Qubit Allocation
as a Combination of
Subgraph Isomorphism and Token Swapping

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SPLASH OOPSLA

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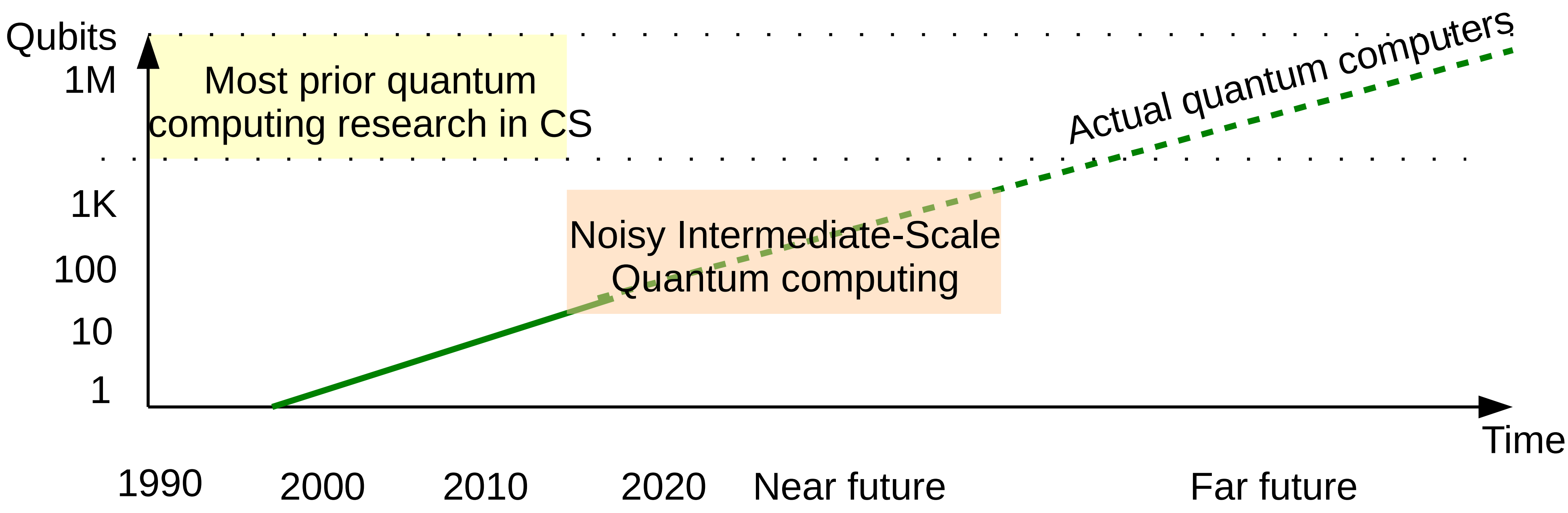
Welcome to the NISQ era

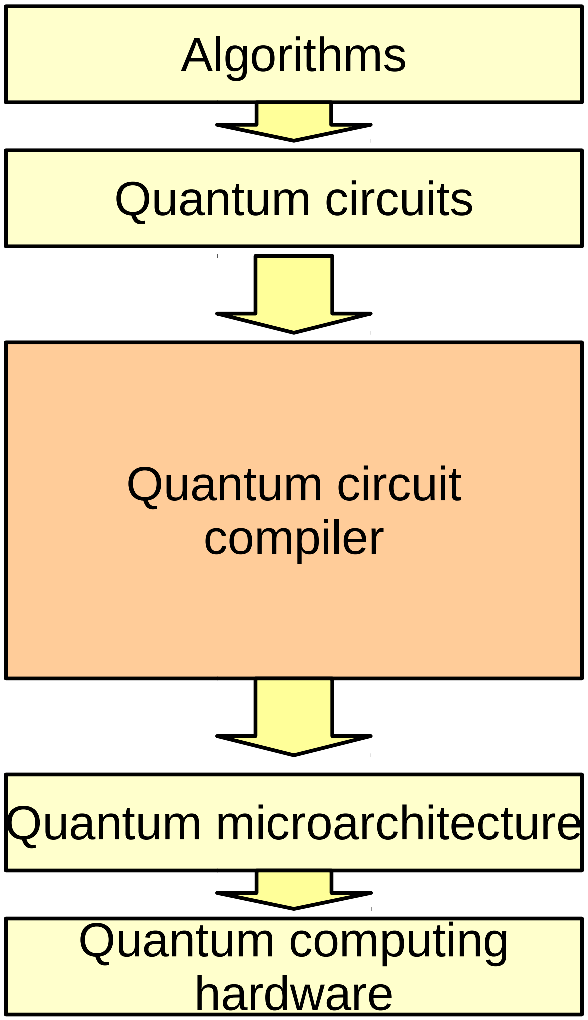
Noisy Intermediate-Scale Quantum computing — John Preskill



