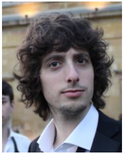
Quantum Software

Aleks Kissinger, Stefano Gogioso



UNIVERSITY OF OXFORD

Oxford, Hillary Term 2024

Quantum software

Quantum software

1. $:=$ the code the runs on a quantum computer

Quantum software

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factoring

search

physical simulation
optimisation problems
linear systems & codes
network flows
natural language processing
...

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2. := the code that makes that code
   - **compilers**

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physical simulation
optimisation problems
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2. := the code that makes that code
   - **compilers**
   - **optimisation**
   - **verification**

Quantum software

1. := the code the runs on a quantum computer

factoring

search

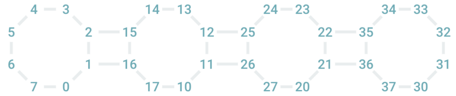
physical simulation
optimisation problems
linear systems & codes
network flows
natural language processing
...

2. := the code that makes that code (better)
   - **compilers**
   - **optimisation**
   - **verification**

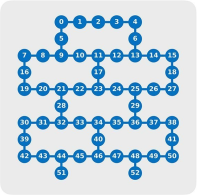
Problem: no quantum computers

Problem: ~~no quantum computers~~

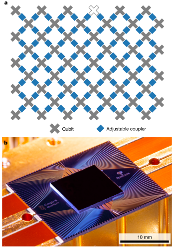
Rigetti Aspen



IBM Q Rochester

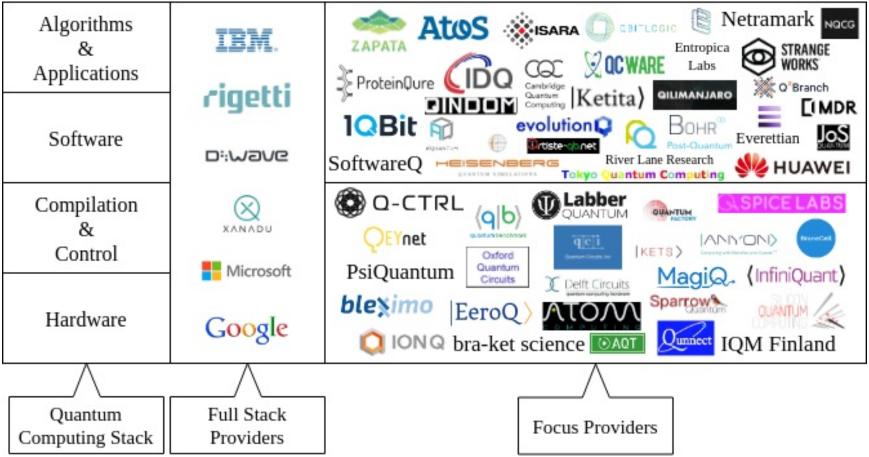


Google Sycamore



(+ Oxford, Vienna, Delft, Sussex, Maryland...)

~~Problem: no quantum computers~~



[1]

1 https://quantumcomputingreport.com/review-of-the-cirq-quantum-software-framework

Problem: limited quantum computers

NISQ := "noisy intermediate-scale quantum"

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NISQ devices have:

- short coherence times
- low numbers of qubits
- noisy operations
- limited connectivity
- ...

Problem: limited quantum computers

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NISQ devices have:

- short coherence times
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- noisy operations
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- ...

$\Rightarrow$ **small** advances in software give **big** gains on NISQ hardware!

