Toward optimizing compilers for quantum computers

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PEQUAN seminar

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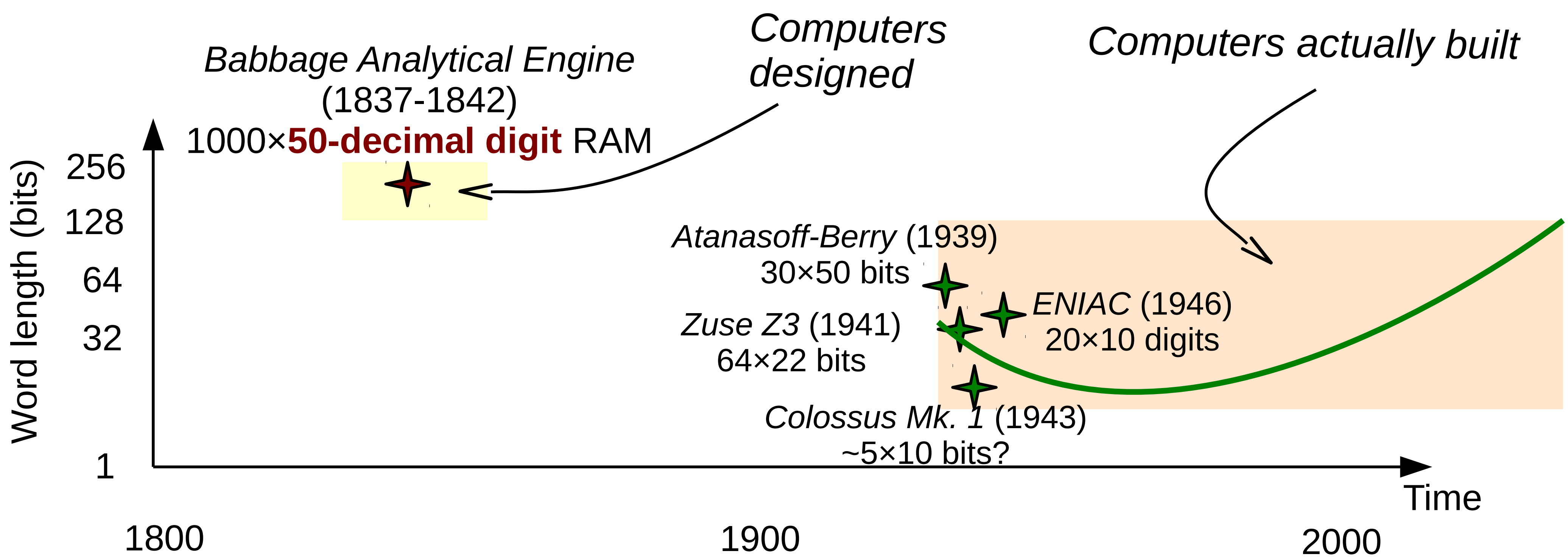
Why Quantum Computing *Today*?

- Already an established research topic since 1990's
  - In theoretical computer science
  - In applied quantum physics
- Usual stance in applied CS: *I'll believe it when I'll see it.*
- Today: no excuse, we got hardware!
  - IBM: **open access**
    16-bit quantum computer,
    20-qubit in limited access,
    50-qubit prototype
  - Rigetti
    19-qubit in limited access
  - Google, Microsoft, Intel…
    various prototypes
    up to 72-qubit

https://quantumexperience.ng.bluemix.net

- Enables **experimental** computer science
- Opportunity for computer architecture and compiler research

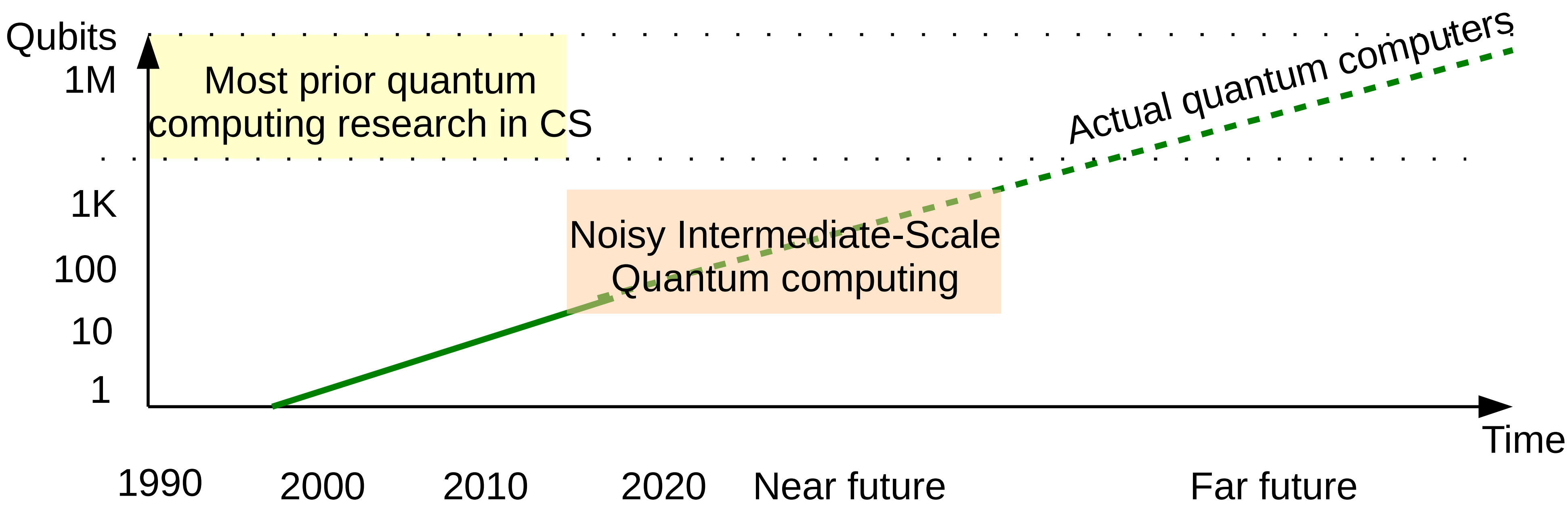
Computer history reduced to "how many bits?"