- 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

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 for new compilers
  - From abstract quantum circuits to low-level commands
  - Quantum counterparts of **register allocation**, instruction scheduling…
  - Different abstractions and constraints than classical compilers

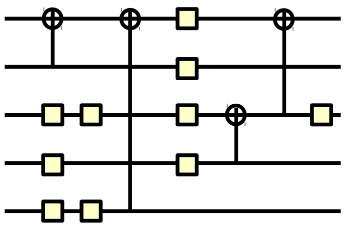


Focus: the qubit allocation phase

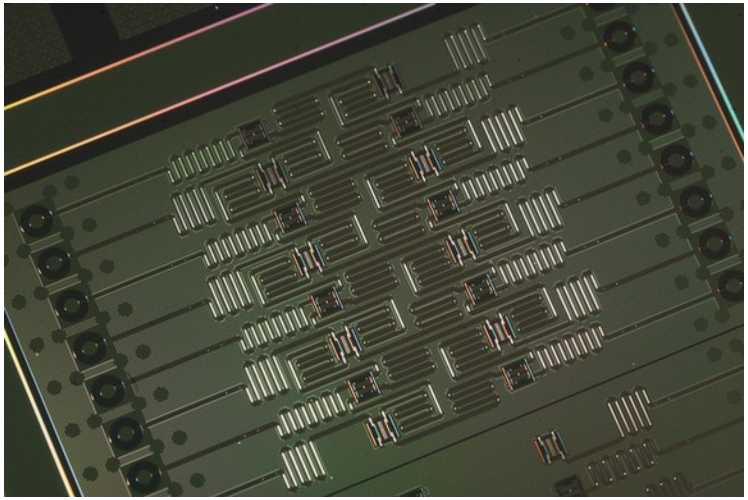
- Map logical qubits to physical qubits
  - Need to meet hardware constraints: connectivity between physical qubits
  - Transform circuit to fit on given quantum computer

