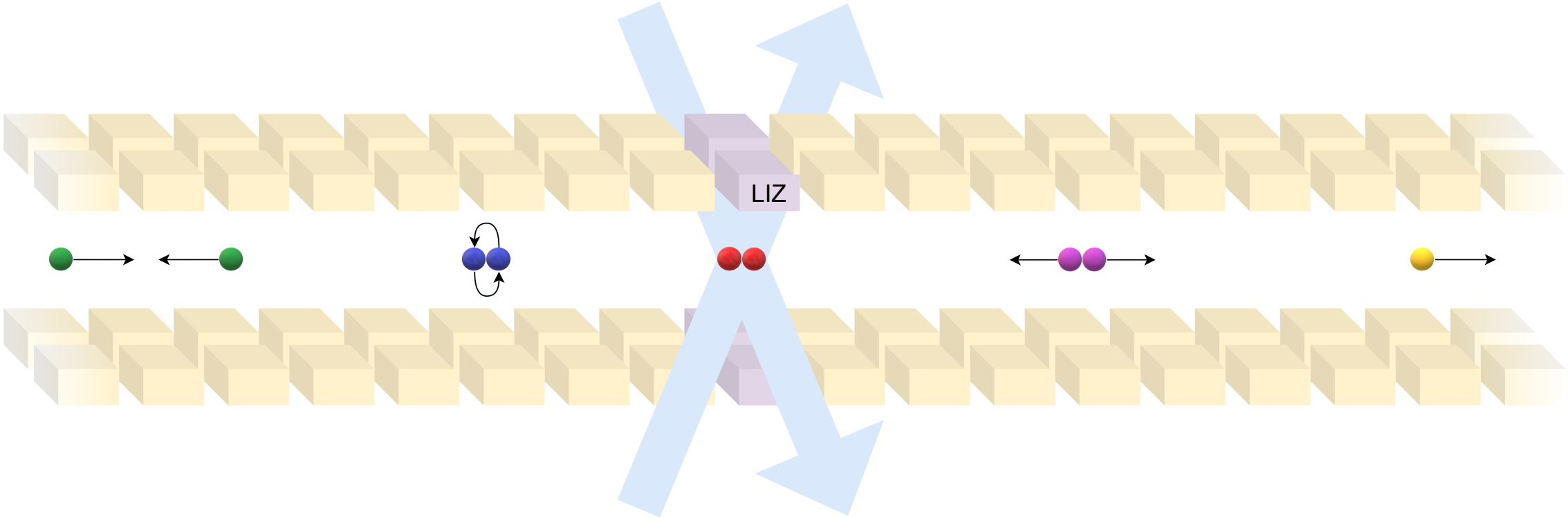
Ludwig Schmid et al.: *Computational Capabilities and Compiler Development for Neutral Atom Quantum Processors: Connecting Tool Developers and Hardware Experts*. arXiv, 2023



Outline

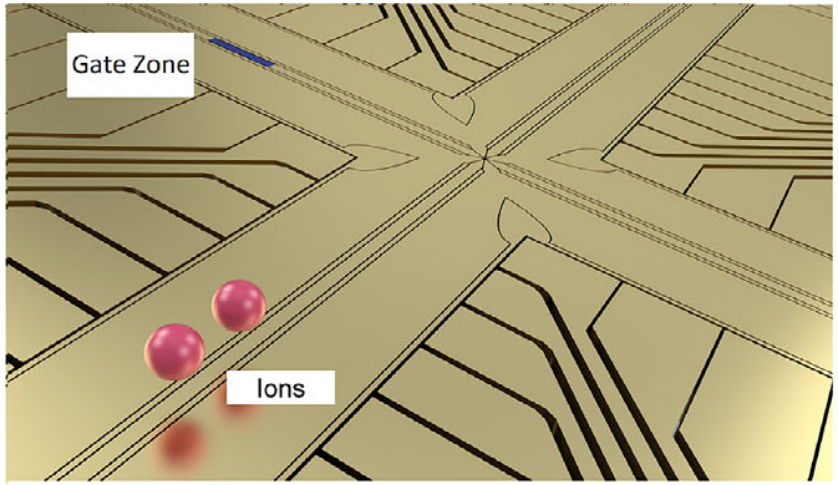
6. Quantum Circuit Compiler for a Shuttling-Based Trapped-Ion Quantum Computer