- Babbage: "*It seems to me probable that a long period must elapse before the demands of science will exceed this limit.*"
- As of 2018
  - 50-digit (~170-bit) numbers still considered ludicrous precision
  - Complete Analytical Engine has yet to be built

Welcome to the NISQ era

John Preskill keynote: *Quantum computing in the NISQ era and beyond*



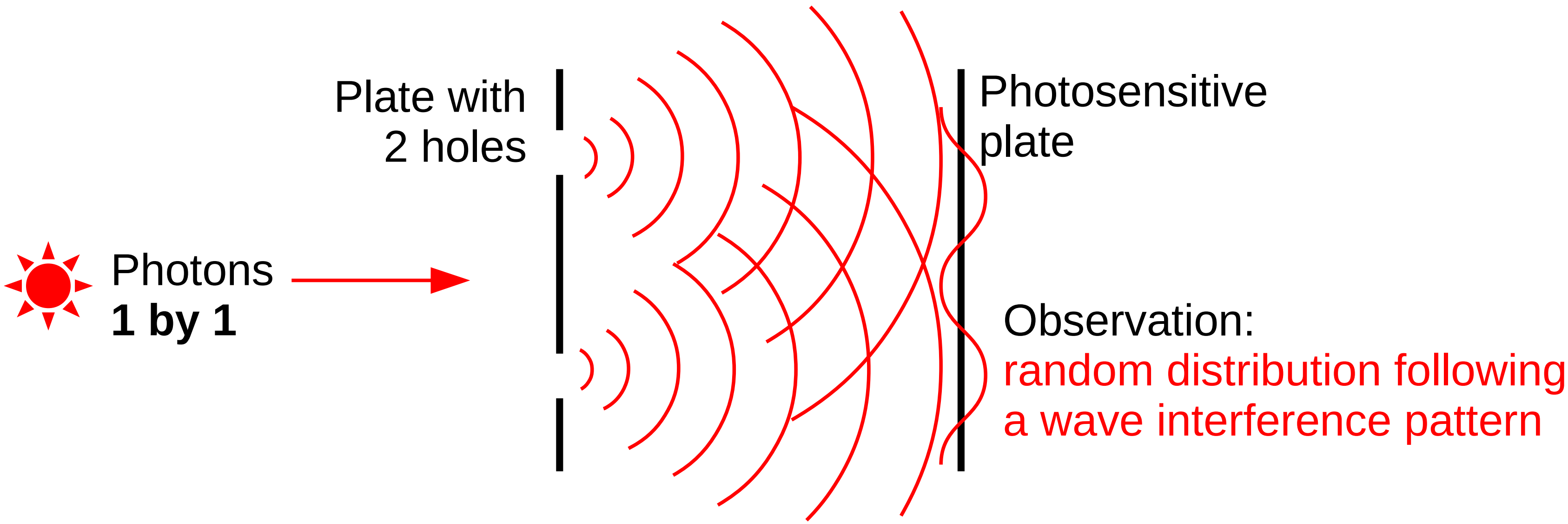
- Today: we have real quantum hardware
  - But too few, noisy, qubits to implement 1990's algorithms
  - A few near-term applications: quantum chemistry simulation
- Crossroads for the quantum computing field
  - Success → sustained investments toward more ambitious applications
  - Failure → quantum computing winter for the next 20-30 years

Agenda

- Introduction to the programming model
  - Logical qubits and quantum gates
- Compiling quantum circuits
  - Allocating logical qubits on physical qubits

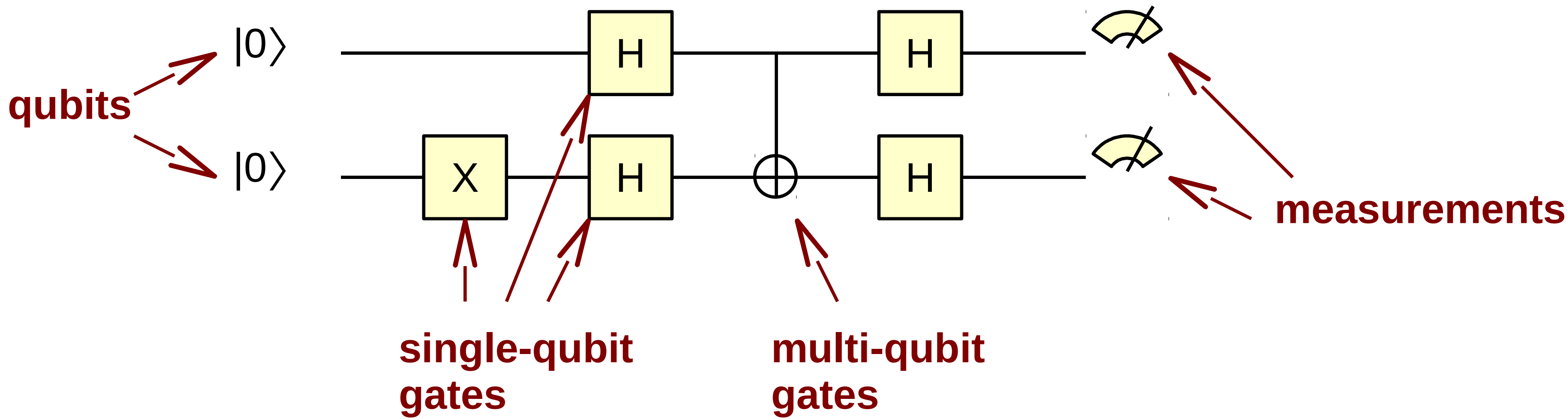
What is so special about quantum?

- Example: Young's double-slit experiment



  - Each photon behaves as a wave:
    goes through both holes and interferes with itself
- Idea: craft quantum experiments to perform computations
- Quantum computing approach
  - Compute on superposed states
  - Exploit interference to select useful information
  - Measure results to infer statistical distribution

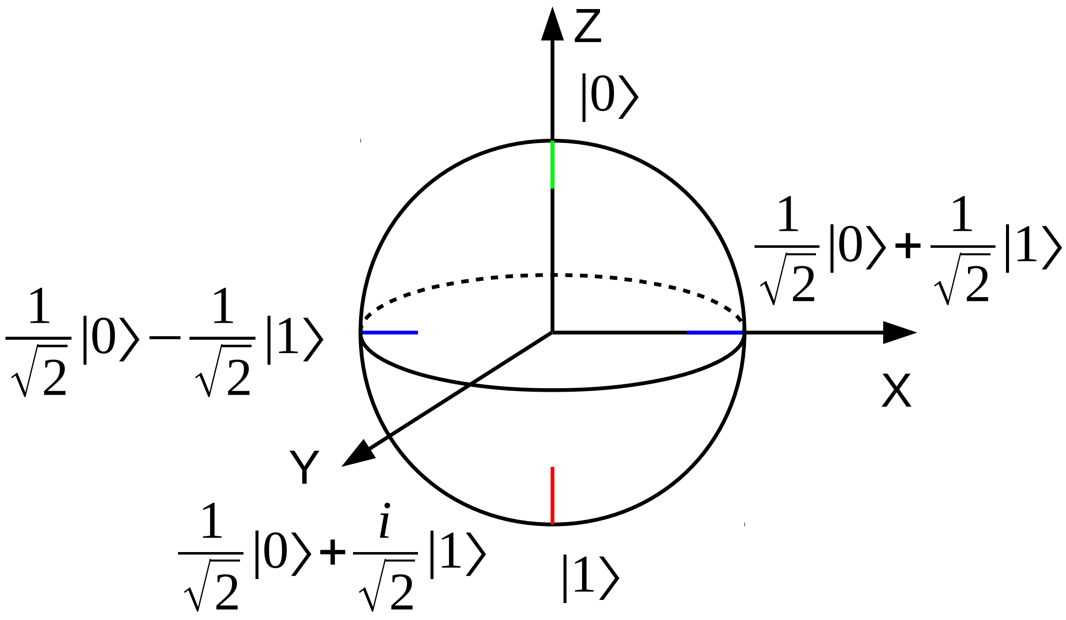
Computing abstraction: Quantum circuit



- Like classical circuit or dataflow graph, except:
  - Operates on qubits
  - Reversible: no creation, destruction, nor duplication of qubits
  - Starts by initialization, ends by measurement

