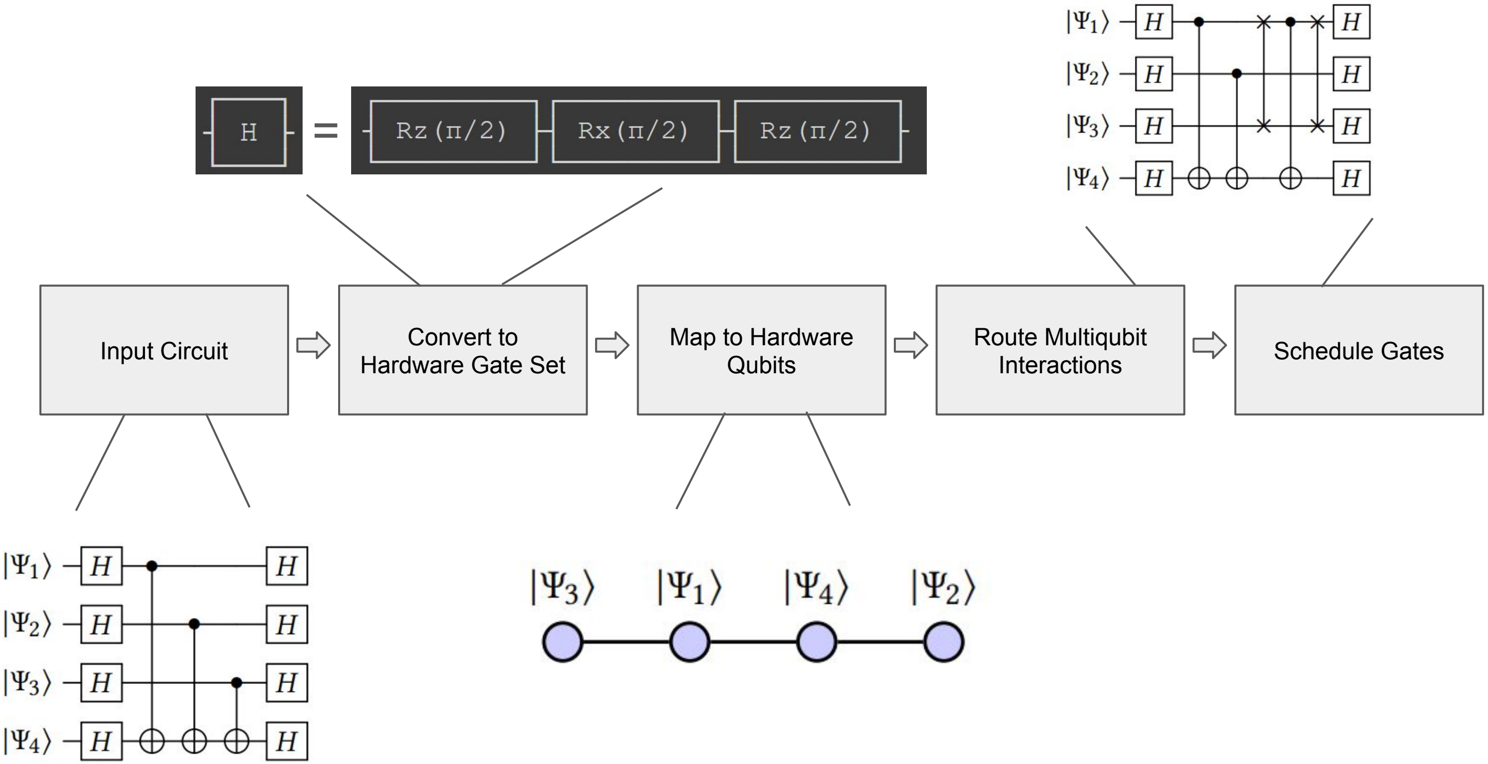
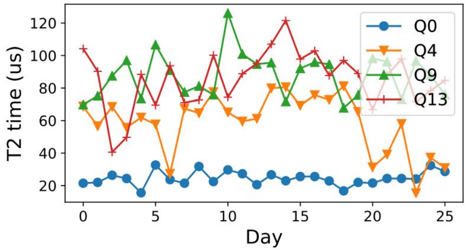
Compilation Beyond Superconducting Systems