Quantum circuits

Quantum circuits

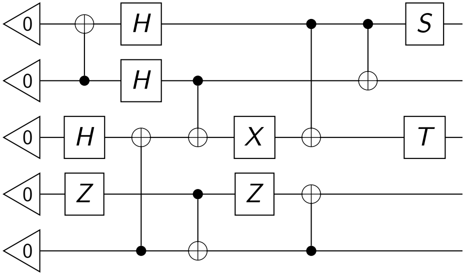
- $:=$ the 'assembly language' of quantum computation

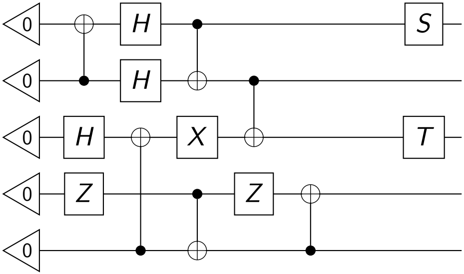
Quantum circuits

- $:=$ the 'assembly language' of quantum computation, e.g.

```
INIT 5
CNOT 1 0
H 2
Z 3
H 0
H 1
CNOT 4 2
...
```

$\Leftrightarrow$

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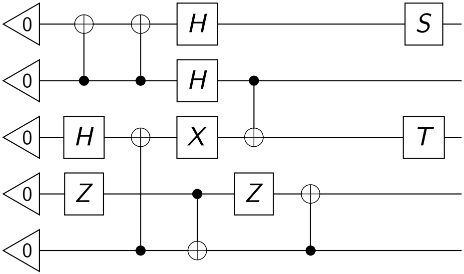
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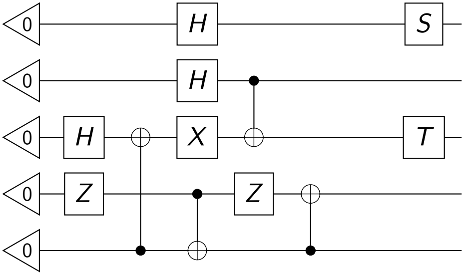
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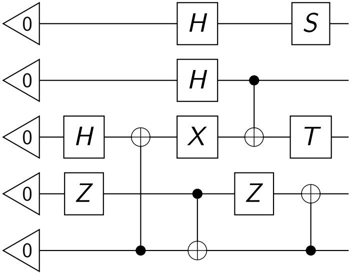
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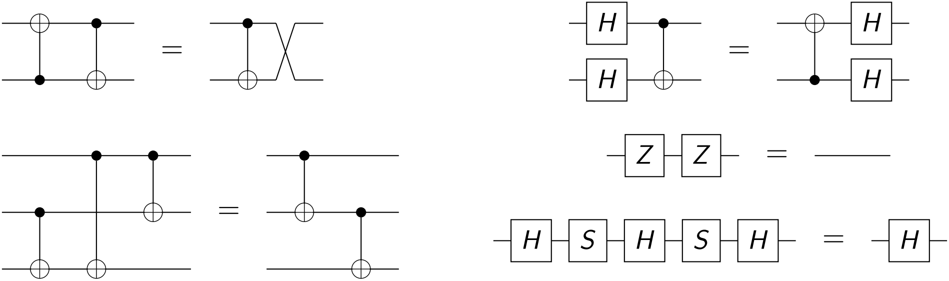
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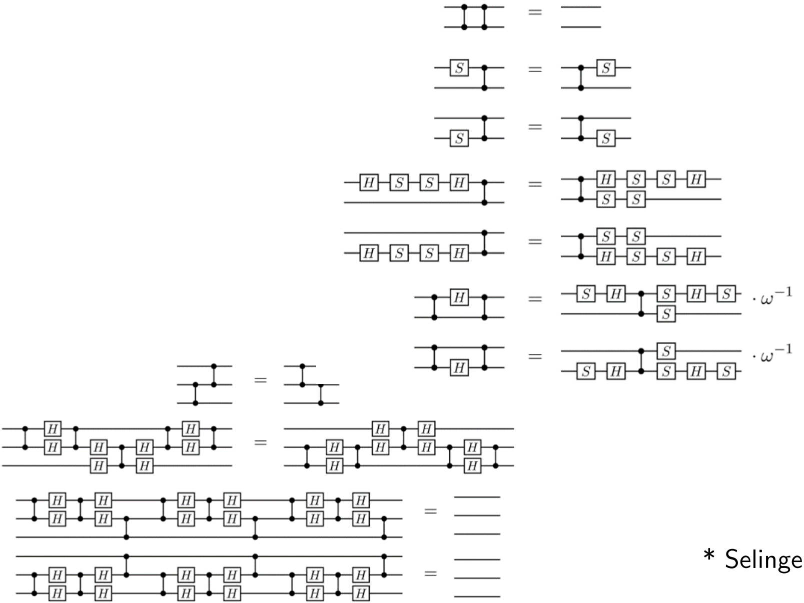