Basic data-type: the qubit

- Superposition of states: $\alpha|0\rangle + \beta|1\rangle$ with $\alpha,\beta \in \mathbb{C}$, $|\alpha|^2+|\beta|^2=1$
  - Representation as vector in basis ($|0\rangle$, $|1\rangle$): $\begin{pmatrix}\alpha\\ \beta\end{pmatrix}$
- We can visualize possible states on the surface of a sphere



Multiple qubits

- State space: exponential number of dimensions
  - *n* classical bits encode **one** of 2^n states: space is $\{0,1\}^n$
  - *n* qubits encode a **superposition** of 2^n states: space is $\mathbb{C}^{2^n}$ (normalized)
- From independent qubits
  - Tensor product of individual states

$a|0\rangle + b|1\rangle$

$c|0\rangle + d|1\rangle$

$\left.\right\}$ $(a|0\rangle + b|1\rangle) \otimes (c|0\rangle + d|1\rangle)$
$= ac\,|00\rangle + ad\,|01\rangle + bc\,|10\rangle + bd\,|11\rangle$

- State may not be separable: qubits are in an ***entangled*** state
  - e.g.

!

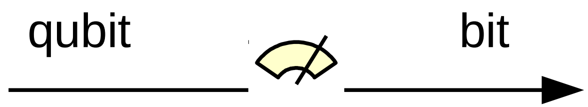
!

$\left.\right\}$ $1/\sqrt{2}\,|00\rangle + 1/\sqrt{2}\,|11\rangle$

No a,b,c,d such that ac=bd=1/√2 and ad=bc=0

  - Need to consider group of entangled qubits as a whole
- Visualization: 2^{2n}-dimension hypersphere? ☹

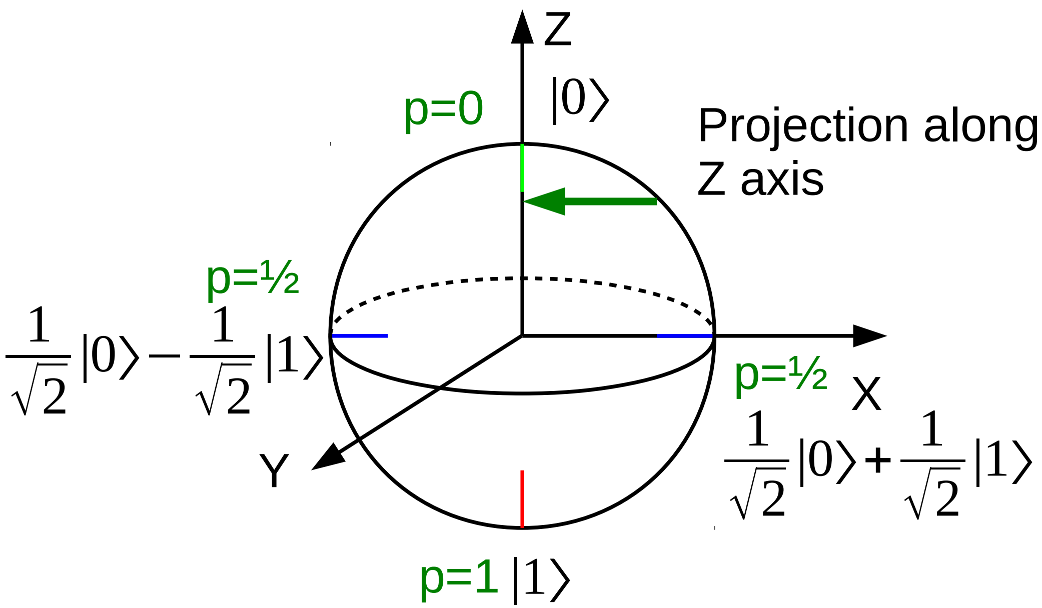
Operation: Measurement



Measurement turns a qubit into a bit

p = probability of measuring a **1**

- Measuring $\alpha|0\rangle + \beta|1\rangle$ gives:
  - **0** with probability $|\alpha|^2$
  - **1** with probability $|\beta|^2$
- Destructive operation
  - State space of the system projected to $\mathbb{C}^{2^{n-1}}$
  - No information on sign / complex phase
  - Random: need to repeat to infer distribution

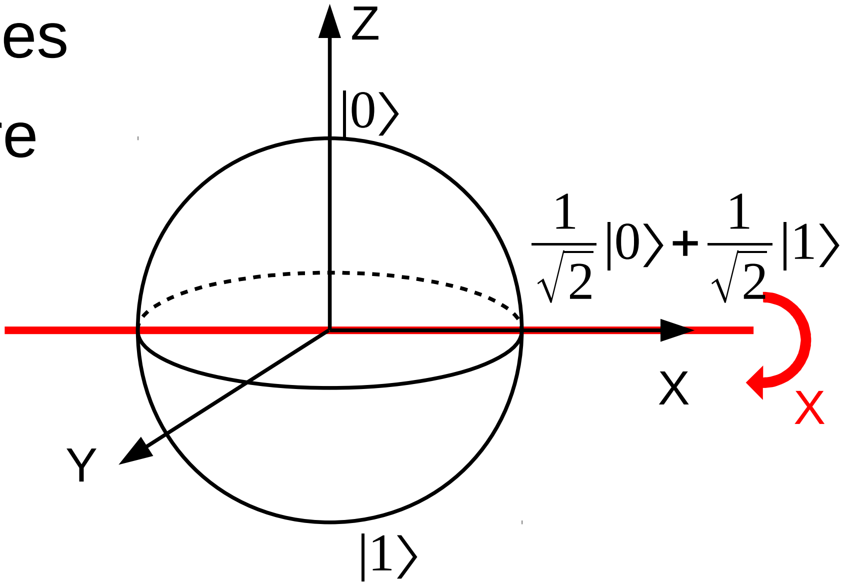


Operation: single-qubit gate

Quantum gates as mul by unitary matrices

- Correspond to rotations on the sphere
- e.g. X gate
  - flip along X axis
  - maps $|0\rangle$ to $|1\rangle$ and $|1\rangle$ to $|0\rangle$
  - "equivalent" of classical NOT