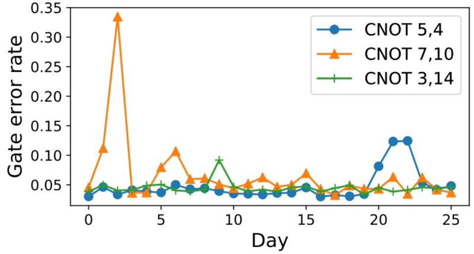
Recap: (Basic) Compilation Pipeline



Recap: Noise Adaptive Compilation

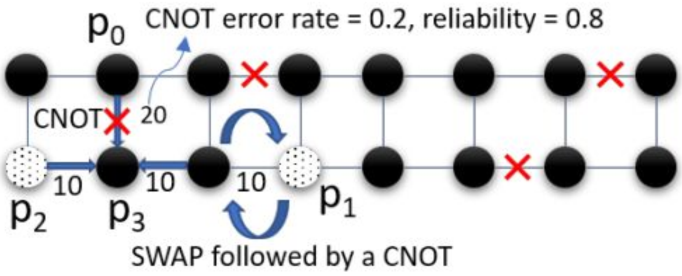


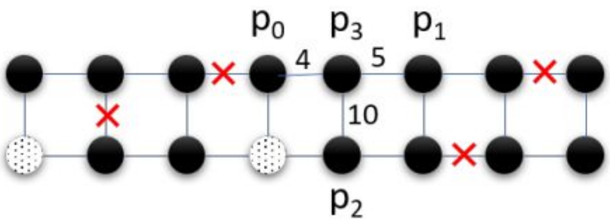
(a) Coherence time (T2)



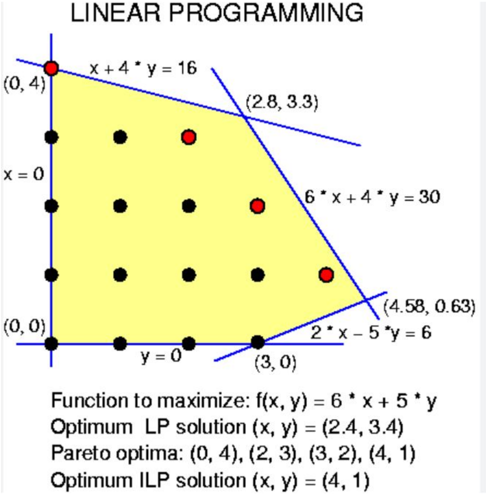
(b) CNOT gate error rate

Recap: Noise Adaptive Compilation





Noise Adaptive Compilation - LP Solution (Simplified)



Noise Adaptive Compilation - LP Solution (Simplified)

Unique Qubit Placement in a Grid

$$\forall q \in Q_P : 0 \leq q.x < M_x \wedge 0 \leq q.y < M_y \tag{1}$$

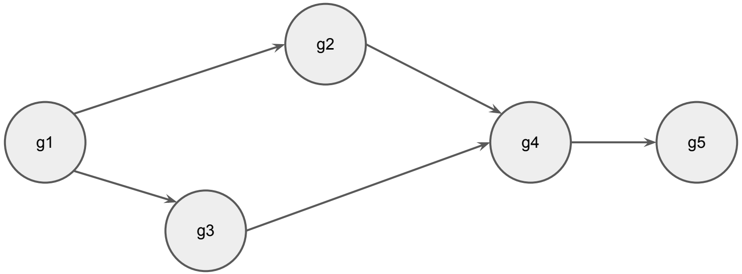
$$\forall q_1, q_2 \in Q_P : q_1.x \neq q_2.x \vee q_1.y \neq q_2.y \tag{2}$$

Noise Adaptive Compilation - LP Solution (Simplified)

Gate Dependencies

$$\forall g_1, g_2 \in G : g_2 > g_1 \Rightarrow g_2.\tau \geq g_1.\tau + g_1.\delta \qquad (3)$$

Program DAG



Noise Adaptive Compilation - LP Solution (Simplified)

Positionally Dependent Gate Durations

$$g_c = h_1 \wedge g_t = h_2 \Rightarrow g.\delta = \Delta_{h_1,h_2} \qquad (5)$$

Noise Adaptive Compilation - LP Solution (Simplified)

Time Ordering

$$g_c = h_1 \wedge g_t = g_2 \Rightarrow g.\tau + g.\delta \leq \min(h_1.\tau, h_2.\tau) \quad (6)$$

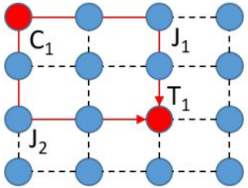
Noise Adaptive Compilation - LP Solution (Simplified)

Routing Constraints

No time or spatial overlap

$$S(R_i, R_j) = \neg(l_x^i > r_x^j \vee r_x^i < l_x^j \vee l_y^i > r_y^j \vee r_y^i < l_y^j) \quad (7)$$

$$T(g_i, g_j) = \neg(g_i.\tau > g_j.\tau + g_j.\delta \vee g_j.\tau > g_i.\tau + g_i.\delta) \quad (8)$$