- Minimize runtime and gate count to **minimize noise**

Software: circuit on logical qubits



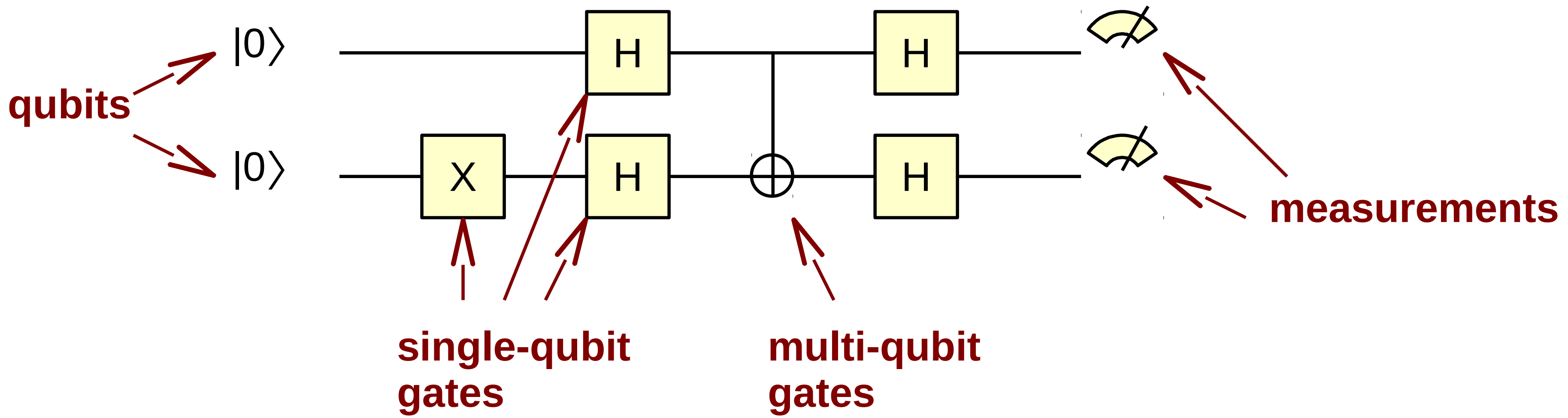
Hardware: physical qubits



Outline

- The qubit allocation problem
- Bounded Mapping Tree algorithm
- Evaluation

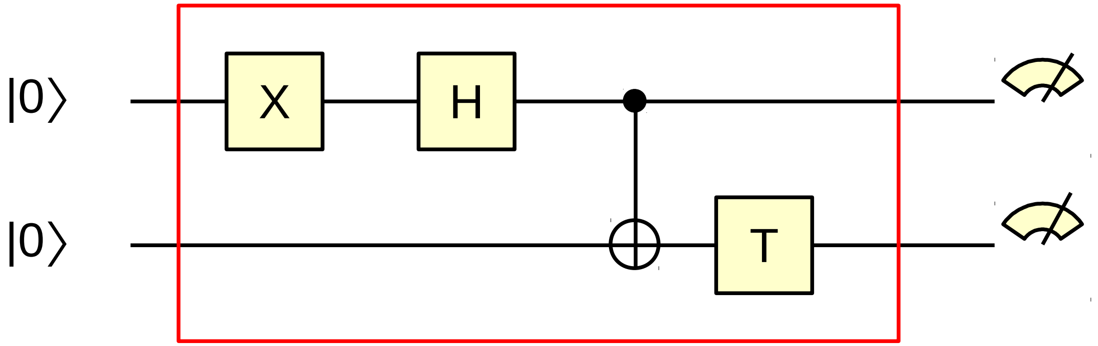
Computing abstraction: Quantum circuit



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

Circuit subset for qubit allocation

Input: reversible quantum circuits described at gate level



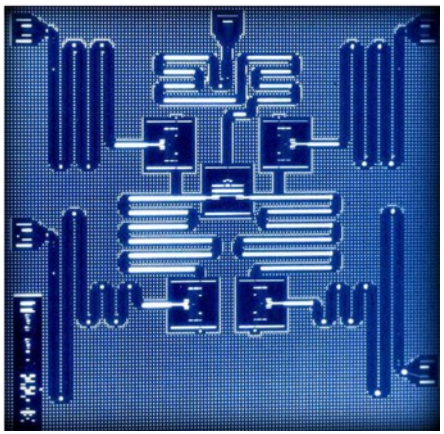
- Between initialization and measurement : unitary gates only
- After decomposition into single-qubit and CNOT gates
- Expressed in QASM language

```
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