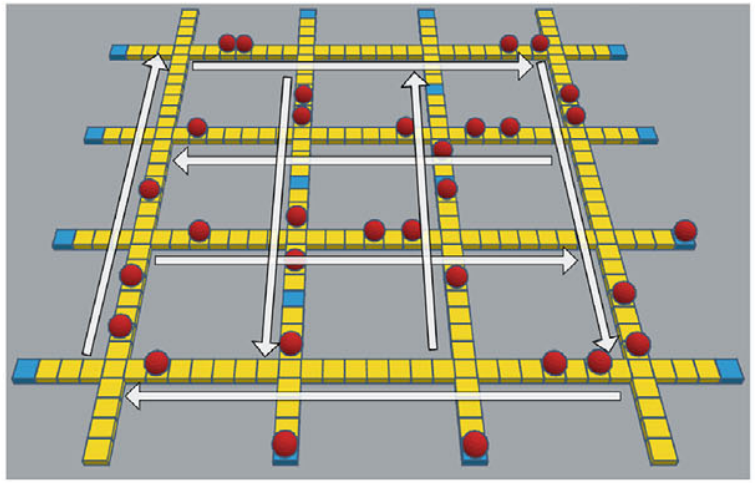
Fabian Kreppel et al.: *Quantum Circuit Compiler for a Shuttling-Based Trapped-Ion Quantum Computer*. Quantum 7, 2023

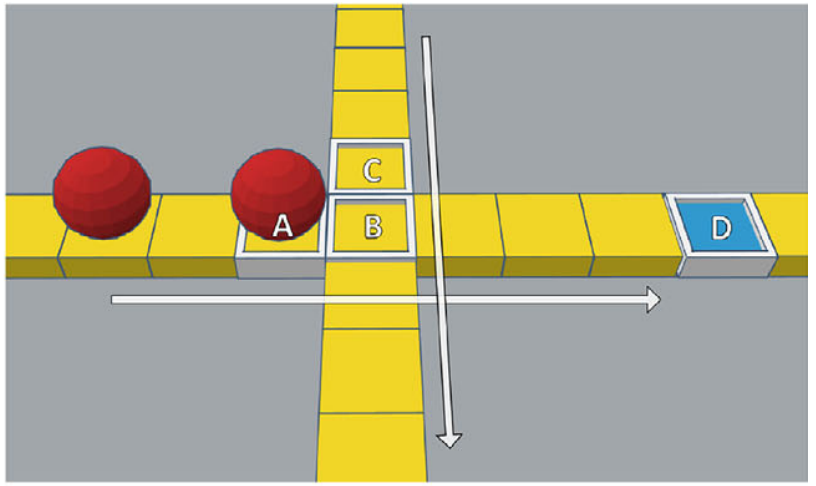


7. Efficient Qubit Routing for a Globally Connected Trapped Ion Quantum Computer

Mark Webber et al.: *Efficient Qubit Routing for a Globally Connected Trapped Ion Quantum Computer*. Adv. Quantum Technologies 3(8), 2020