No overlap between parallel CNOTs

$$\begin{aligned} Overlap(i,j) = & S(R_i^{cj}, R_j^{cj}) \vee S(R_i^{cj}, R_j^{jt}) \vee \\ & S(R_i^{jt}, R_j^{cj}) \vee S(R_i^{jt}, R_j^{jt}) \end{aligned} \quad (9)$$

Noise Adaptive Compilation - LP Solution (Simplified)

Objectives:
Positionally Dependent Errors

$$\forall g \in G_{Readout} : \forall h \in Q_H : g.q = h \Rightarrow g.\epsilon = E_h^R \qquad (10)$$

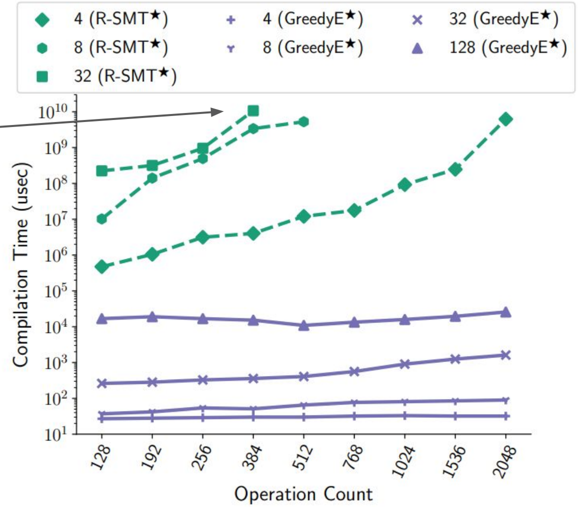
$$g_c = h_1 \wedge g_t = h_2 \wedge g.j = h_j \Rightarrow g.\epsilon = E^C_{h_1,h_2,j} \qquad (11)$$

Linearized Objectives: min total error

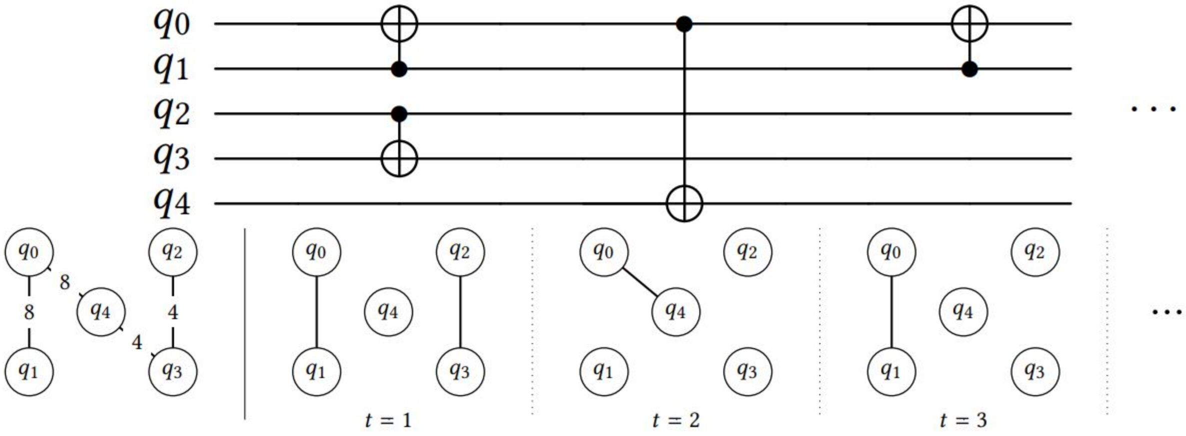
$$\omega \sum_{g \in G_{Readout}} \log(g.\epsilon) + (1 - \omega) \sum_{g \in G_{CNOT}} \log(g.\epsilon).$$

Noise Adaptive Compilation - LP Solution (Simplified)

Approx 3 Hours

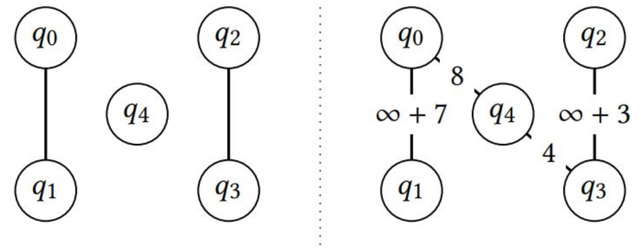


Effective Heuristics: Lookahead



Effective Heuristics: Lookahead

Lookahead
Weighting



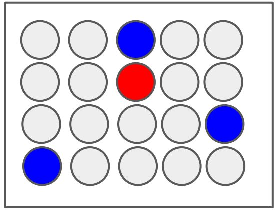
$$w_t(q_i, q_j) = \sum_{t < m \leq T} I(m, q_i, q_j) \cdot D(m - t)$$