$\boxed{X}$



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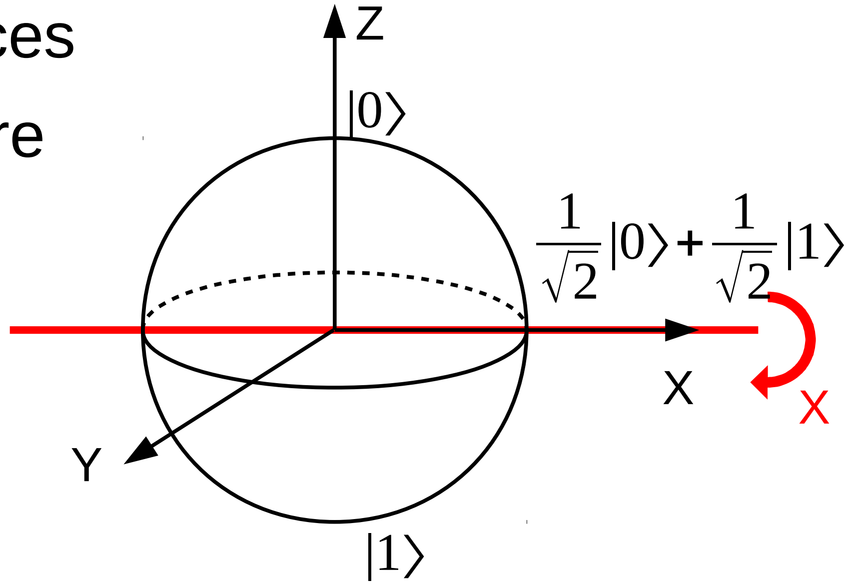
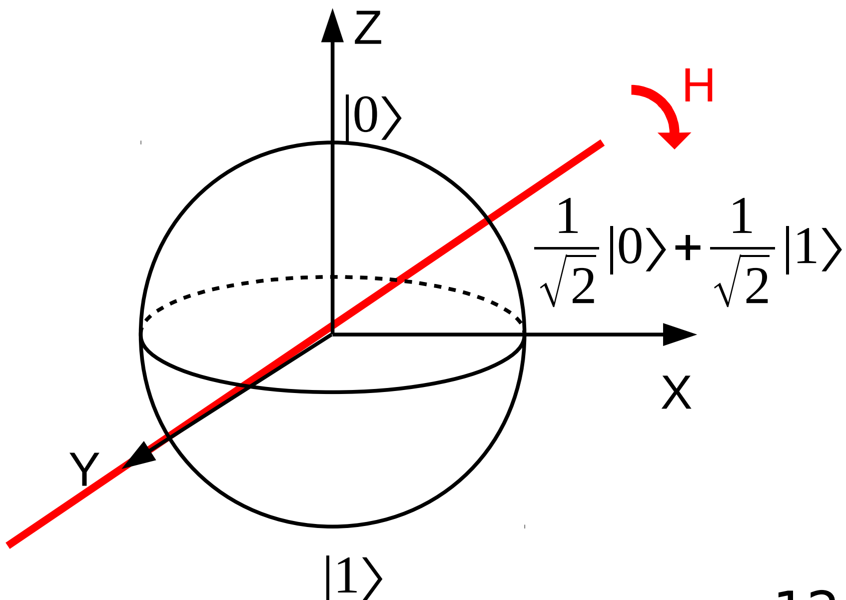


- e.g. Hadamard-Walsh gate
  - maps $|0\rangle$ to $1/\sqrt{2}\ |0\rangle + 1/\sqrt{2}\ |1\rangle$ and $|1\rangle$ to $1/\sqrt{2}\ |0\rangle - 1/\sqrt{2}\ |1\rangle$

H

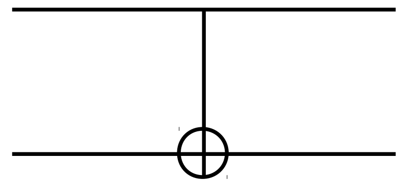


- Any single-qubit gate can be decomposed into sequence of X and Z axis rotations

Multi-qubit gate: Controlled NOT

- CNOT or Controlled-X: analog of classical XOR

$a|00\rangle + b|01\rangle + c|10\rangle + d|11\rangle$



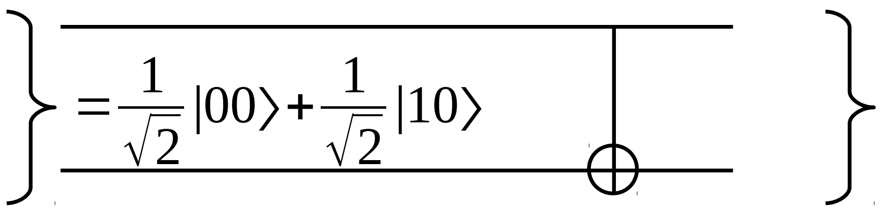
$a|00\rangle + b|01\rangle + \mathbf{d}|10\rangle + \mathbf{c}|11\rangle$

"Flips second qubit
when first qubit is $|1\rangle$"

- As a way to entangle qubits

$$\frac{1}{\sqrt{2}}|0\rangle + \frac{1}{\sqrt{2}}|1\rangle$$

$$|0\rangle$$



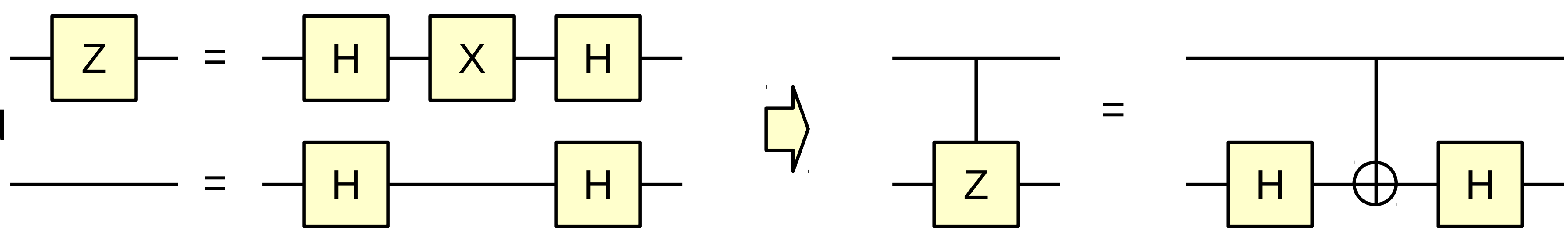
$$= \frac{1}{\sqrt{2}}|00\rangle + \frac{1}{\sqrt{2}}|10\rangle$$

$$\frac{1}{\sqrt{2}}|00\rangle + \frac{1}{\sqrt{2}}|11\rangle$$

- As a building block to make arbitrary controlled gates

e.g.