* Selinger 2015

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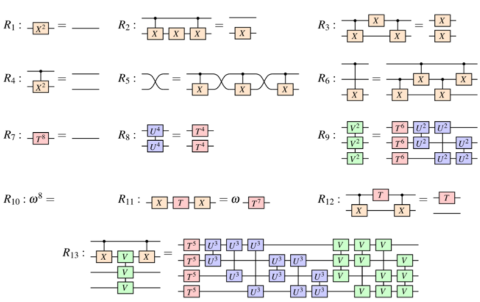
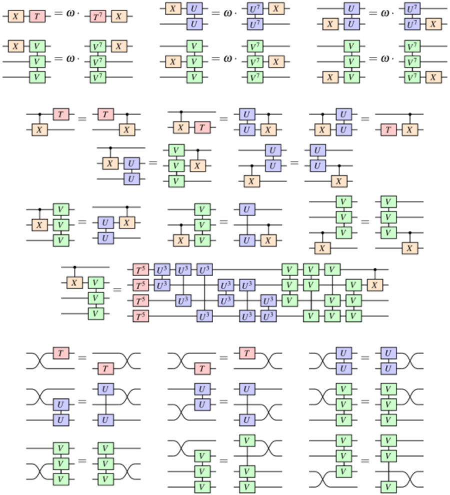
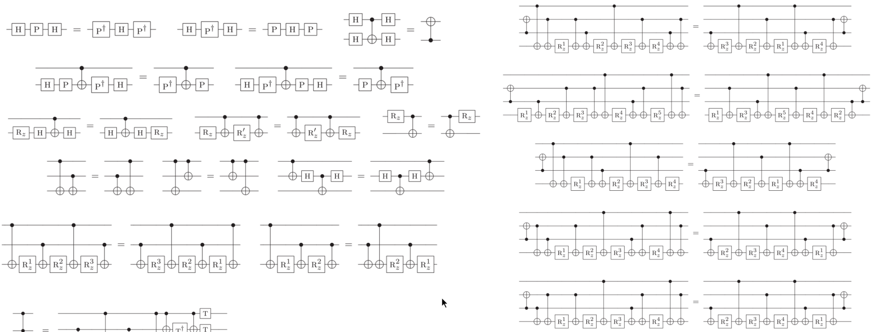
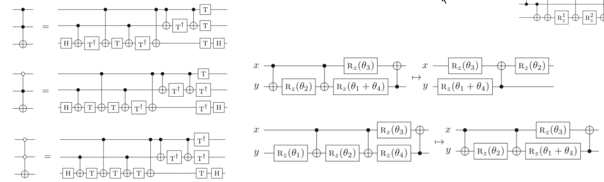


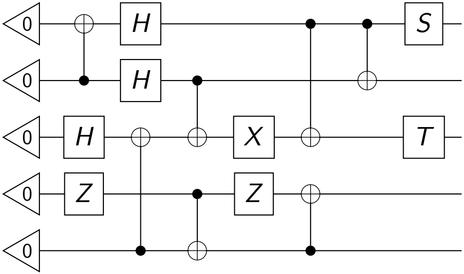


* Amy, Chen, & Ross 2018





* Nam *et al* 2018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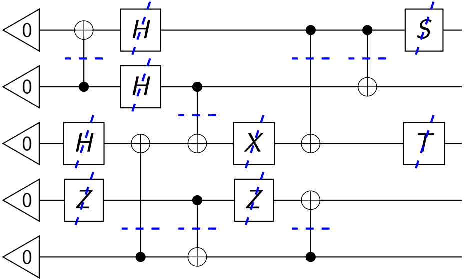