Effective Heuristics: Mapping

$$s(u,h) = \sum_{\text{mapped } v} d(h, \varphi(v)) \times w(u,v)$$

The "score" of placing qubit u in position h depends on interactions with other mapped qubits

Hardware h, with mapping phi

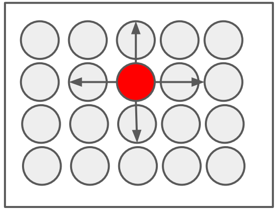


Effective Heuristics: Routing

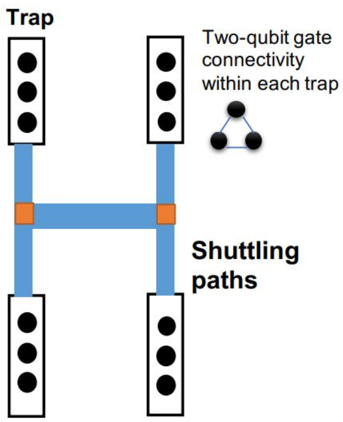
$$s(u,h) = \sum_v [d(\varphi(u),\varphi(v)) - d(h,\varphi(v))] \times w(u,v) + [d(h,\varphi(v)) - d(\varphi(u),\varphi(v))] \times w(\varphi^{-1}(h),v)$$

We want to *move u* to position *h* in a way that minimizes how much it disrupts other interactions with qubit *v*

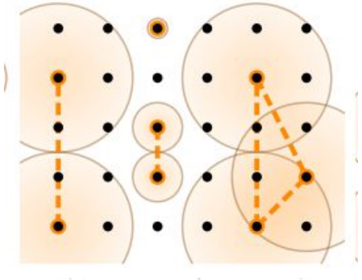
Hardware h, with mapping phi



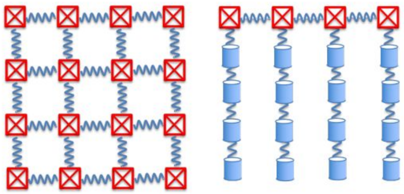
Compilation Choices Depend on Hardware Parameters