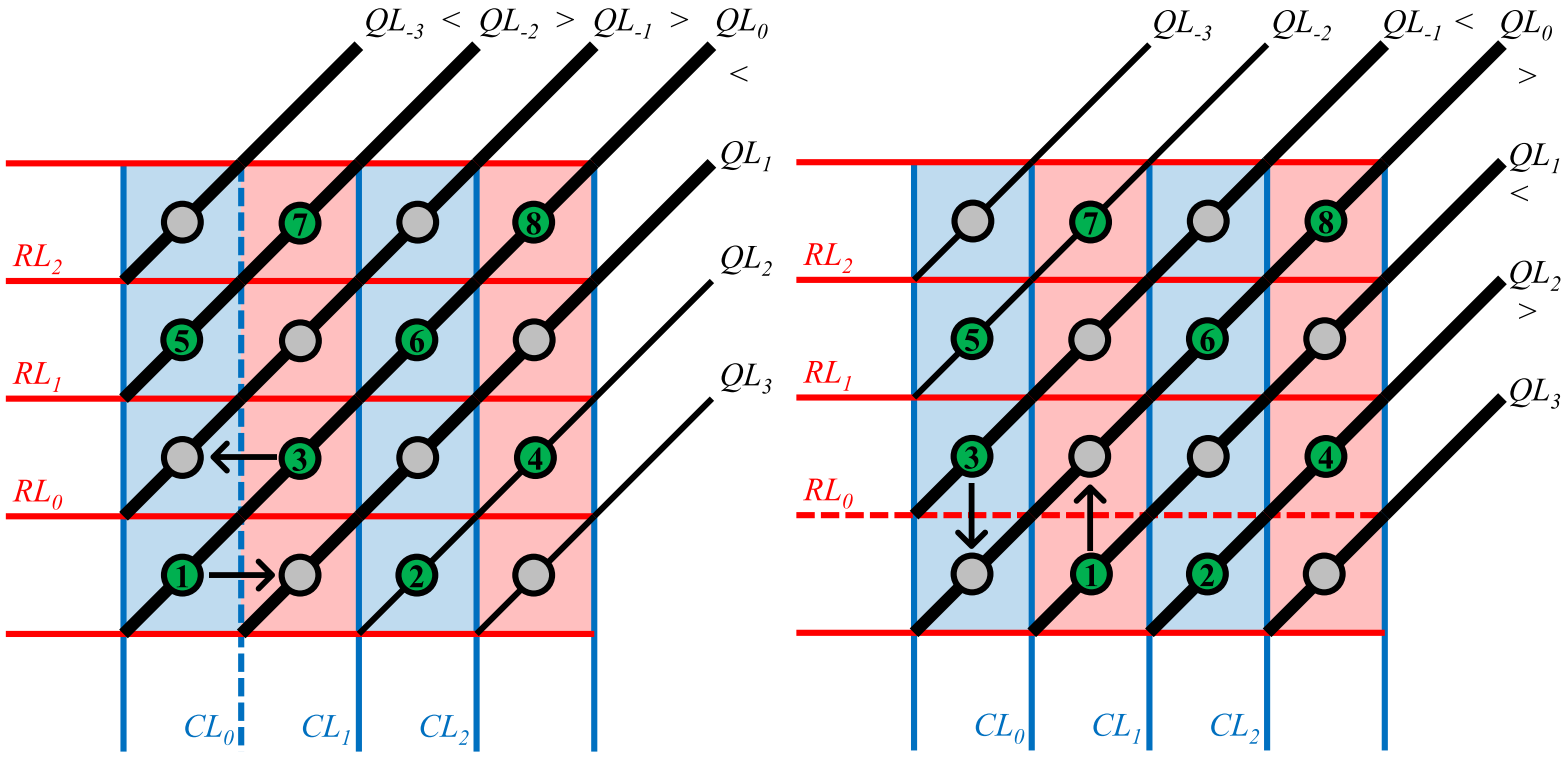




Outline

8. SpinQ: Compilation strategies for scalable spin-qubit architectures

Nikiforos Paraskevopoulos et al.: *SpinQ: Compilation strategies for scalable spin-qubit architectures*. ACM Transactions on Quantum Computing 5(1), 2023