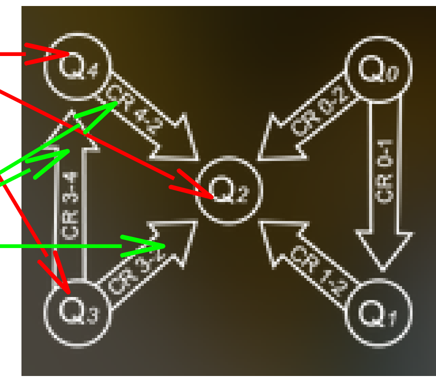
Target: superconducting qubit based quantum computers

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

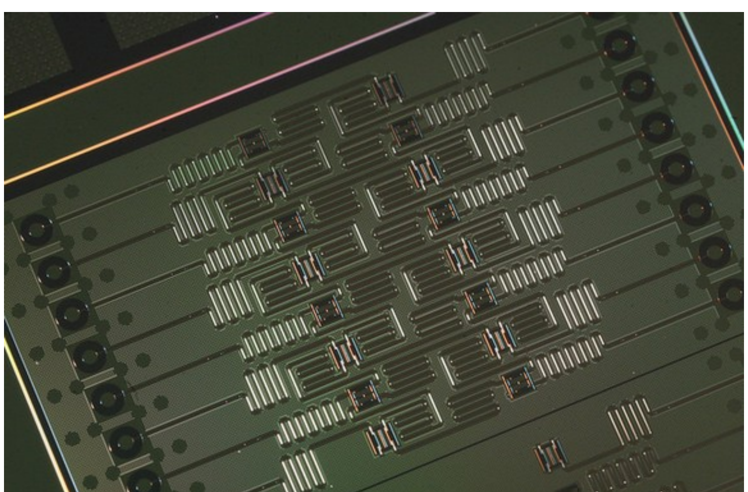


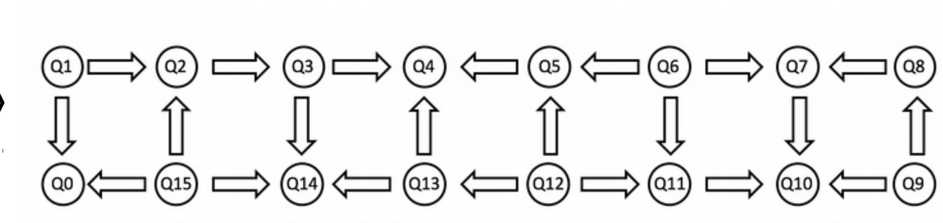
Qubits

Possible CNOT gates



- e.g. IBM QX5, 16 qubits

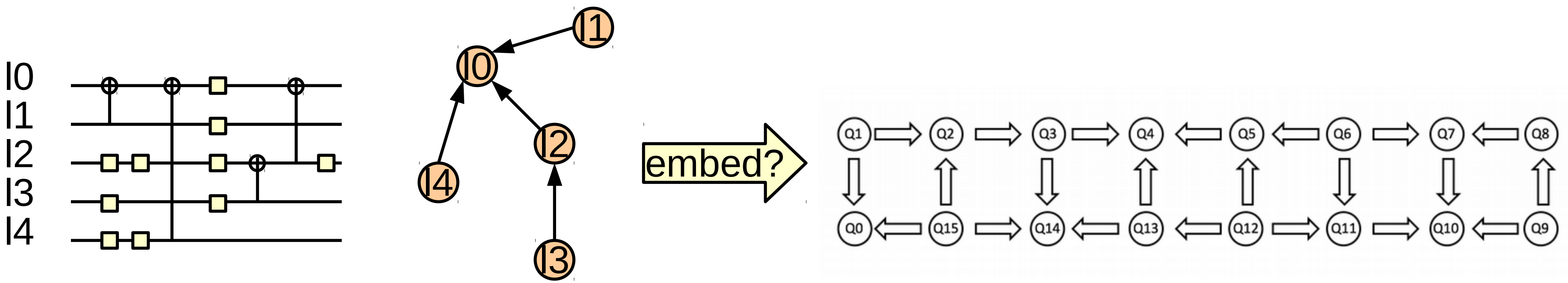




Qubit assignment is Subgraph Isomorphism

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

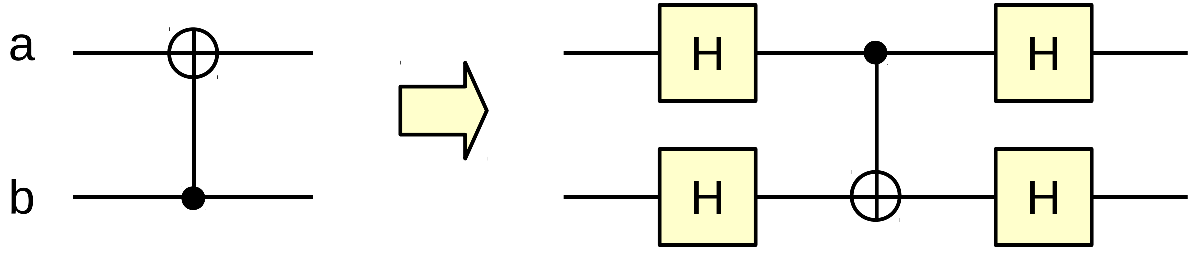
- In practice, most circuits will need transformations to “fit” the connectivity graph

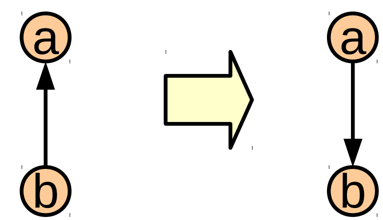
Circuit transformation primitives

Transformation

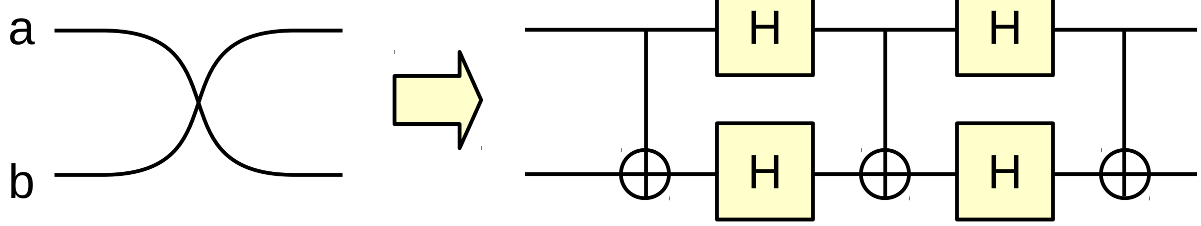
Effect on dependency graph