Trapped Ions

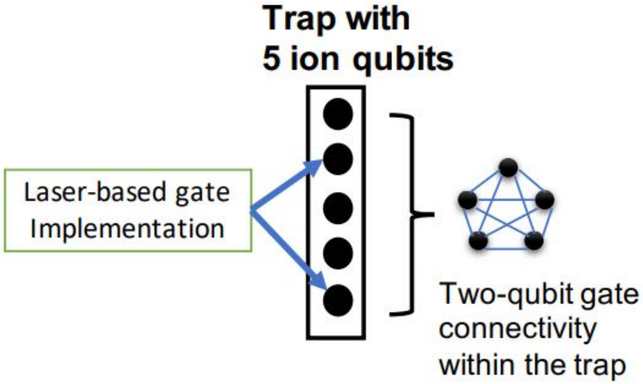


Neutral Atoms



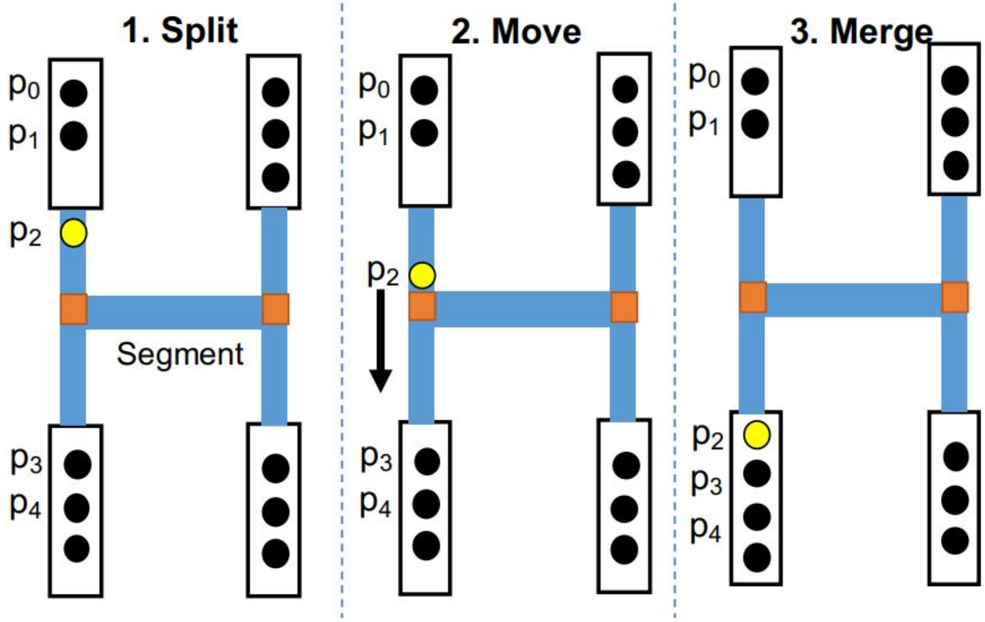
SC Cavities

Trapped Ion Compilation - QCCD (Quantum Charged Coupled Device)



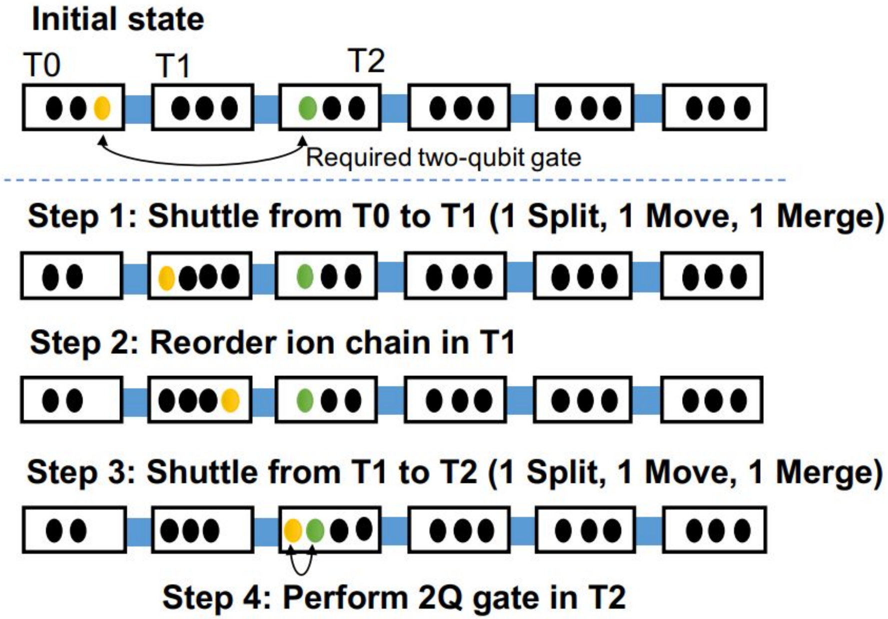
- Fully connectivity - No resonators
- Individual addressing by a single laser
- Gates: Rx, Rz, MS (Molmer Sorenson)
- Gates are slow but long coherence times
- ~ 1 order of magnitude slower than SC systems, but over 1 second of coherence

Trapped Ion Compilation - QCCD (Quantum Charged Coupled Device)



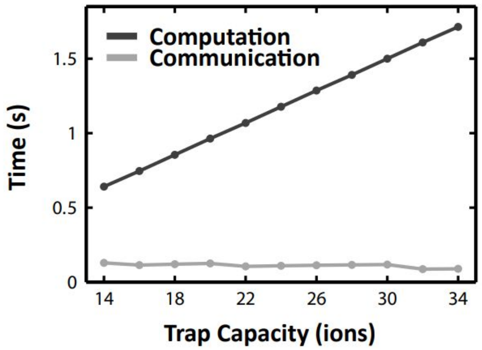
- Bounded sized traps
- Longer interactions → more heat → lower fidelity
- No parallelism within a single trap → longer circuit duration
- Multiple traps → more control overhead
- Routing: Splits + Merges
-
- Junctions → More heat

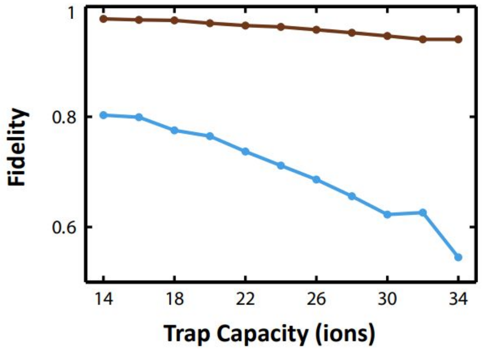
Trapped Ion Compilation - QCCD (Quantum Charged Coupled Device)



- Position matters
- Trap topology matters
- IonSwap? GateSwap?
- Long distance interactions can be very expensive: swapping through traps inhibits parallelism

