MIRAGE: Quantum Circuit Decomposition and Routing Collaborative Design using Mirror Gates

University of Pittsburgh

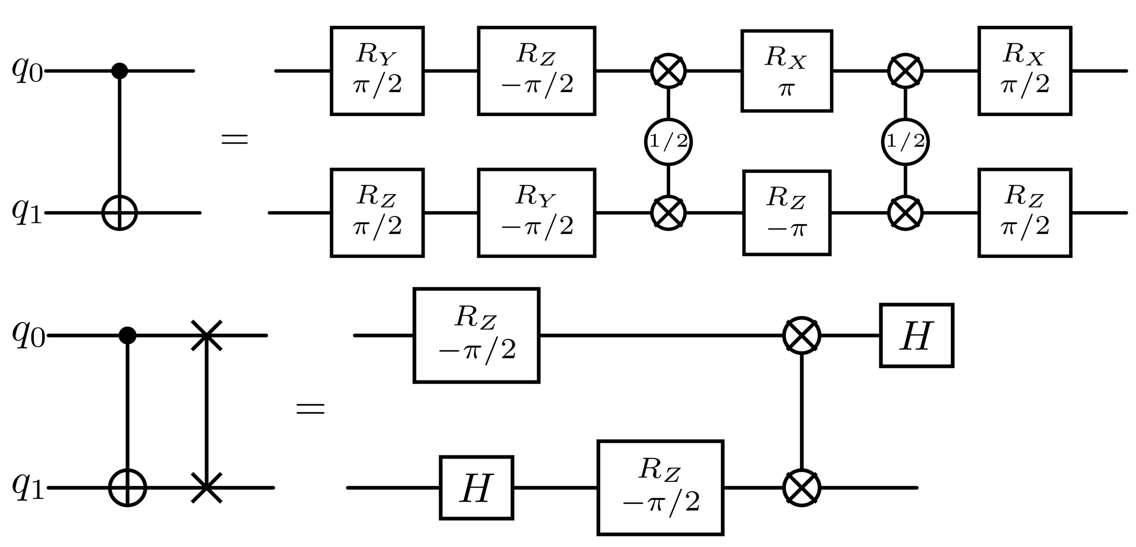
Evan McKinney†, Michael Hatridge‡, Alex K. Jones†

†Department of Electrical and Computer Engineering
‡Department of Physics and Astronomy