and

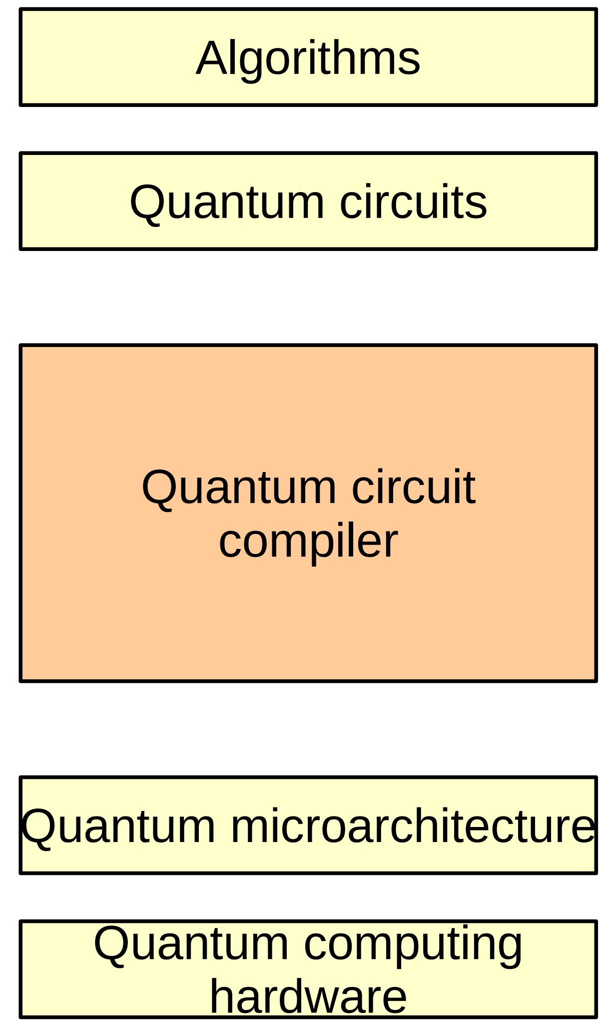


Agenda

- Introduction to the programming model
  - Logical qubits and quantum gates
- Compiling quantum circuits
  - Allocating logical qubits on physical qubits

Compilers for quantum computing

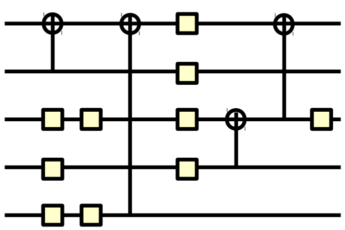
- Existing and near-future architectures:
  - 10s to 100 qubits
  - No error correction
  - Low-level **constraints** on circuits:
    set of gates, qubit connectivity
- Need compilers of circuits down to low-level gates
  - Many differences from classical compilers

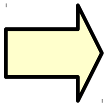


Focus: the qubit allocation phase

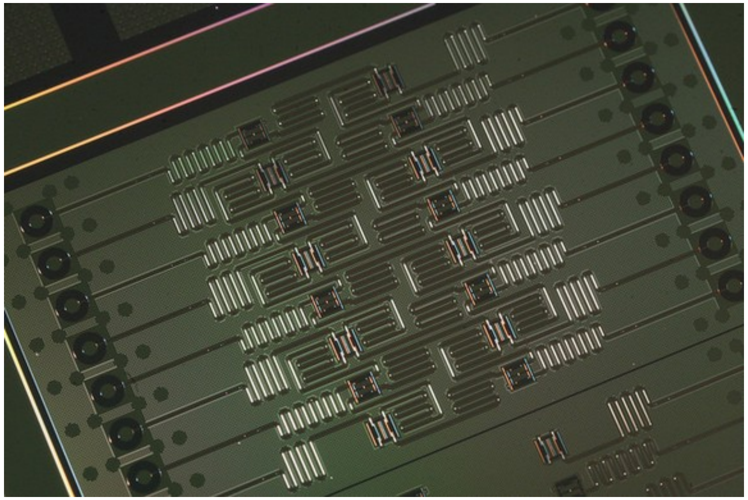
- Map logical qubits to physical qubits
  - Need to meet hardware constraints: connectivity between physical qubits
  - Transform circuit to fit on given quantum computer
- Minimize runtime and gate count to **minimize noise**

Software: circuit on logical qubits





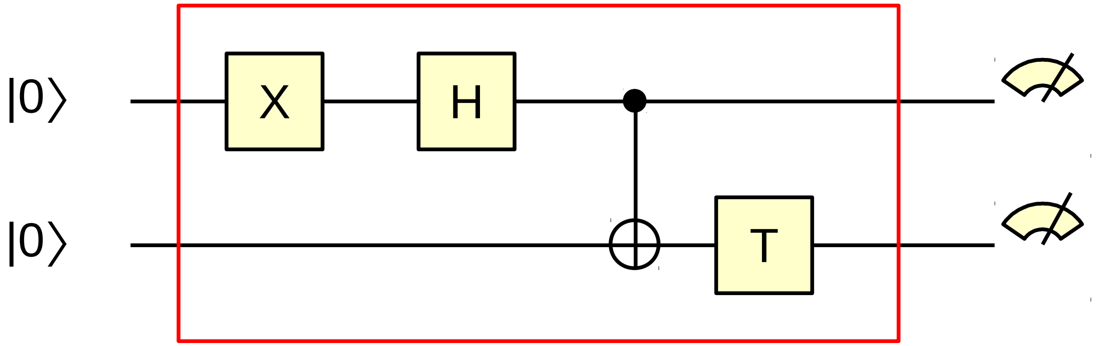
Hardware: physical qubits



- Joint work with Marcos Yukio Siraichi, Vinícius Fernandes dos Santos and Fernando Magno Quintão Pereira, *DCC, UFMG, Brazil*

Circuit subset for qubit allocation

Input: reversible quantum circuits described at gate level



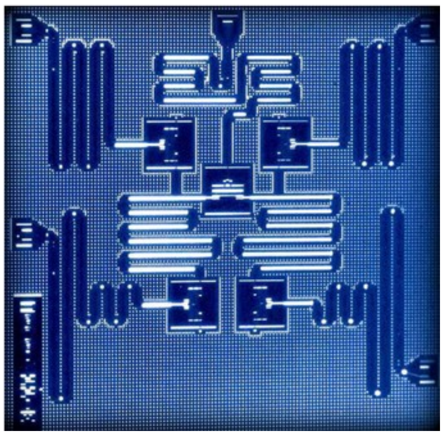
- Between initialization and measurement : unitary gates only
- After decomposition into single-qubit and CNOT gates
- Expressed in QASM language