Trapped Ion Compilation - QCCD (Quantum Charged Coupled Device)

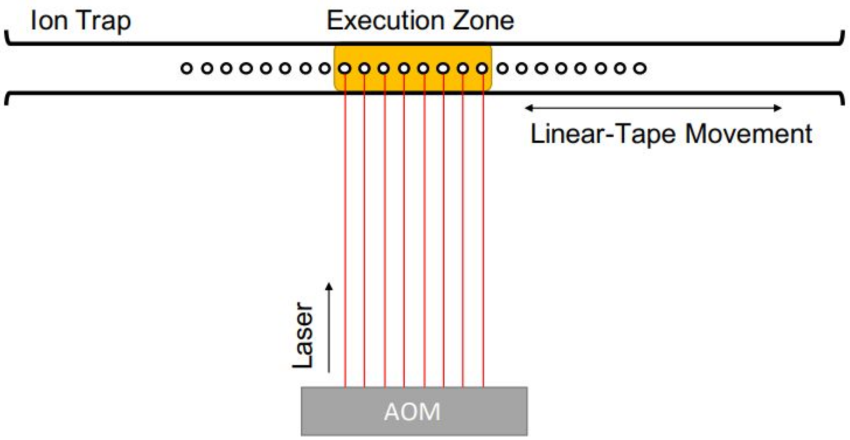




Application Dependent

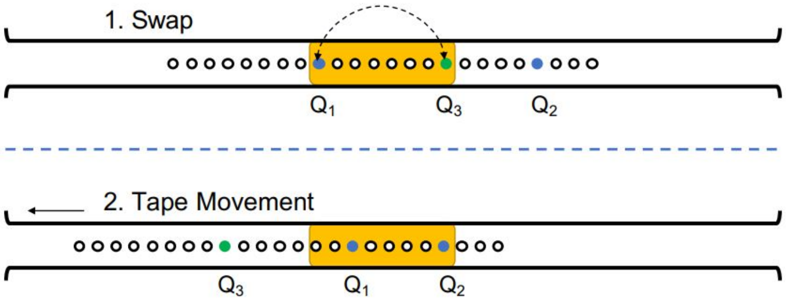
- How to design these systems?
- More computation BUT lower fidelity

Trapped Ion Compilation - Linear Tape

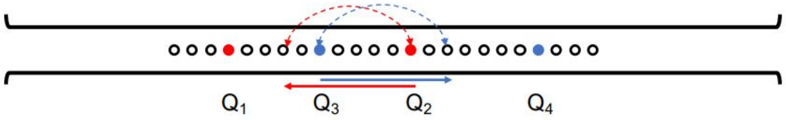


- Alternative Turing Machine like design
- “Fully Connected” under the tape head
- Ions can be moved horizontally in the chain
- “Race Track” Like designs