(a) Horizontal shuttling

(b) Vertical shuttling

Outline

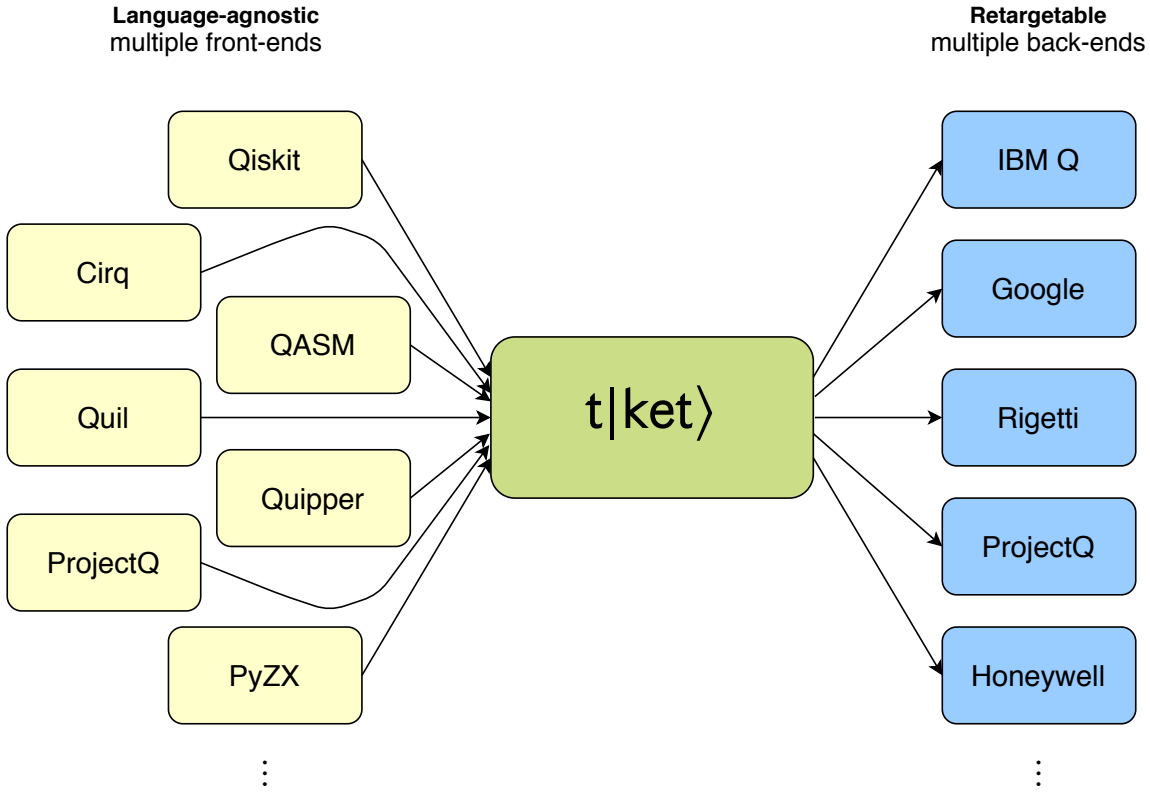
9. Qiskit

Robert Wille, Rod Van Meter, Yehuda Naveh: *IBM's Qiskit Tool Chain: Working with and Developing for Real Quantum Computers*. DATE 2019

```
from qiskit import QuantumCircuit, QuantumRegister,
    ClassicalRegister
q = QuantumRegister(4, 'q')
circ = QuantumCircuit(q)
circ.h(q[2])
circ.cx(q[2], q[3])
circ.cx(q[0], q[1])
circ.h(q[1])
circ.cx(q[1], q[2])
circ.t(q[0])
circ.cx(q[2], q[0])
circ.cx(q[0], q[1])
```

