Characterization and compilation of Hardware Efficient Gates

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Extending entangling gate set to boost algorithmic performance

Expressive entangling gate sets:

- Compile Unitaries using shorter gate sequences:
  - Reduction in accumulated gate errors
  - Efficiently use finite qubit coherence time

Useful for near term algorithms:

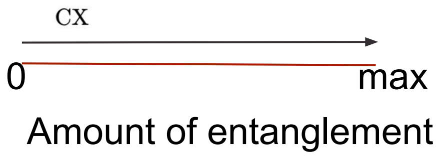
- Implement smaller 2q gate rotations (natively):
  - Accuracy of Hamiltonian Simulation ~ finer slicing of time evolution

Challenges with extending gate-sets

Gate characterization is easier than calibration

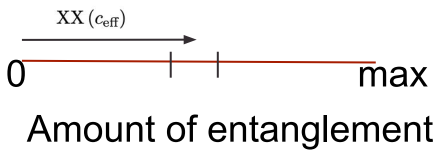
Calibrating entangling gates is hard:

- Resource intensive
- Target unitary has residual coherent error (example ZZ crosstalk)



Our approach: compiler understandable characterization

- Generate partial entanglement
- Define characterized entangling unitary to be a basis gate

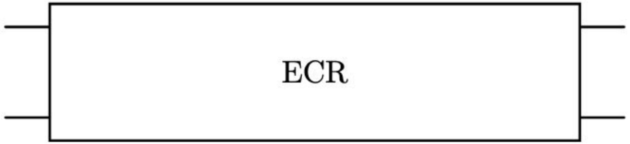


Build faithful models: Learn generating Hamiltonian corresponding to control pulse

Effective Hamiltonian description in the 2-qubit subspace

$$\mathrm{H}_{\mathrm{eff}}\left(\nu_{ab}\right) = \frac{1}{2}\left(\nu_{zx} ZX + \nu_{ix} IX + \nu_{zz} ZZ + \nu_{iz} IZ + \nu_{zi} ZI + \nu_{iy} IY + \nu_{zy} ZY\right)$$

(backend)



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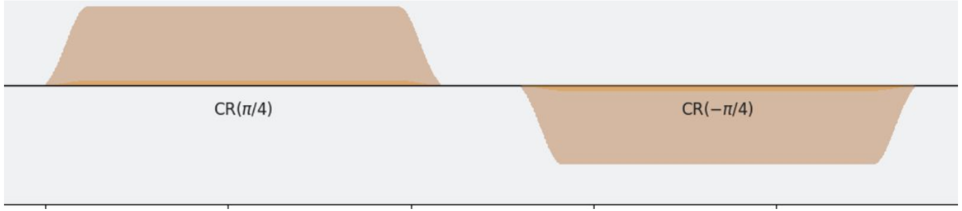
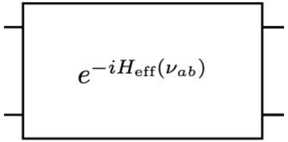


50% duration



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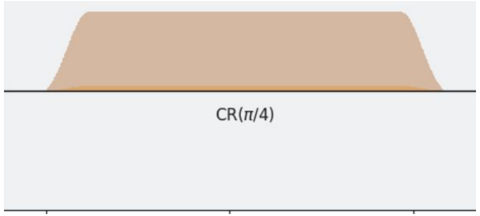
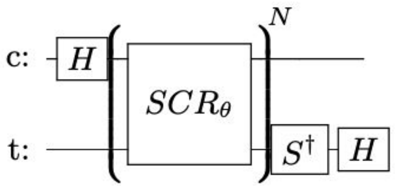
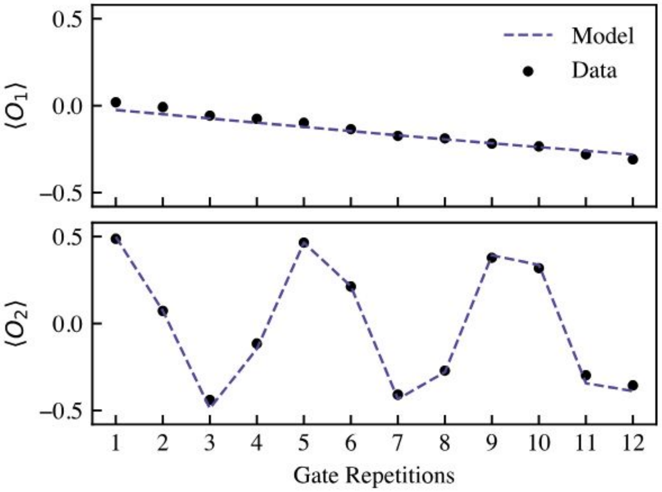


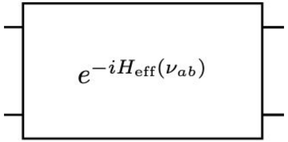
Pulse-efficient circuit transpilation for quantum applications on cross-resonance-based hardware, 2021, Earnest et al. IBM
Reducing Unitary and Spectator Errors in Cross Resonance with Optimized Rotary Echoes, 2021, Sundaresan et al, IBM.