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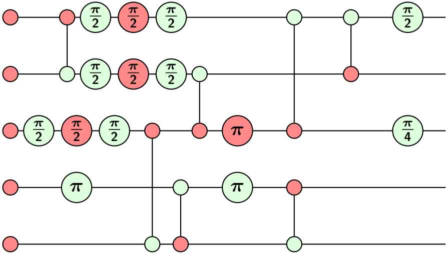
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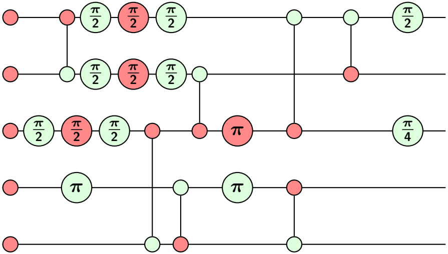
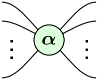


ZX-diagram

ZX-diagrams

ZX-diagrams

...are like circuits, but made from **spiders** instead of gates:

$\mathcal{Z}_\alpha \;=$ 

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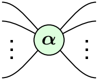
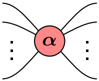
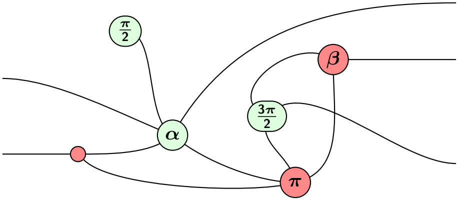
$\mathcal{Z}_\alpha$ = 

$\mathcal{X}_\alpha$ = 

ZX-diagrams are bendy



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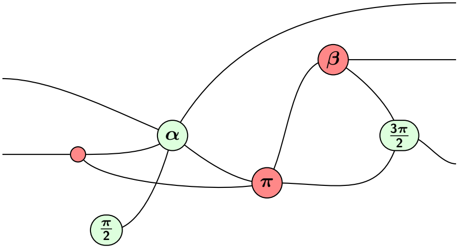

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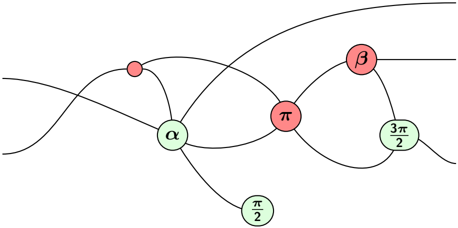

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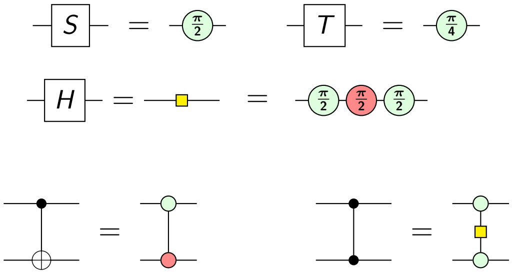

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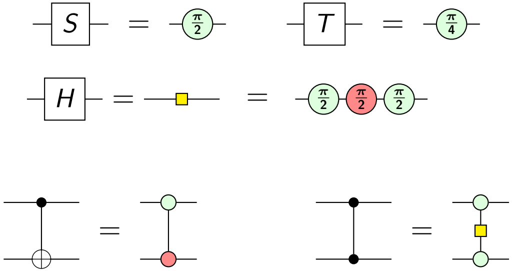
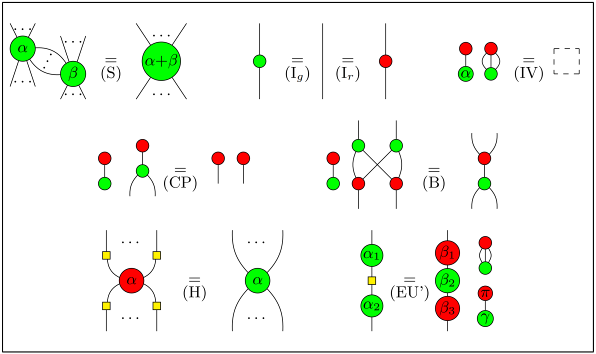