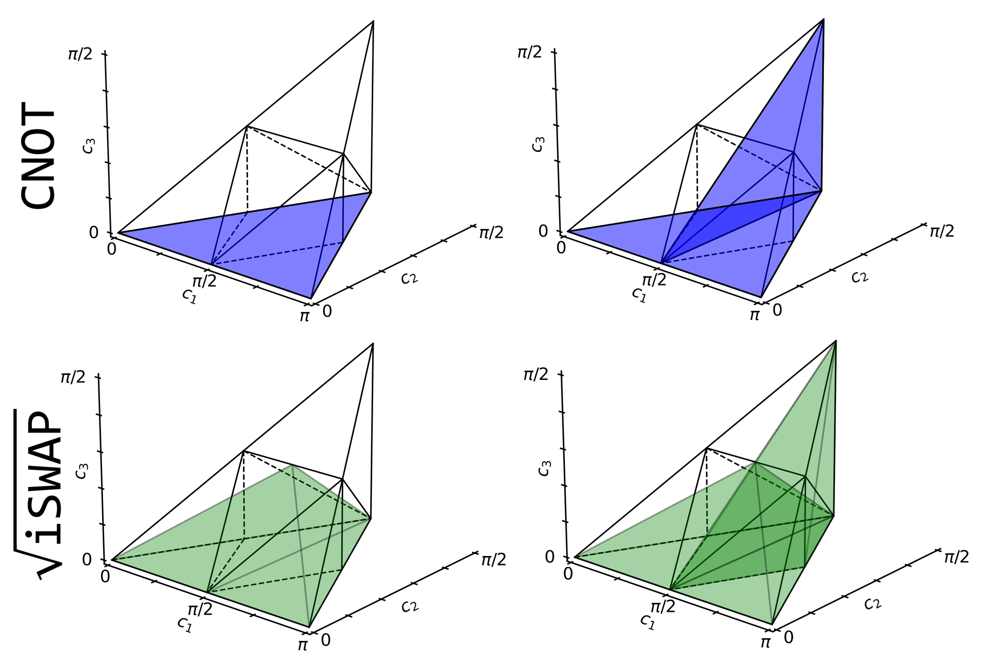
LPS LABORATORY FOR PHYSICAL SCIENCES

Objective: Enhance quantum ISAs with mirror gates to (a) amplify effective computational power and (b) absorb data movement costs into basis translation and gate decomposition.

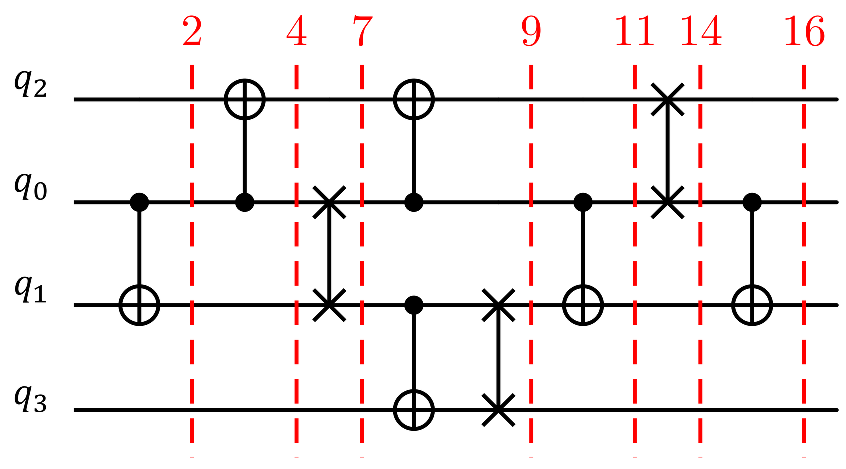
Decomposition of CNOT, CNS into iSWAP basis



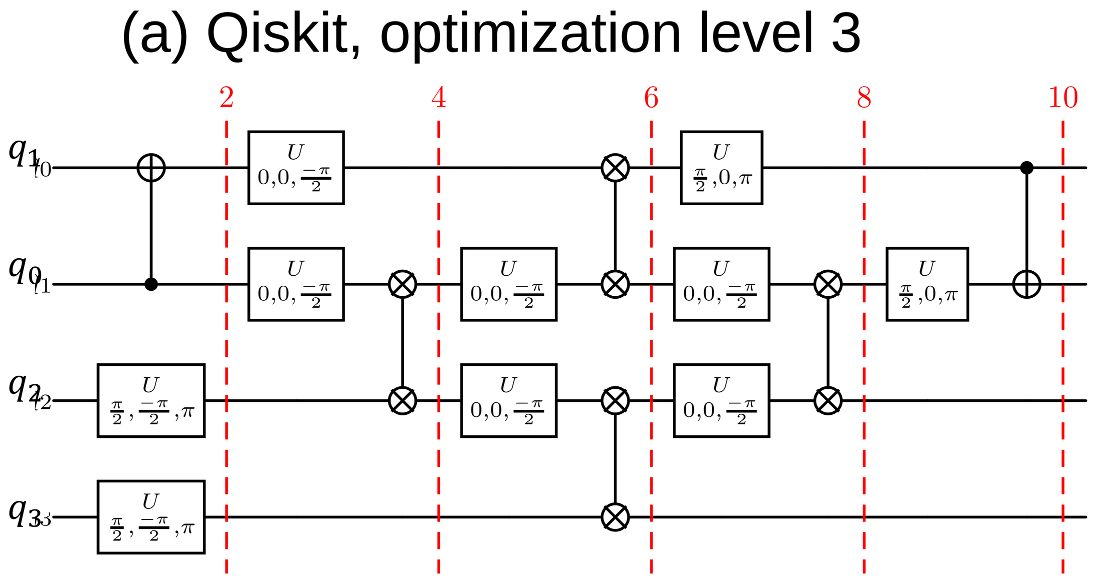
Weyl chamber coverage between base and mirror-inclusive polytopes ($k = 2$)