Device wide model learning using error amplification sequences

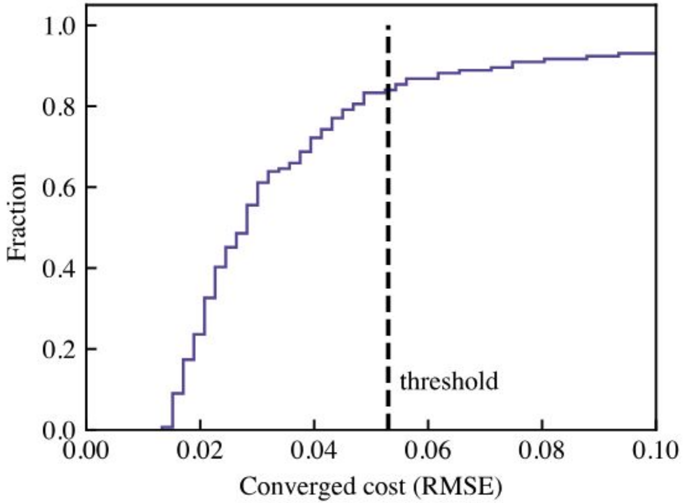


$$\nu_{ab}^* = \arg\min_{\nu_{ab}} \sum_i |O_i^{exp} - O_i(\nu_{ab})|^2$$





Scalable: Gate added to 123/144 edges under 3 min



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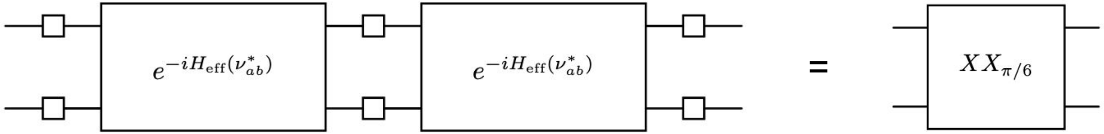
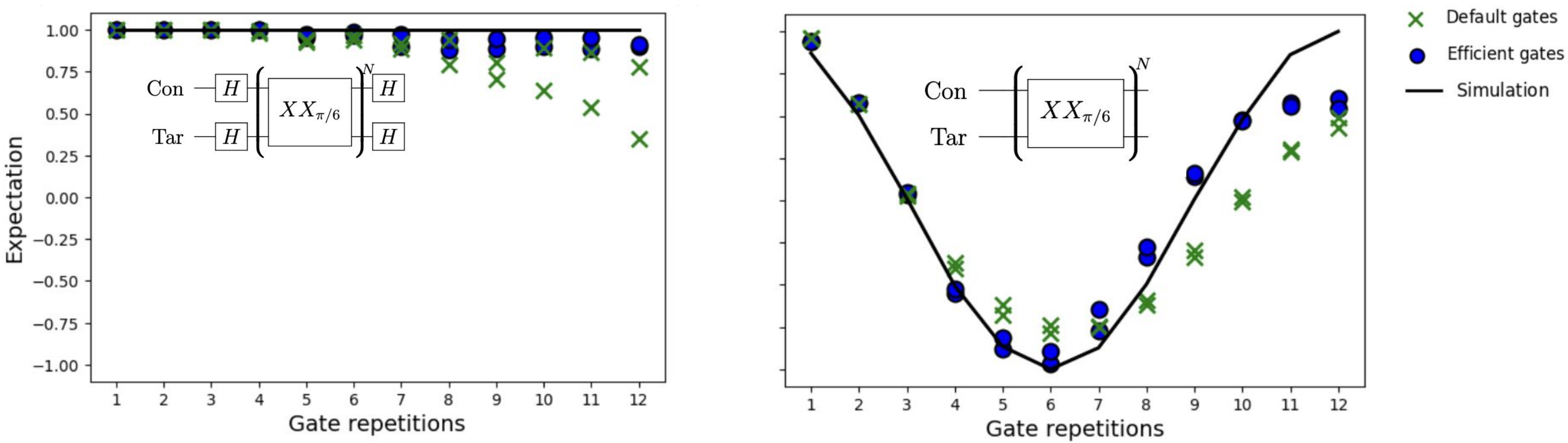
Validation test: the model gate outperforms default on unseen circuits