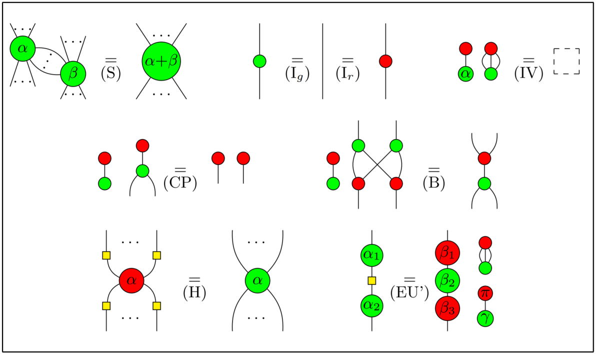
- ....and....



[2]

ZX calculus

[2] Vilmart 2018. arXiv:1812.09114



[2]

ZX calculus

these 8 rules $\implies$ everything before

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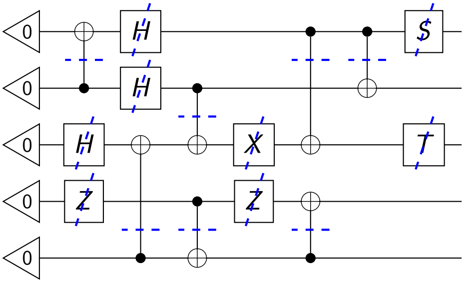
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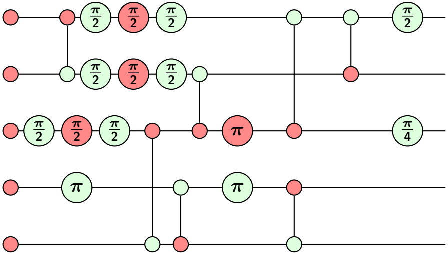
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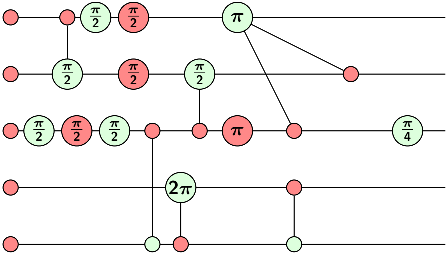

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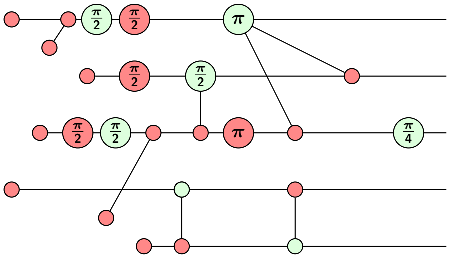

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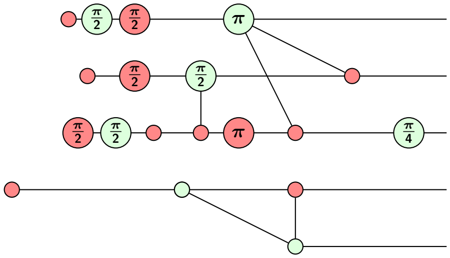
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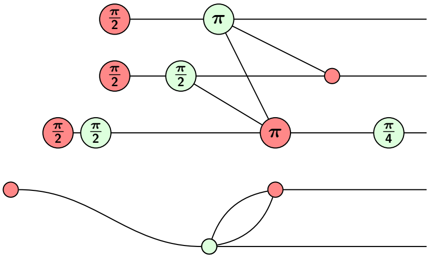
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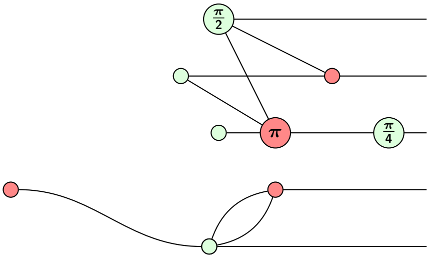
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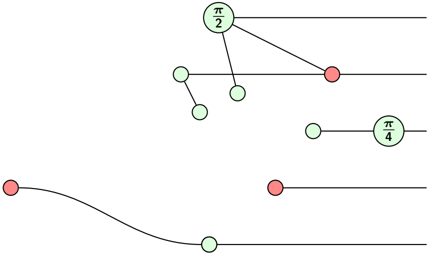