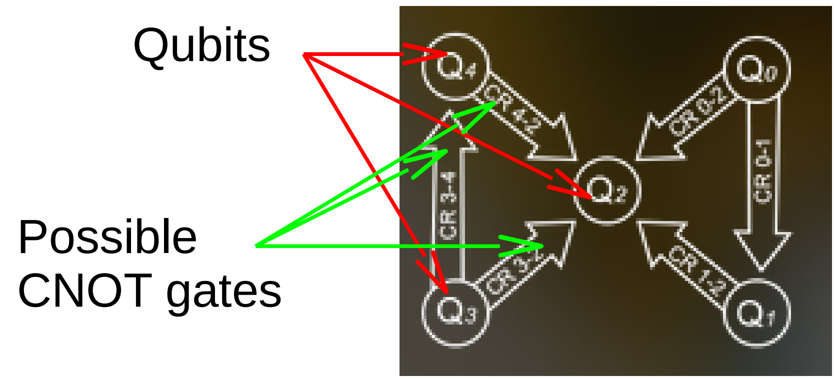
```
qreg l[2];
creg c[2];
x l[0];
h l[0];
cx l[0] l[1];
t l[1];
measure l[0] -> c[0];
measure l[1] -> c[1];
```

Limited-connectivity quantum computer

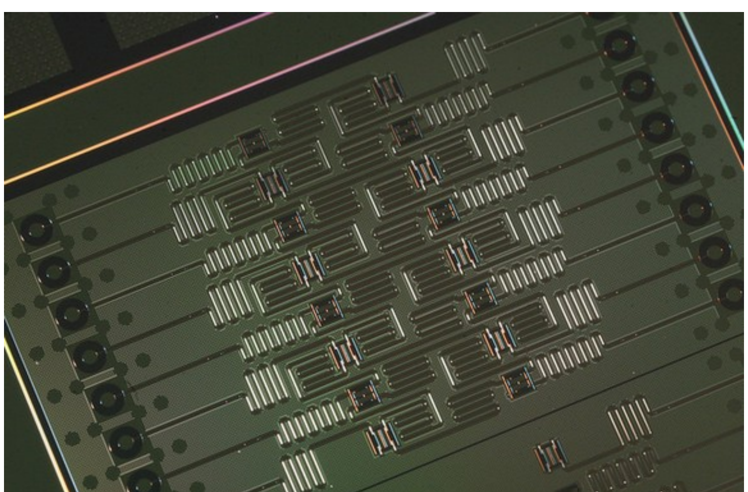
Target: superconducting qubit based quantum computers

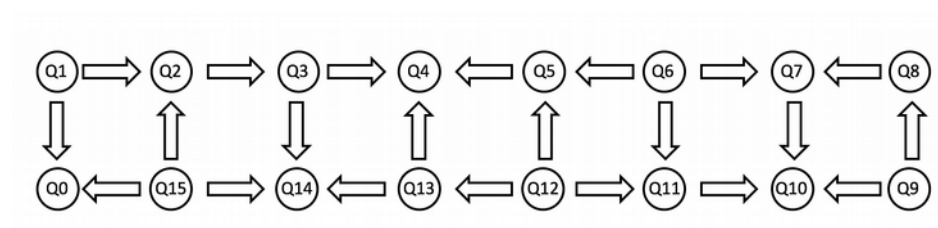
- Constraints on which qubits are allowed to interact
- e.g. IBM QX2, 5 qubits





- e.g. IBM QX5, 16 qubits

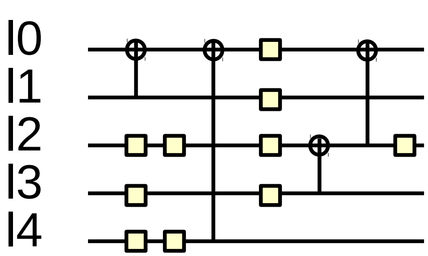




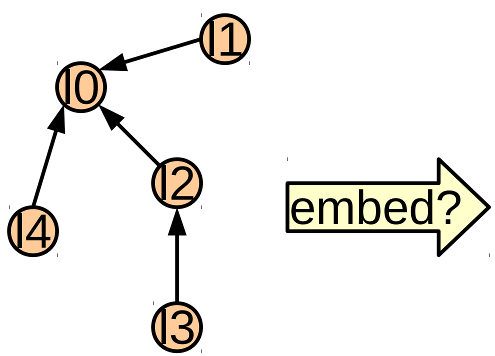
Qubit assignment is Subgraph Isomorphism

Can we label logical qubits with physical qubits
so that all gates obey machine connectivity constraints?

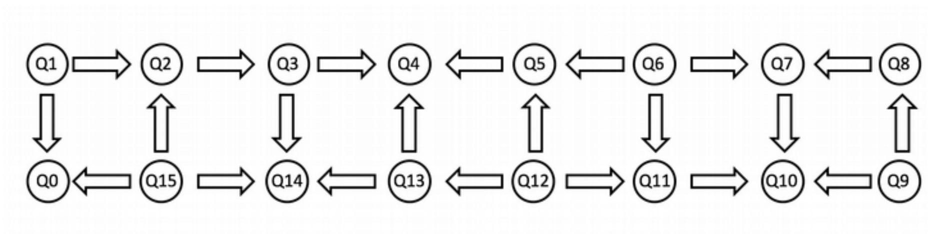
- Known as the Subgraph Isomorphism problem
- “Easy part” of qubit allocation
- Already NP-Complete



Circuit



Dependencies
on logical qubits



Connectivity
of physical qubits

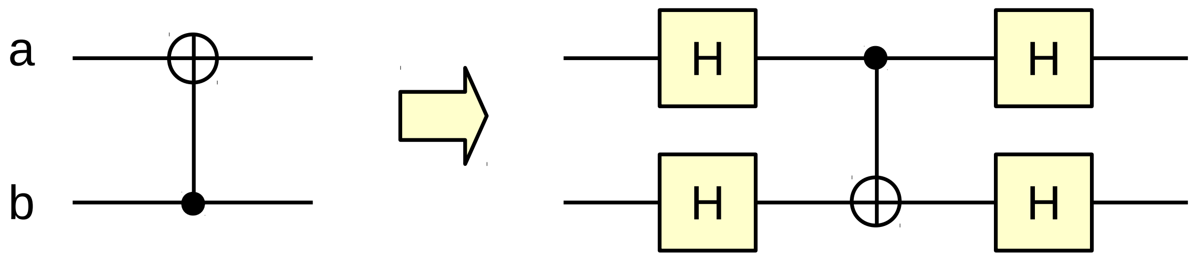
- In practice, most circuits will need transformations to “fit” the connectivity graph