Depth Comparison of TwoLocal (full) circuits



(a) Qiskit, optimization level 3



(b) MIRAGE

Conclusions:

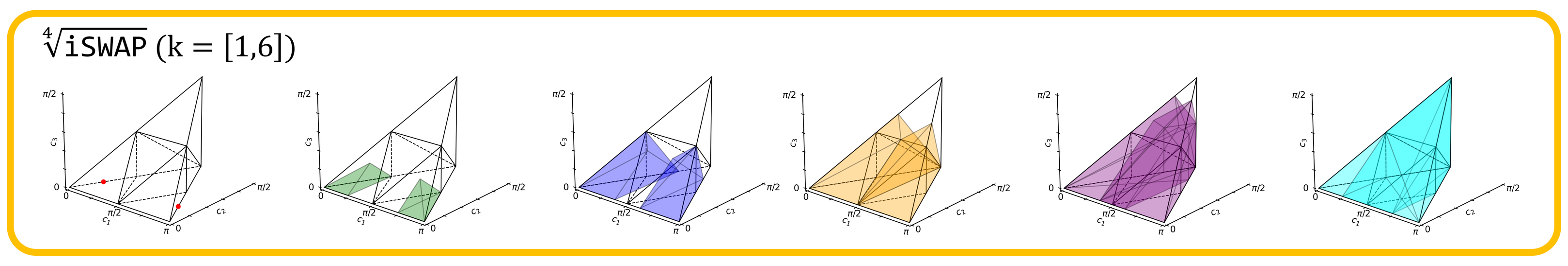
- Implemented an integrated *transpiler pass* for gate routing and decomposition using mirrors
- Use approximate-mirror decompositions to **reduce relative expected fidelity by up to 9.4%**
- **Decrease SWAP gates by more than 55%** on Heavy-Hex and Square-Lattice topologies
- Significant circuit optimization, **reducing depth by ~30%**, key for overall fidelity benchmarks

[1] Li, et al. **ASPLOS** (2019)
[2] Peterson, et al. **Quantum 4** (2020)
[3] Peterson, et al. **Quantum 6** (2022)

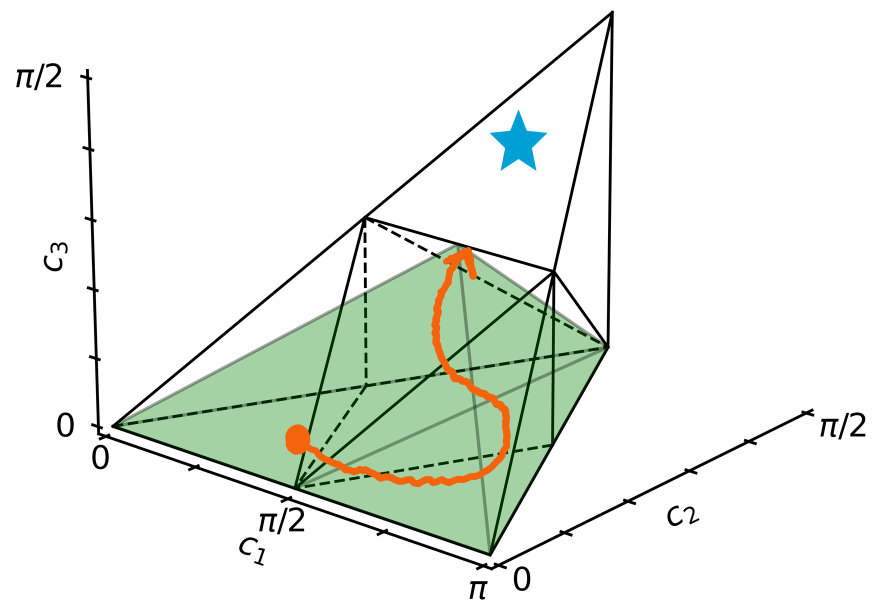
Expected gate computability via Monte Carlo sampling over Haar measure