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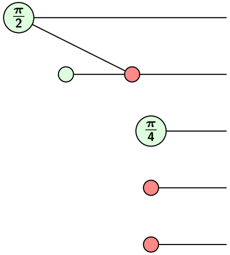
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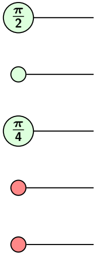
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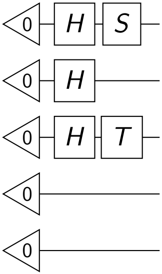
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Q: How do we scale up?

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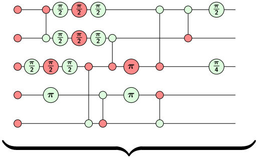
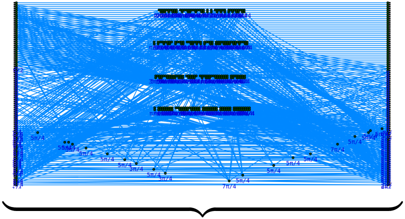


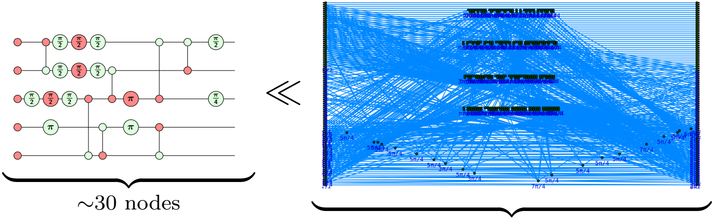
$\sim$30 nodes

$\ll$



10^2-10^5 nodes

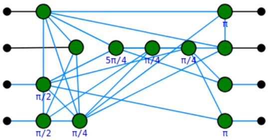
Q: How do we scale up?



~30 nodes ≪ 10^2-10^5 nodes

A: Automation.

In [11]:
```
zx.simplify.clifford_simp(g)
g.normalise()
zx.d3.draw(g)
```



In this course...

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- We'll look at **fundamental structures** underlying quantum computations:

$$\textbf{ZX-diagrams} \qquad \longleftrightarrow \qquad \begin{cases} \text{graph states} \\ \text{stabiliser groups} \\ \text{exponentiated Paulis} \\ \text{phase polynomials} \\ \ldots \end{cases}$$

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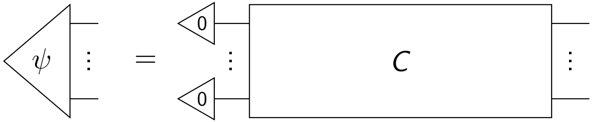
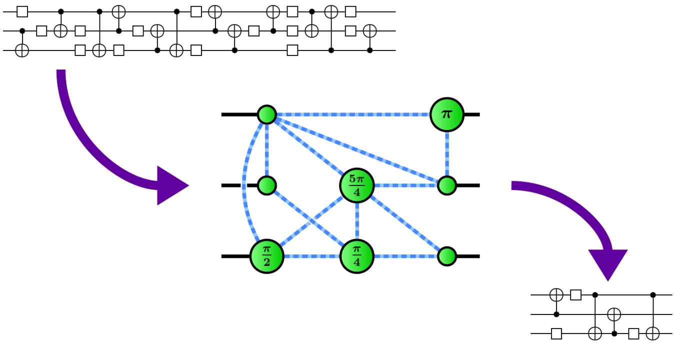
- And apply them to...