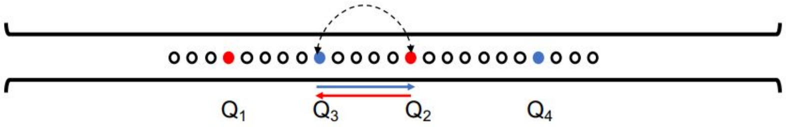
Trapped Ion Compilation - Linear Tape



(a) Applying a two-qubit gate with swap



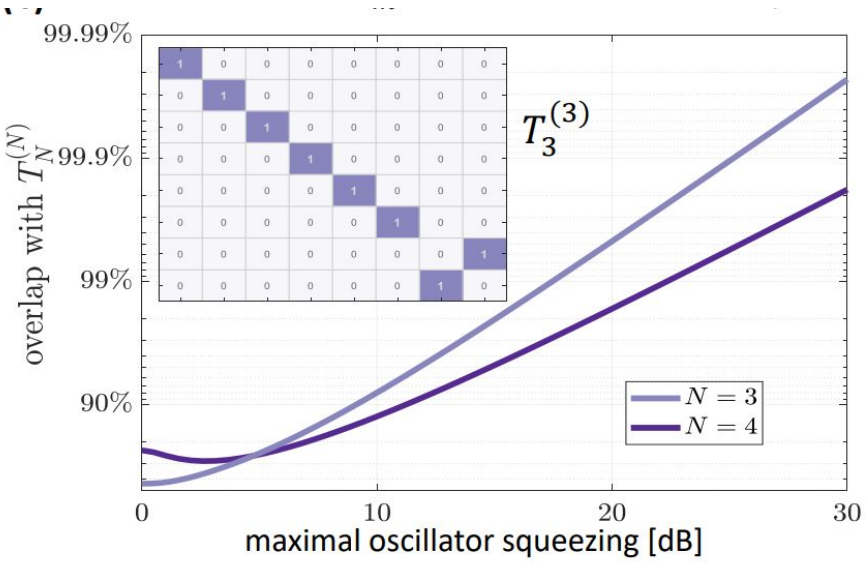
(b) Regular swap

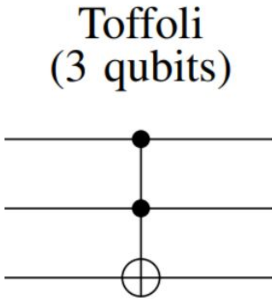


(c) Opposing swap

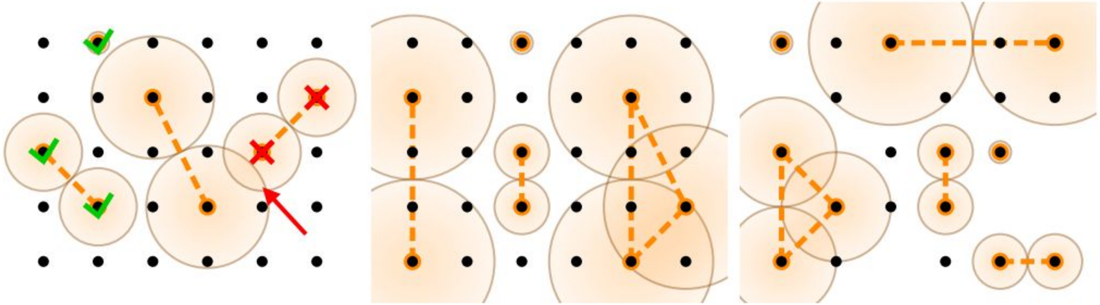
- Ion movement is not individualized i.e. we maintain them all in the same chain
- Two types of moves: Ion Chain Move + Ion Swap
- How to mix and match to enable arbitrary interactions?

Trapped Ion Compilation - Multiqubit gates?

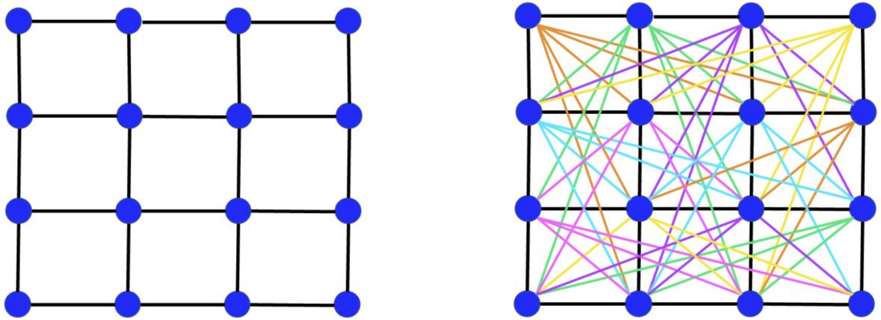




Neutral Atoms - Model 1: Individual Addressing



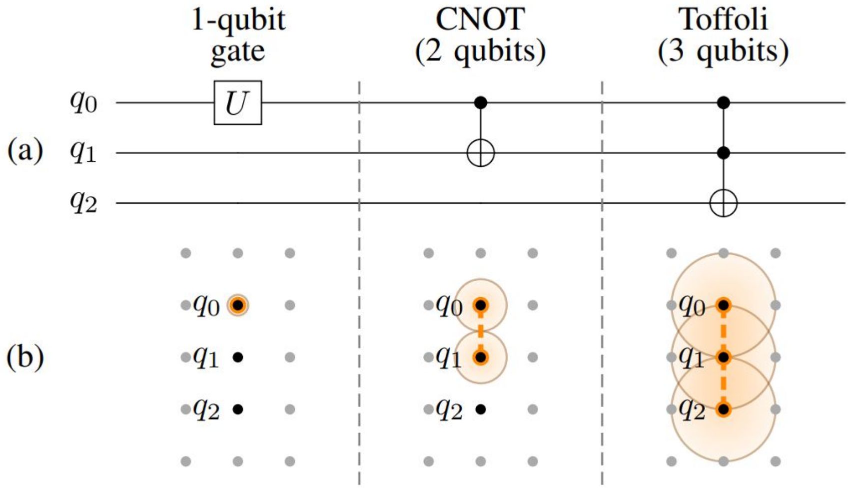
(a) Restriction Zone (b) Max Distance 3 (c) Atom Loss



(a) (b)