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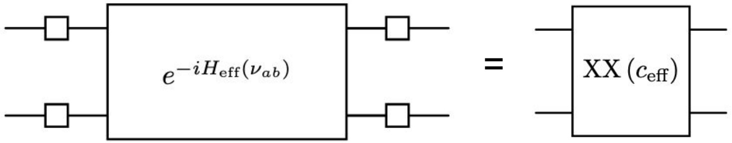
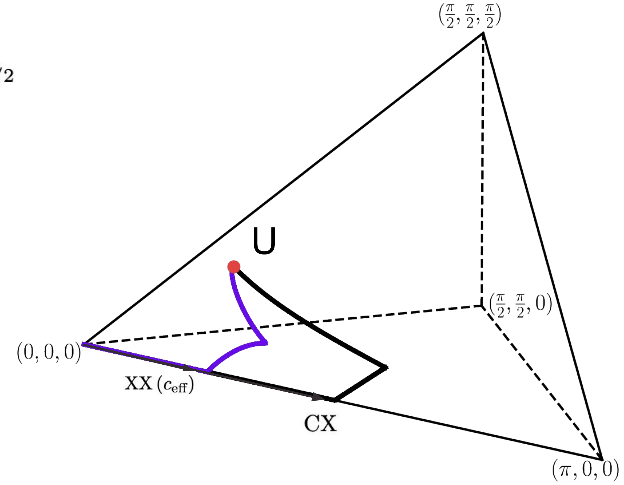
Co-design compiler and gate models to use diverse gate-set efficiently for circuit synthesis

Exploit geometric framework for 2-qubit interactions

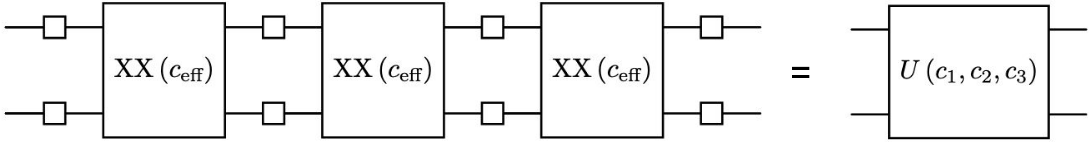
- Rotate the characterized pulse into a pure XX rotation (basis gate)

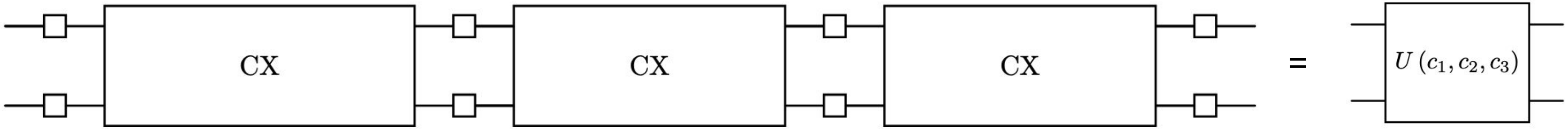


$$c_{\text{eff}} = \left(\nu_{zx}^2 + \nu_{zy}^2 + \nu_{zz}^2\right)^{1/2}$$



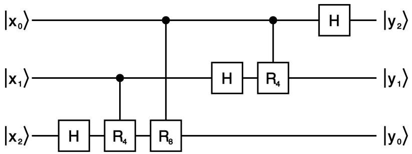
- Construct 2-qubit blocks using synthesis motifs:

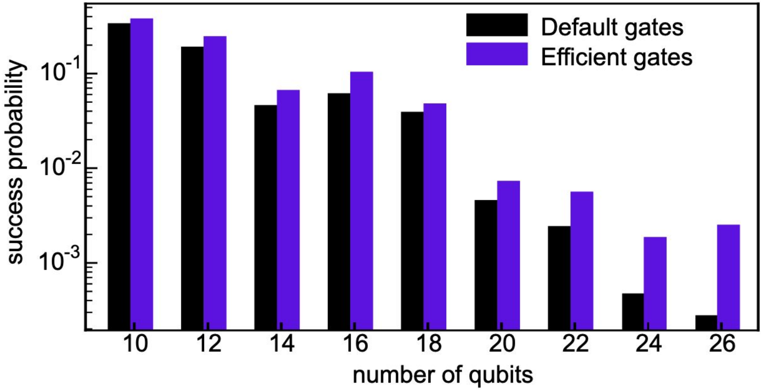


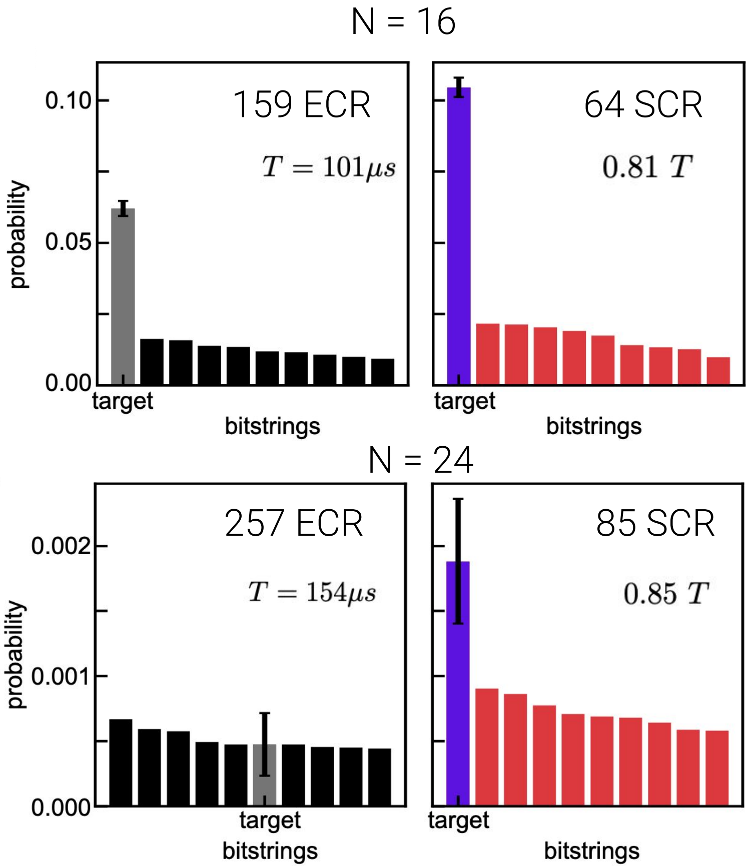


Demonstrating efficient gates on real algorithms

One-hot inverse QFT benchmark: Improve success probability up to 3x







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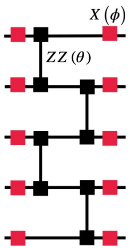
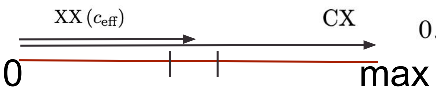
Demonstrating Hamiltonian Simulation algorithms to higher depths

Improving observables in Trotterized Transverse Field Ising model

$$H = -J\sum_i Z_i Z_{i+1} + h\sum_i X_i$$

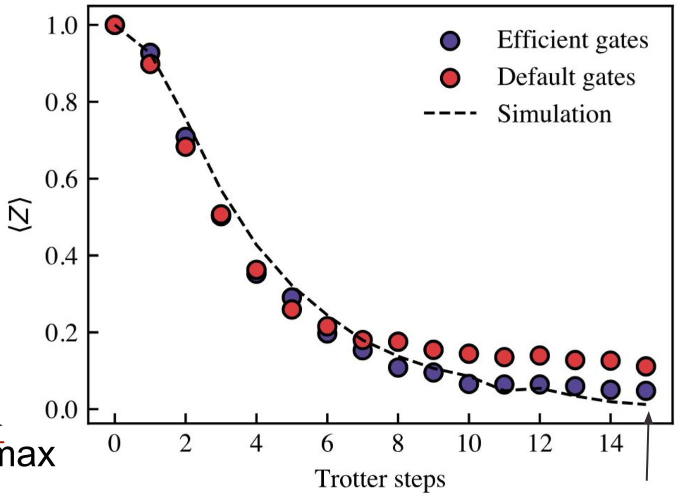
$$N = 25 \quad h/J = 1,\ \delta t = 0.2$$





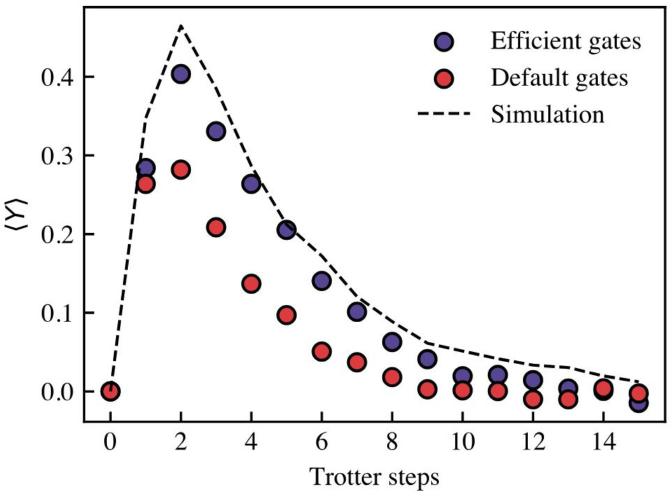
Amount of entanglement

5 times smaller MSE



600 E gates

9 times smaller MSE



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Extra slides