(assuming no other dependency)

- CNOT reversal

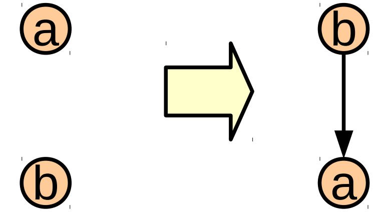




- Swap



Change mapping!



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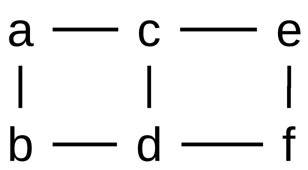
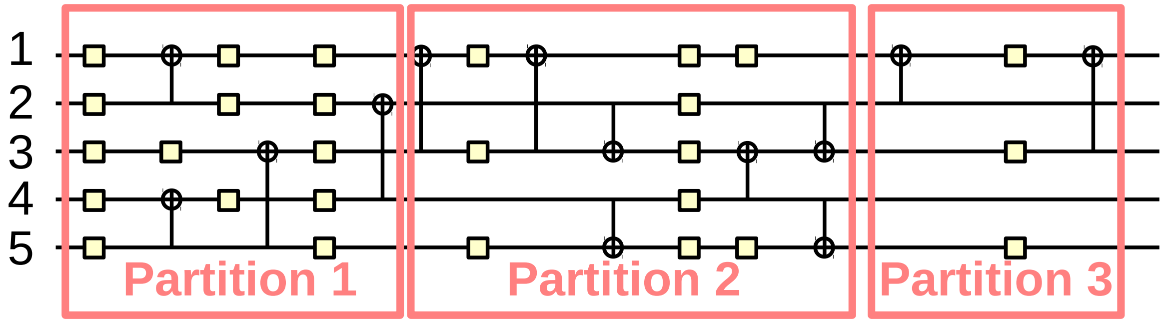
1. Compute maximal isomorphic partitions

- 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

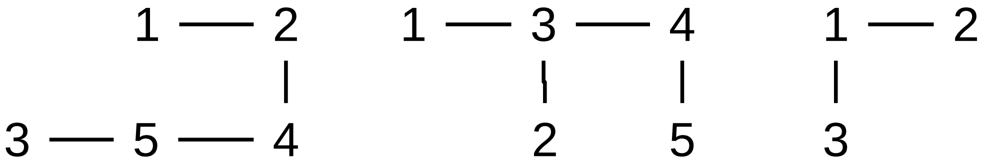
Connectivity graph



Circuit



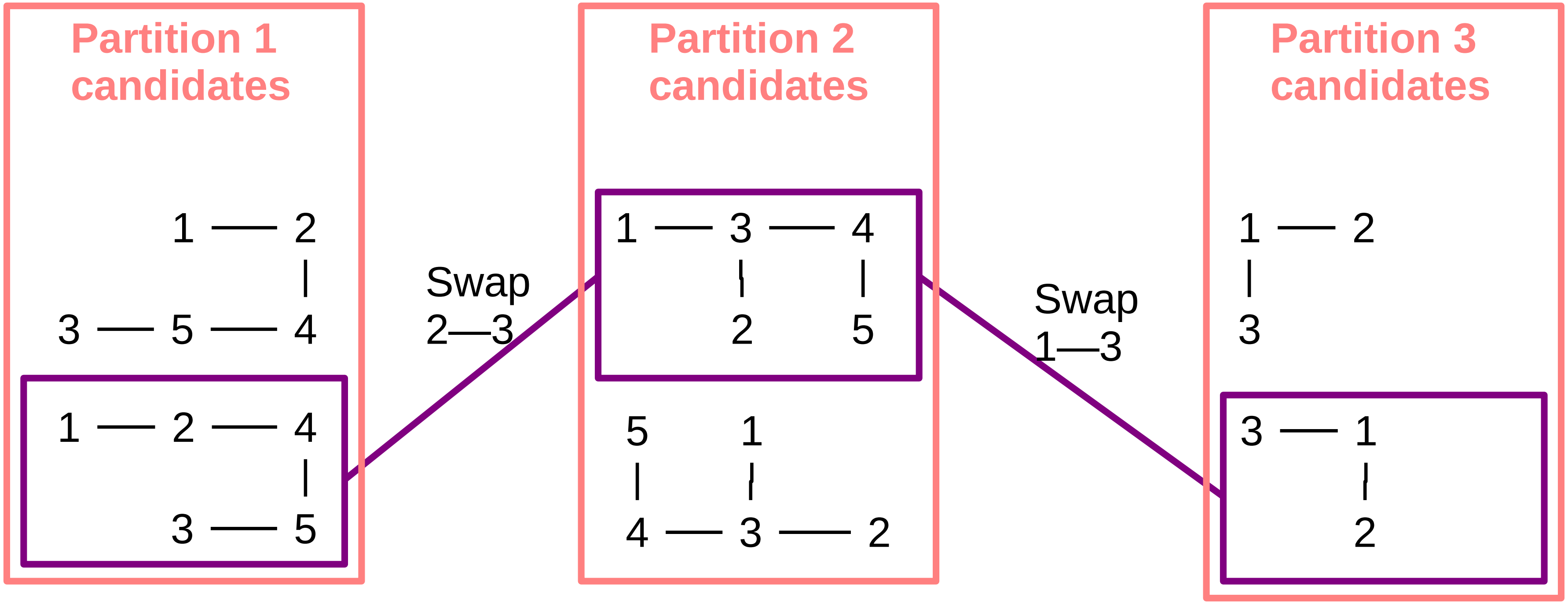
Example candidate mappings



2. Choose qubit mappings

Select one mapping in each partition

- Goal: minimize total number of swaps
- Can estimate the number of swaps from one mapping to another
- Solve using **dynamic programming**



3. Generate swap sequences