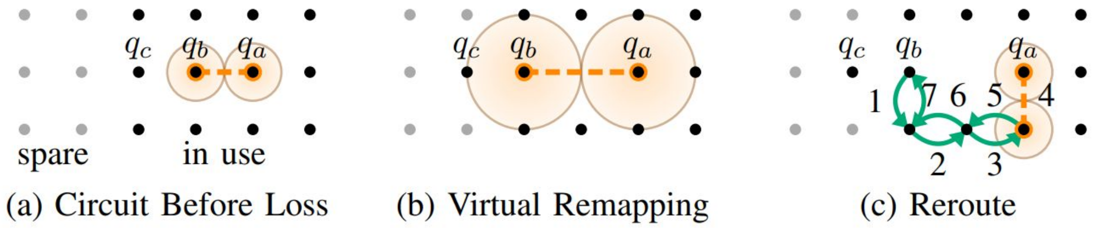
- Every atom trapped individually
- Every atom individually address - 1 laser per atom
- Interactions mediated via the “Rydberg” state which can be made “arbitrarily” large → Locally complete graph of arbitrary density

Neutral Atoms



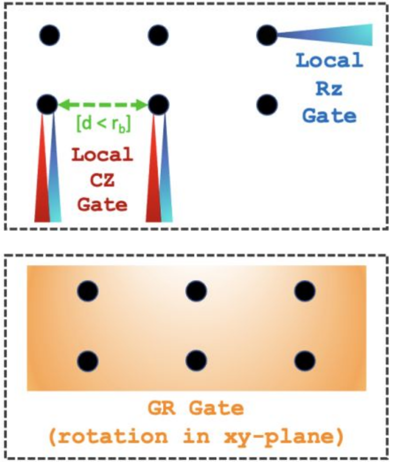
- Support of multiqubit interactions

Neutral Atoms



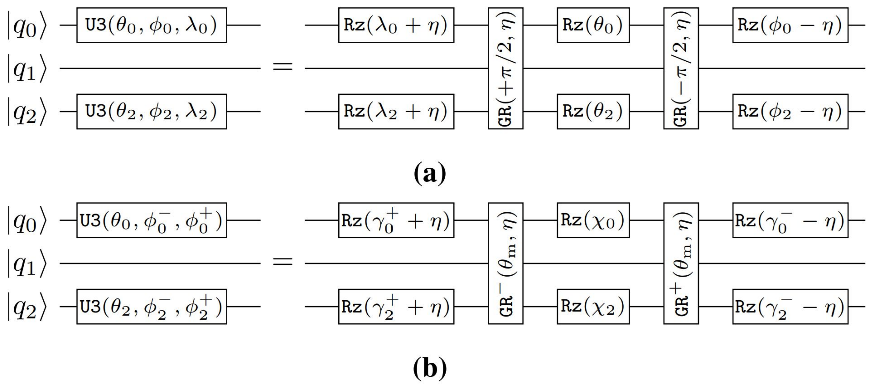
- Atoms are unstable → Loss (induced by interactions with environment + Measurement)

Neutral Atoms: Model 2: Global Gates



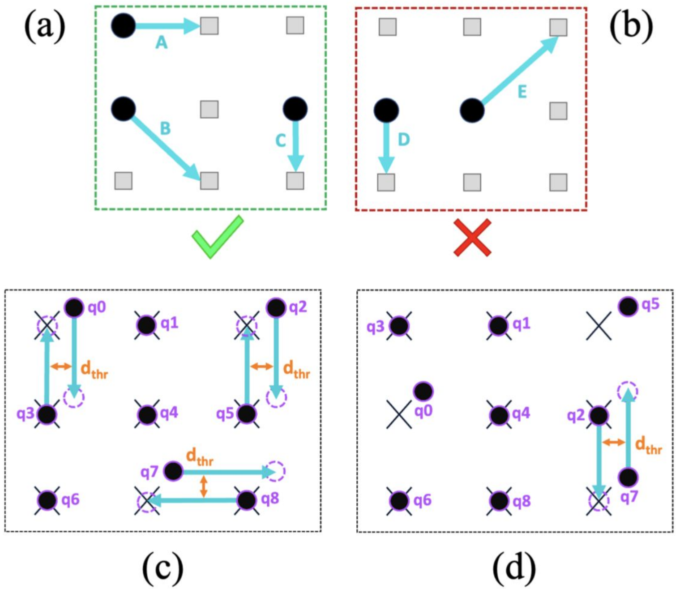
- Individual addressing is expensive (lots of laser control)
- Some gates can be done on all gates in a region

Neutral Atoms: Model 2: Global Gates



- Require new types of decompositions which are non-trivial
- More than just mapping / routing

Neutral Atoms



- Restrictive movement types
- Directional challenges
- Displacement issues + Parallel operations?