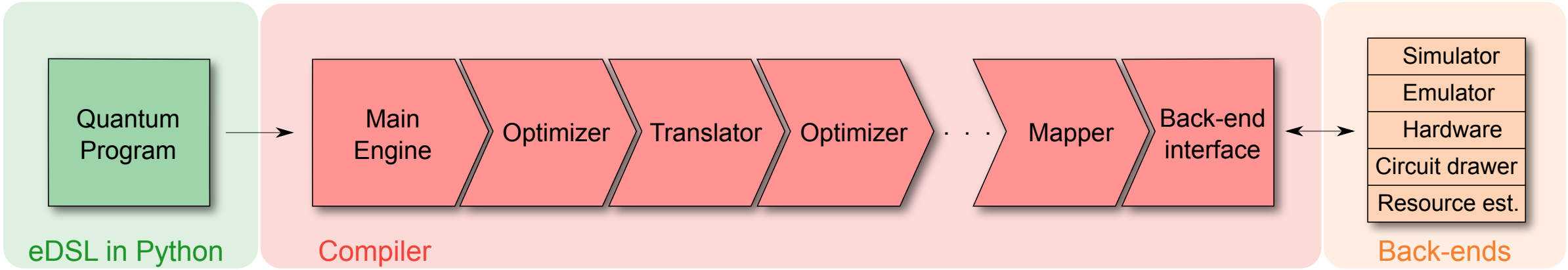
10. t|ket⟩

Seyon Sivarajah et al.: *t|ket⟩: A Retargetable Compiler for NISQ Devices*. arXiv, 2020



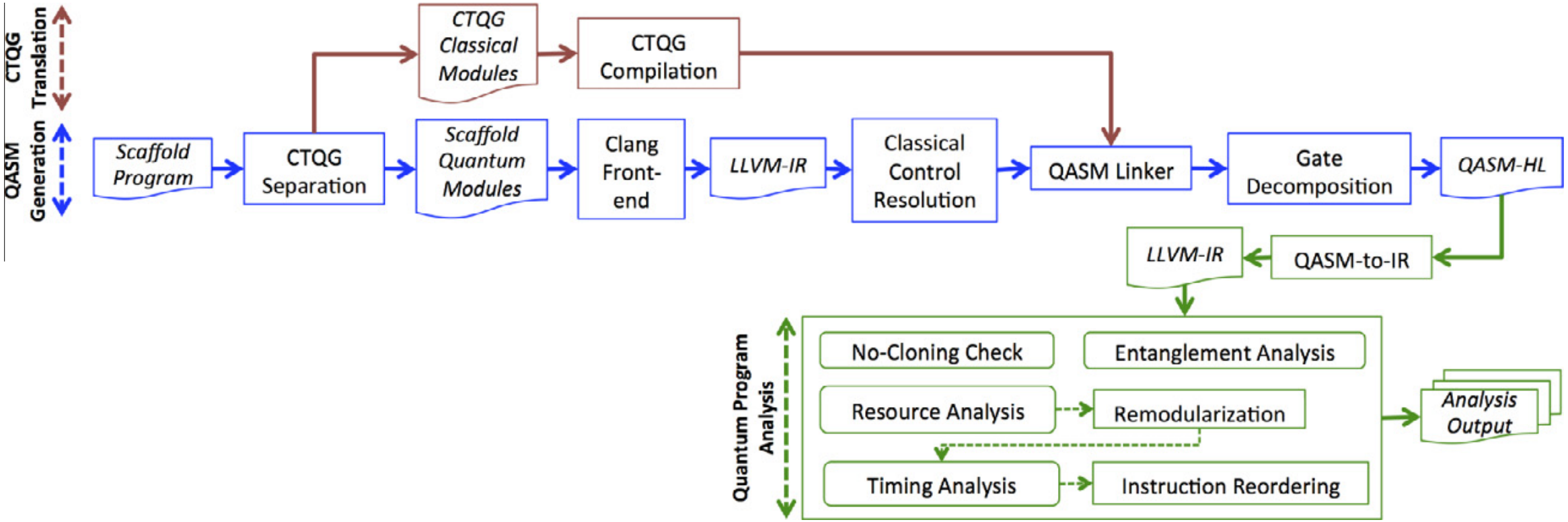
11. ProjectQ

Damian S. Steiger, Thomas Häner, Matthias Troyer: *ProjectQ: an open source software framework for quantum computing*. Quantum 2, 2018



12. ScaffCC

Ali Javadi Abhari et al.: *ScaffCC: Scalable compilation and analysis of quantum programs*. Parallel Computing 45, 2015



Outline

Some Final Hints

Hints

- Take your time to understand your literature.
- Be proactive! Look for additional literature and information.
- Discuss the content of your report with other students.
- Be proactive! Contact your supervisor on time.
- Prepare the meeting(s) with your supervisor.
- Forget the idea that you can prepare a talk in a day or two.

We wish you success and look forward to an enjoyable and high-quality seminar!