Generate the minimal number of swaps from one mapping to the next

- Equivalent to Token Swapping problem (NP hard)
- Use recently-proposed 4-approximation algorithm [Miltzow et al. 2016]
  - Complexity $O(|Q|^3)$
  - Modified to take make untouched qubits undifferentiated
  - Also gives upper-bound in number of swaps used in step 2

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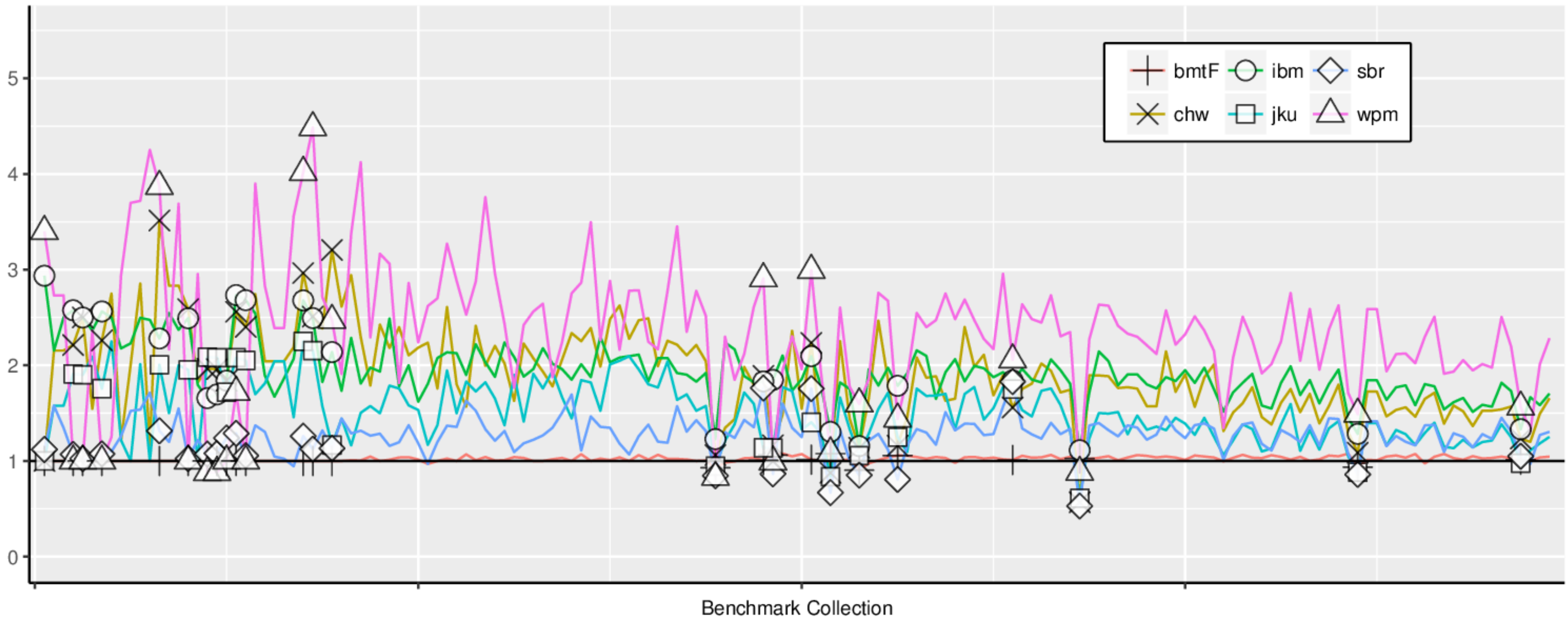
Evaluation and results

- Proposed Bounded Mapping Tree algorithm gives lowest cost on 94% of benchmarks
  - vs. *IBM QISKit* (ibm), Siraichi et al. *Weighted Partial Mapper* (wpm), Zulehner et al. *A* search* (jku), Li et al. *SABRE* (sbr), Zulehner. et al. *IBM challenge* (chw)
- Faster version (bmtF) within 2% accuracy, 3× faster on average



- Benchmarks from RevLib, Quipper and ScaffCC
- Target architecture IBM QX20 Tokyo

Conclusion

- Formulate qubit allocation based on know problems
  - Subgraph isomorphism
  - Token swapping
- Derive an efficient algorithm
  - Bounded search for subgraph isomorphisms partitions
  - Dynamic programming to assemble partition solutions
  - Token Swapping approximation
- Parameterized algorithm allows runtime-accuracy tradeoffs
  - Scales to 100 qubits
- Future directions
  - Support classical control flow
  - Within this framework, develop heuristics to scale further

Come play with qubit allocation online: http://cuda.dcc.ufmg.br/enfield/

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