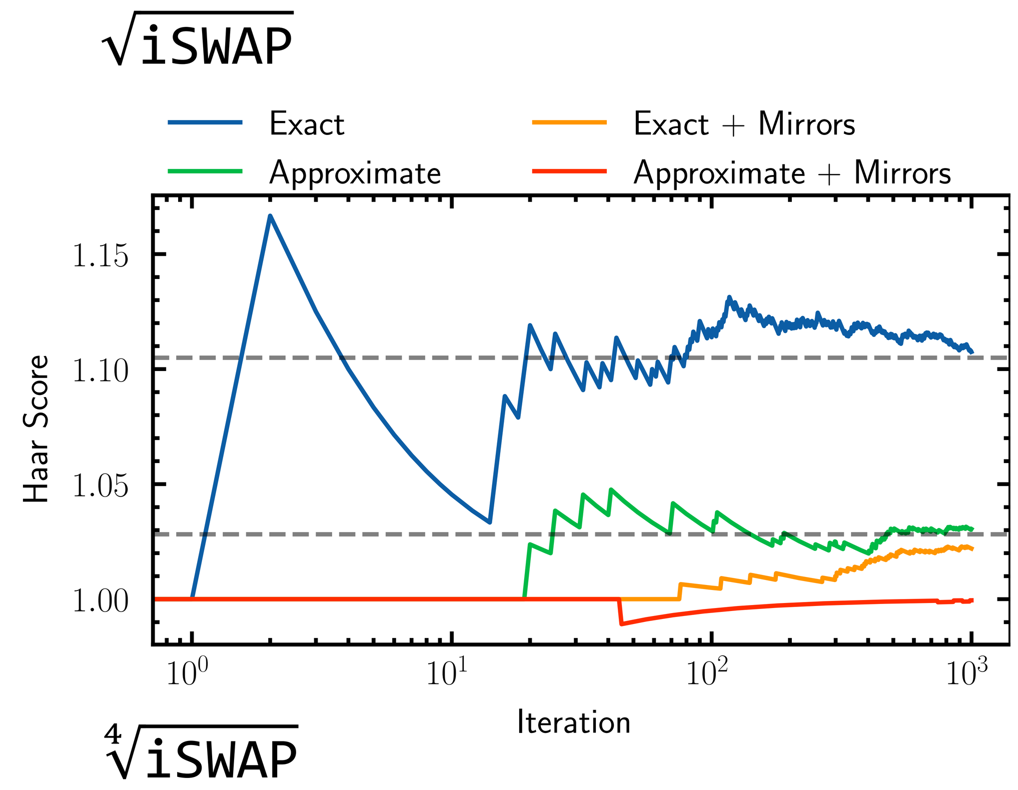
- Decomposability given by convergence of numerically optimized parameterized circuits
- Approximate decomposition threshold sets a permissible increase in polytope volume