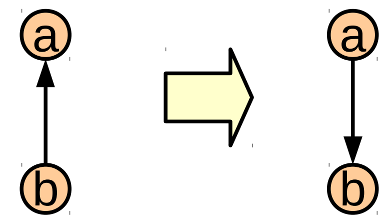
Circuit transformation primitives

Transformation

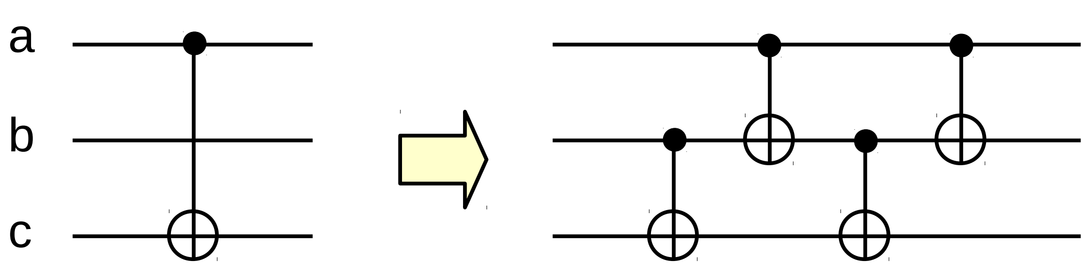
Effect on dependency graph
(assuming no other dependency)

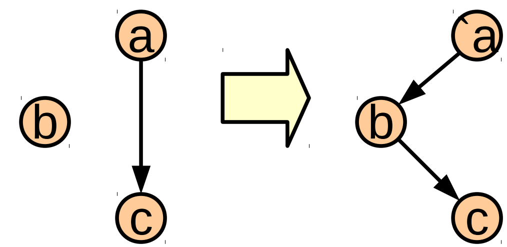
- CNOT reversal



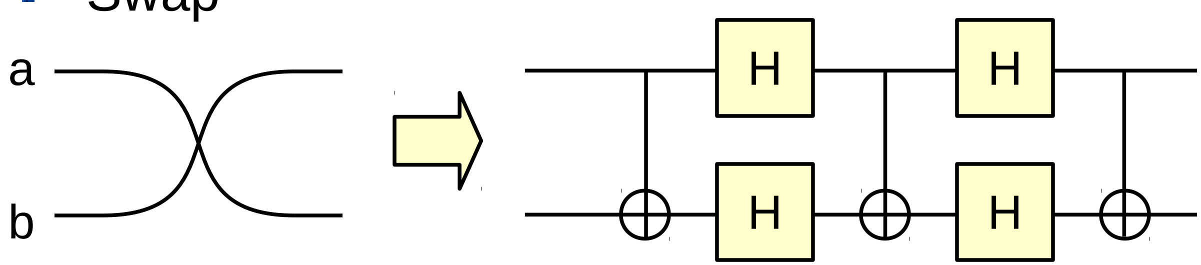


- Bridge

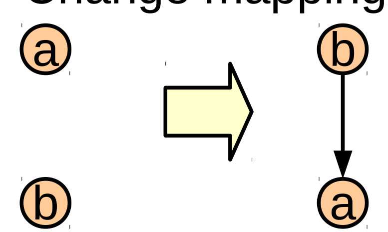




- Swap



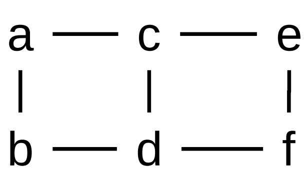
Change mapping!



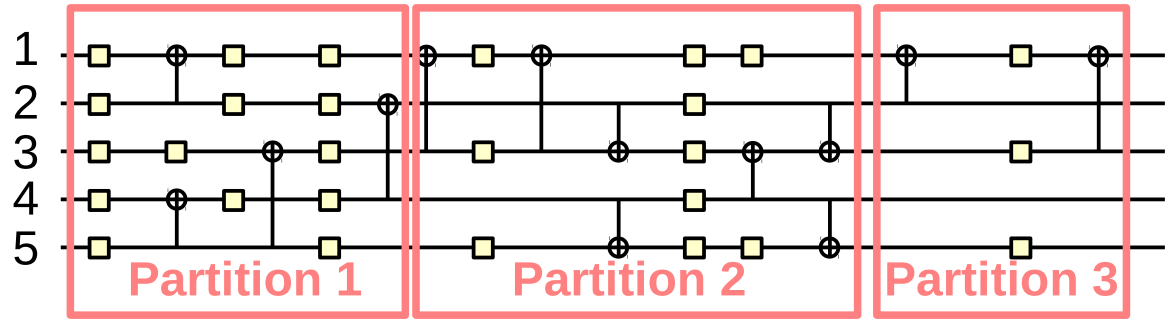
1. Compute maximal isomorphic partitions

- Break circuit into solvable instances of subgraph isomorphism
  - Maximal: adding one dependency makes it unsolvable
- Approximated with bounded exhaustive search
  - For each partition, build collection of candidate mappings