Classical simulation

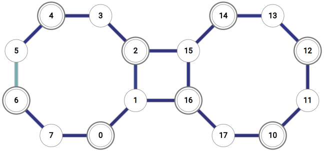


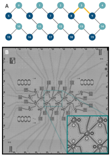
$$\text{Prob}\left(i \,\middle|\, |\psi\rangle\right) = ???$$

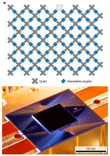
Circuit optimisation

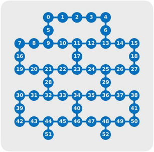


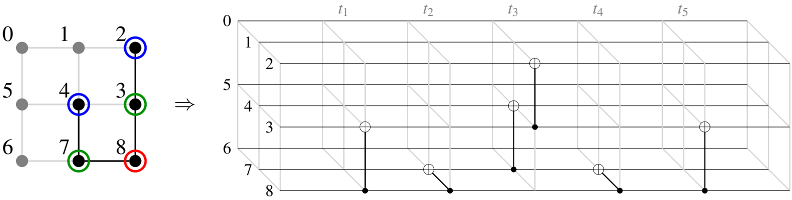
Circuit routing



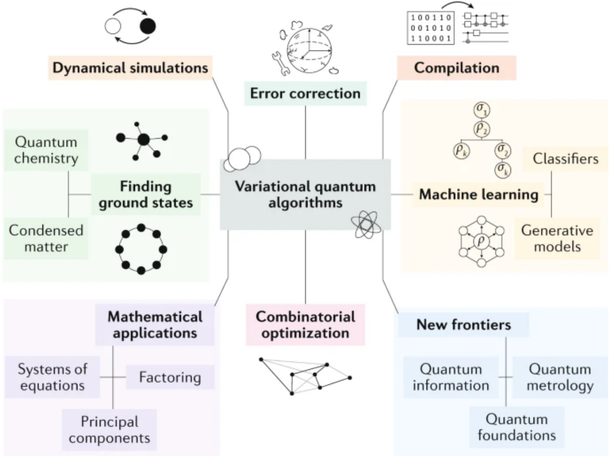








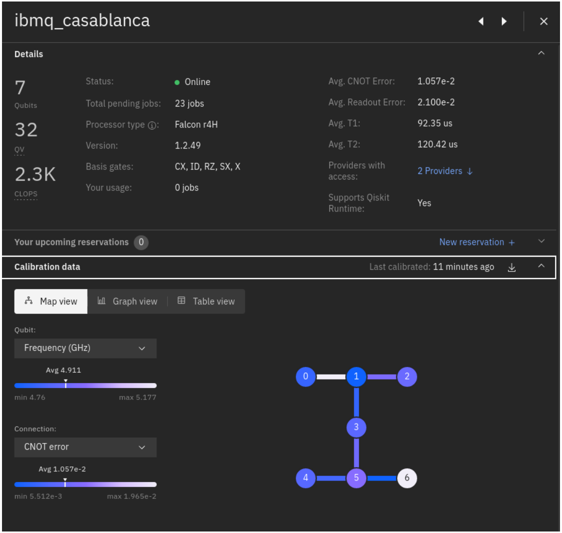
(NISQ) quantum algorithms



[3]

[3] https://www.nature.com/articles/s42254-021-00348-9

Implementation



[4]

[4] IBMQ calibration data. `https://quantum-computing.ibm.com`

Format of the course

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- 3 weeks live coding (Stefano)
  - *algorithms, implementation on IBMQ*
- Materials:
  - *handwritten lecture notes, matching Aleks' lectures*
  - *textbook: preprint of Picturing Quantum Software. Kissinger & van de Wetering*
  - *Jupyter notebooks from live coding*

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  - *basics, ZX, classical simulation, quantum compilation, quantum error correction*
- 3 weeks live coding (Stefano)
  - *algorithms, implementation on IBMQ*
- Materials:
  - *handwritten lecture notes, matching Aleks' lectures*
  - *textbook: preprint of Picturing Quantum Software. Kissinger & van de Wetering*
  - *Jupyter notebooks from live coding*
  - *Picturing Quantum Processes*. Coecke & Kissinger. CUP (optional)
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- Exam is by take-home miniproject
  - *expect a theory and a (Python) coding component*