$$F_d(U_d, U_t) = \frac{\mathrm{Tr}(U_d^\dagger U_t)}{\dim(U_d)}$$

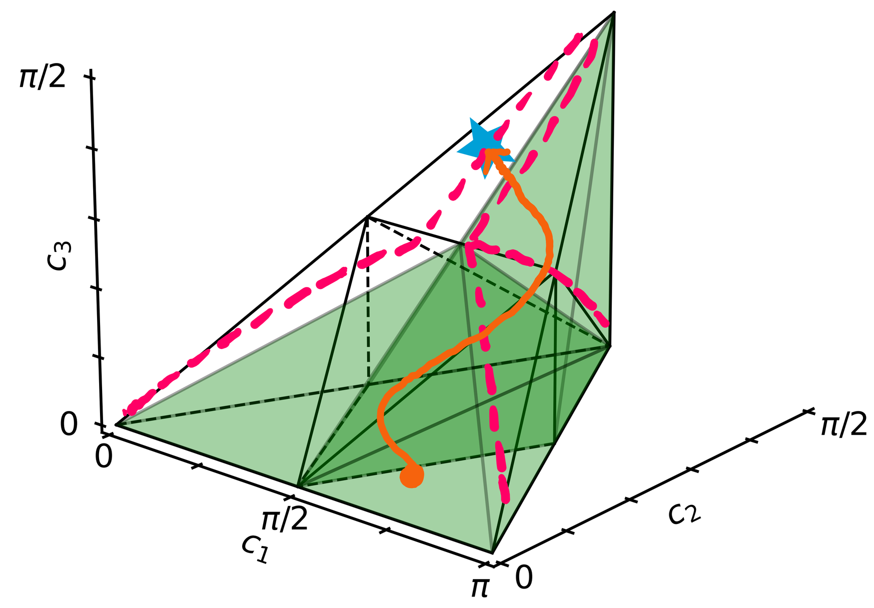


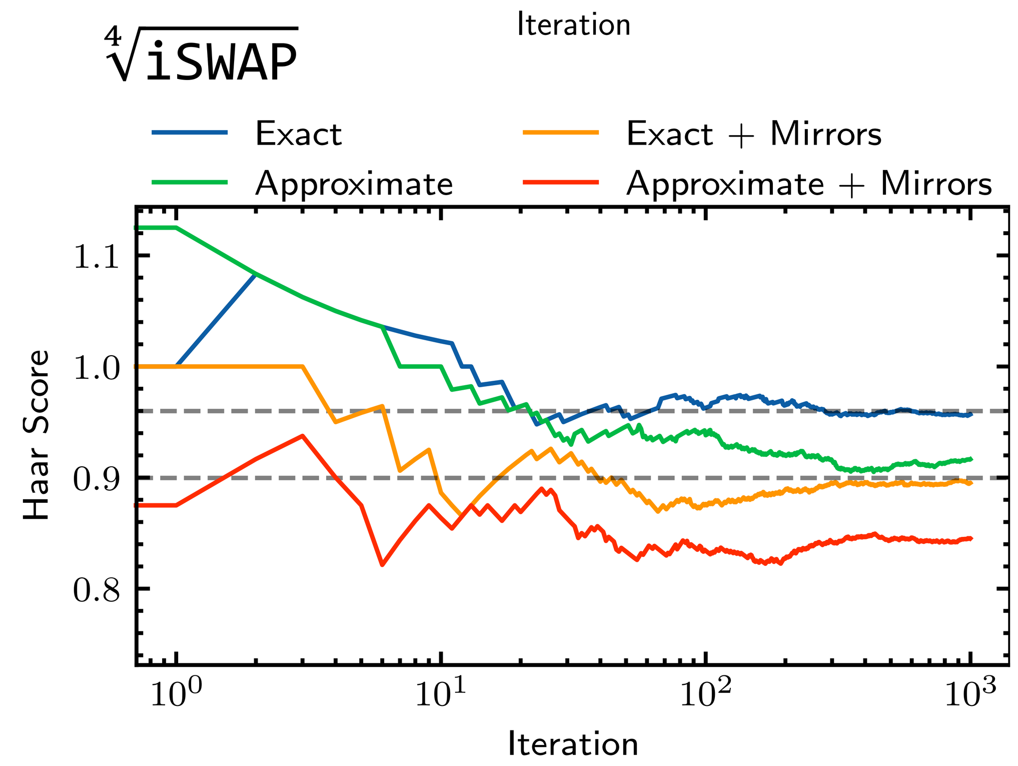
Exact: Fail





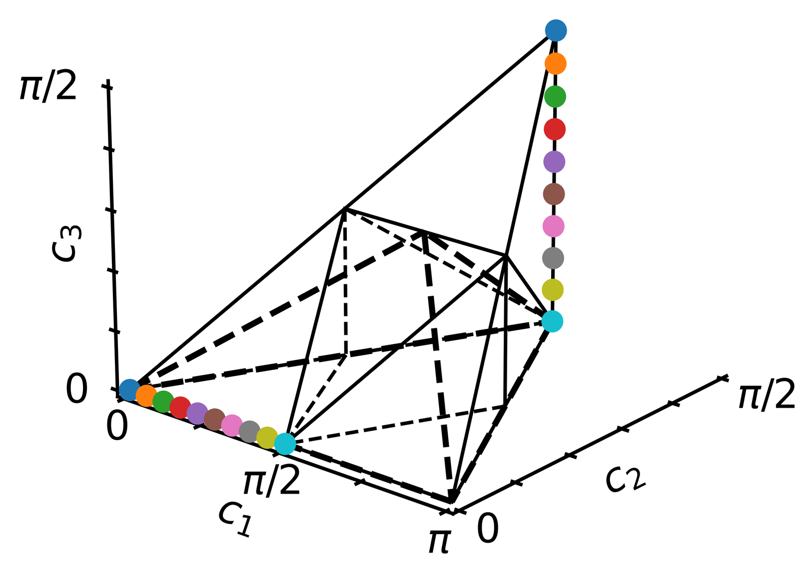
Approx. + Mirrors: Success



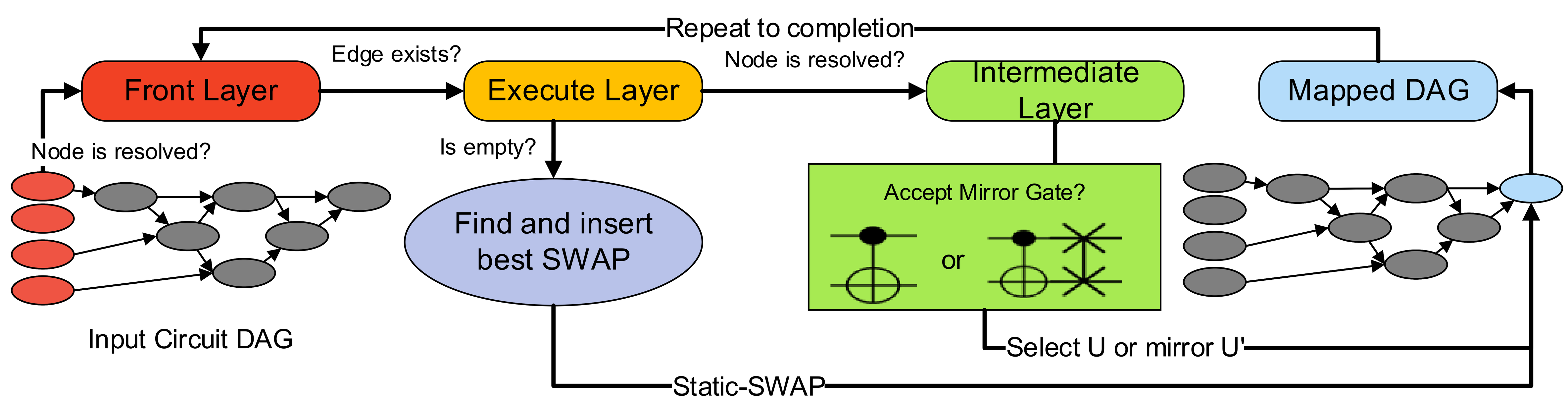


CPHASE gates and their mirrored counterparts in pSWAP; only CNOT and CNS are contained by $\sqrt{\texttt{iSWAP}}$ ($k = 2$)

$$(a', b', c') = \begin{cases} \left(\frac{\pi}{4} + c, \frac{\pi}{4} - b, \frac{\pi}{4} - a\right) & \text{if } a \leq \frac{\pi}{4} \\ \left(\frac{\pi}{4} - c, \frac{\pi}{4} - b, a - \frac{\pi}{4}\right) & \text{else} \end{cases}$$



MIRAGE SWAP Routing Transpilation Flow Diagram



Transpiled quantum circuit critical-path optimization