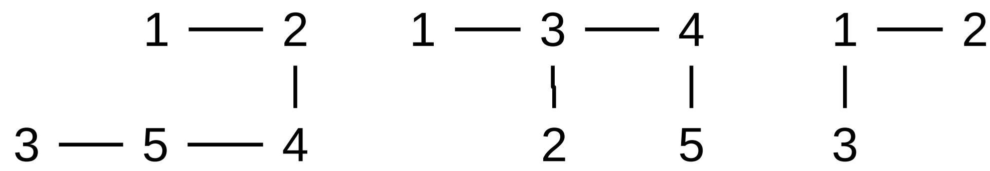
Connectivity graph



Circuit



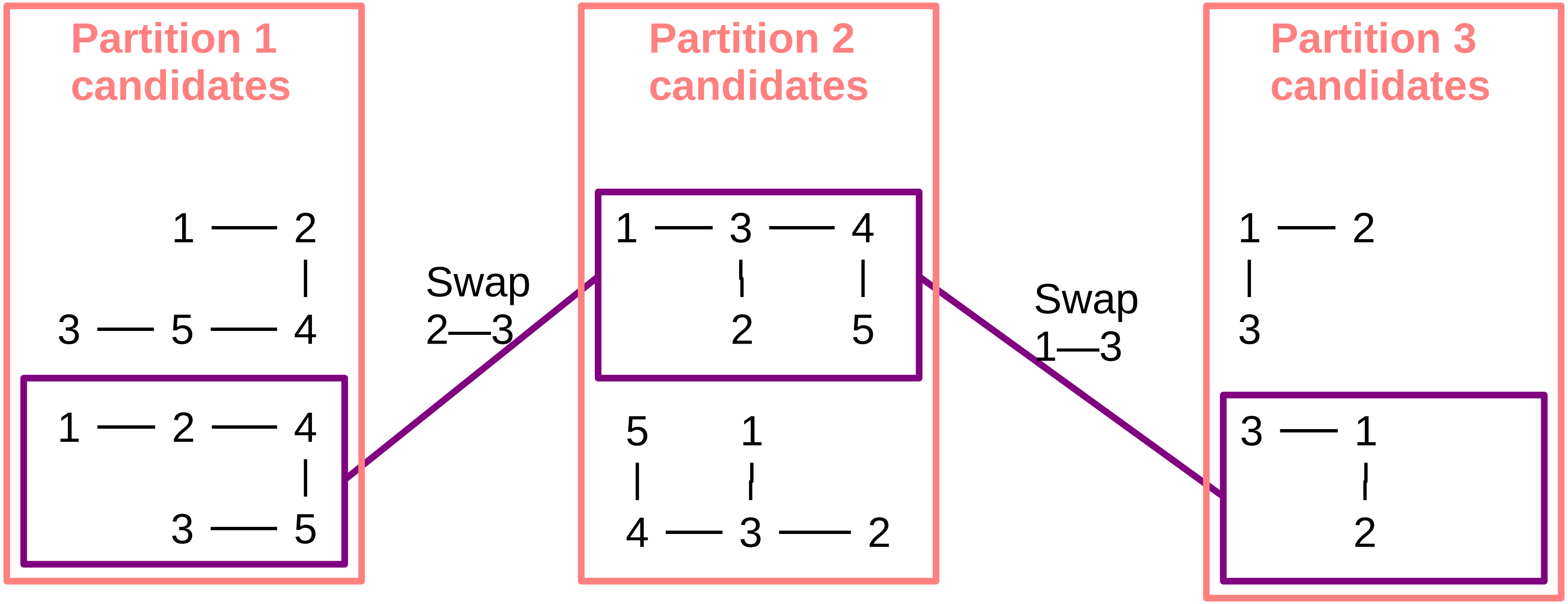
Example candidate mappings



2. Choose qubit mappings, add swaps

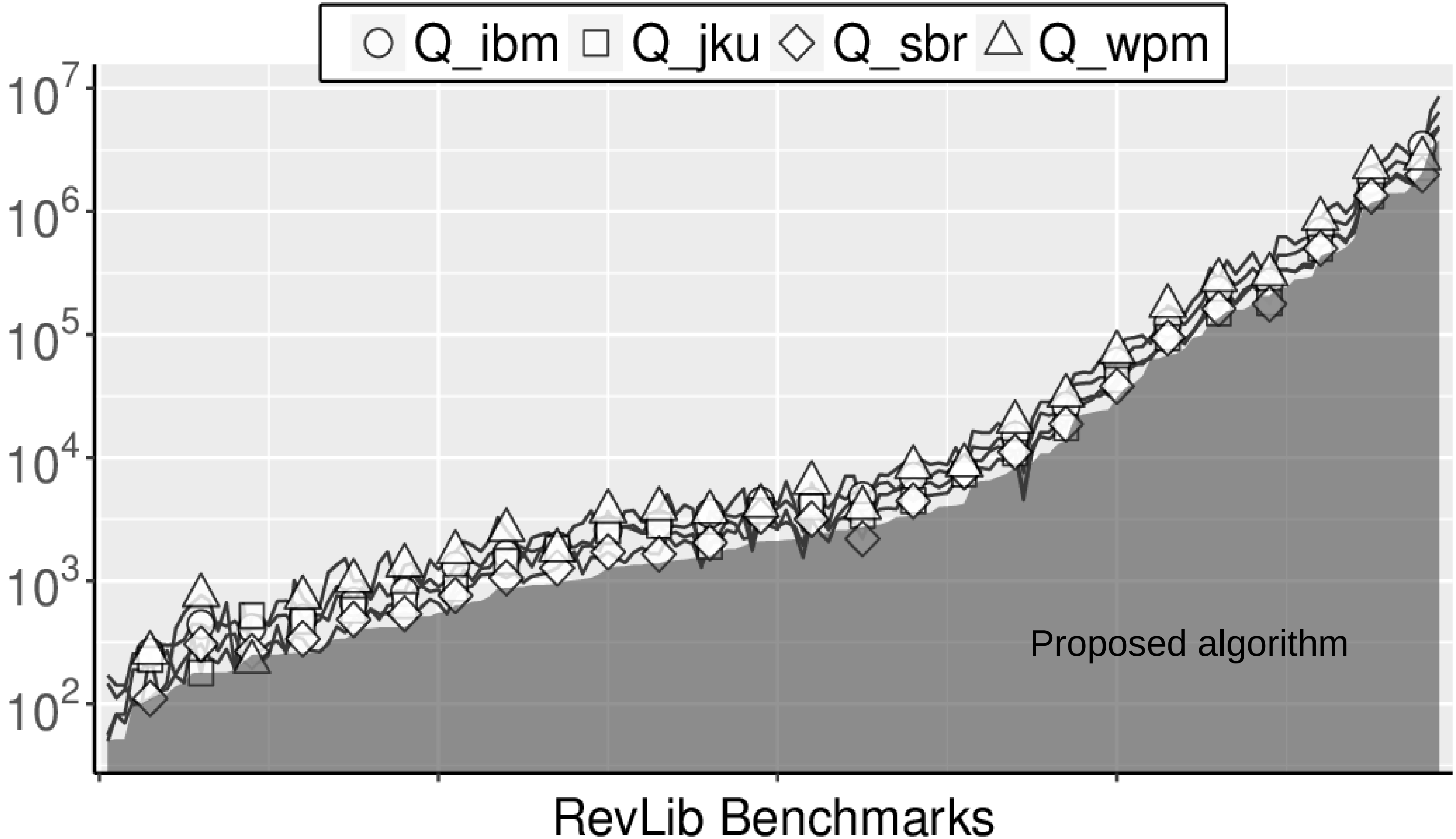
Select one mapping in each partition

- Goal: minimize total number of swaps
- Equivalent to Token Swapping problem (NP hard)
- Use 4-approximation algorithm proposed in 2016



Comparison with other approaches

- Cost (lower is better)



Conclusion: compiler optimization for quantum circuits

An entire domain to explore

- Qubit allocation
  - Seek run-time vs. accuracy tradeoffs, optimize for fidelity
  - Specialize for regular quantum computer structures
  - Take advantage of quantum circuit properties: spacial, temporal locality
- Mapping high-level gates to hardware-supported gates
  - High-level gate implementation: accuracy/cost tradeoffs
  - Selecting gate sequences: use degree of freedom on relative phase
- Time/space tradeoffs
  - Adapt number of helper qubits to resource availability
- Formalization
  - Which semantics for quantum programs and quantum computers?
  - Which intermediate representation for quantum circuits?