Error mitigation with Clifford quantum-circuit data

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The outline

- Quantum advantage and error mitigation.
- Clifford date regression (CDR) - arXiv:2005.10189.

Error mitigation with Clifford quantum-circuit data

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- Variable noise Clifford data regression (vnCDR) - arXiv:2011.01157.

Unified approach to data-driven quantum error mitigation

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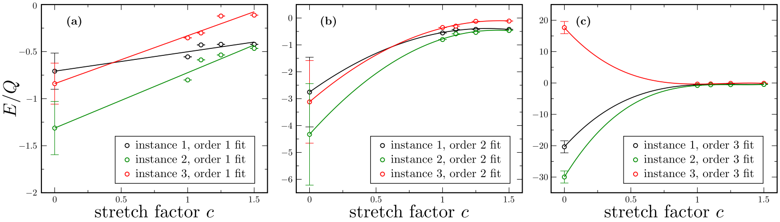
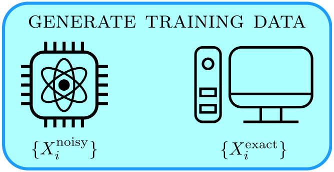
- Fault-tolerant quantum computing is not possible with near-term (NISQ) quantum computers.
- Error mitigation methods reduce noise effects without performing full error correction.
- Error mitigation is expected to be necessary for quantum advantage with NISQ devices.
- Error mitigation for quantum advantage circuits is challenging.



- X - an observable of interest, $|\psi\rangle$ - a quantum circuit of interest.
- $X_\psi^{\text{exact}} = \langle\psi|X|\psi\rangle$, X_ψ^{noisy} - the noisy expectation value.

1. Choose near-Clifford classically simulable training circuits $\mathcal{S}_\psi = \{|\phi_i\rangle\}$.



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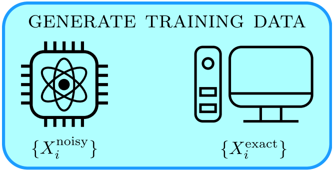

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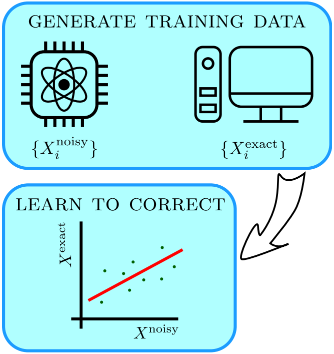
3. Learn a model for X^{exact}:

$$X^{\text{exact}} = a_1 X^{\text{noisy}} + a_2,$$

$$\underset{a_1, a_2}{\text{argmin}} \sum_{\phi_i \in \mathcal{T}_\psi} (X_{\phi_i}^{\text{exact}} - a_1 X_{\phi_i}^{\text{noisy}} - a_2)^2.$$



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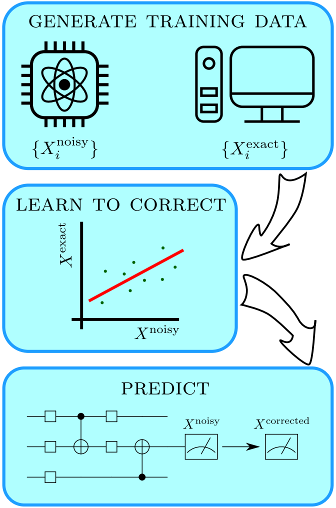
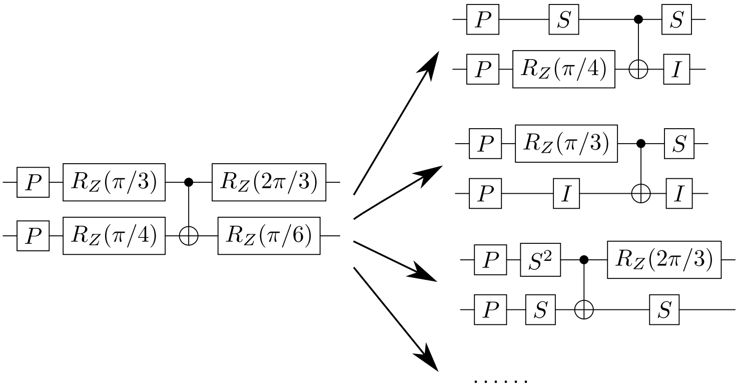
4. Use the model to correct X_ψ^{noisy}.



- Near-Clifford circuits with up to $N \approx 50$ non-Clifford gates can be simulated classically.
- Replace non-Clifford gates by Clifford gates.
- An algorithm for IBM:

$$R_Z(\alpha) \to S^n, \quad S = R_Z(\pi/2), \quad n = 0, 1, 2, 3.$$



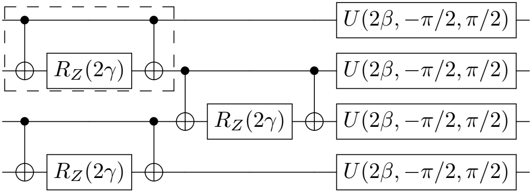
- The problem: Ground state simulation of a transverse-field 1D quantum Ising model ($g = 2$).

$$H = -g \sum_j \sigma_X^j - \sum_{\langle j,j' \rangle} \sigma_Z^j \sigma_Z^{j'}$$

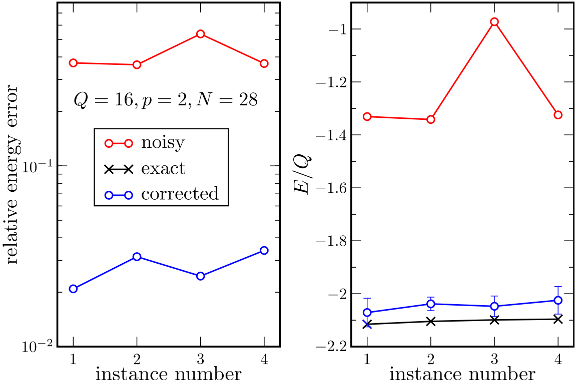
- The QAOA (Quantum Alternating Operator Ansatz) ansatz:

$$H = H_1 + H_2,\ H_2 = -g \sum_j \sigma_X^j,\ H_1 = -\sum_{\langle j,j' \rangle} \sigma_Z^j \sigma_Z^{j'},$$

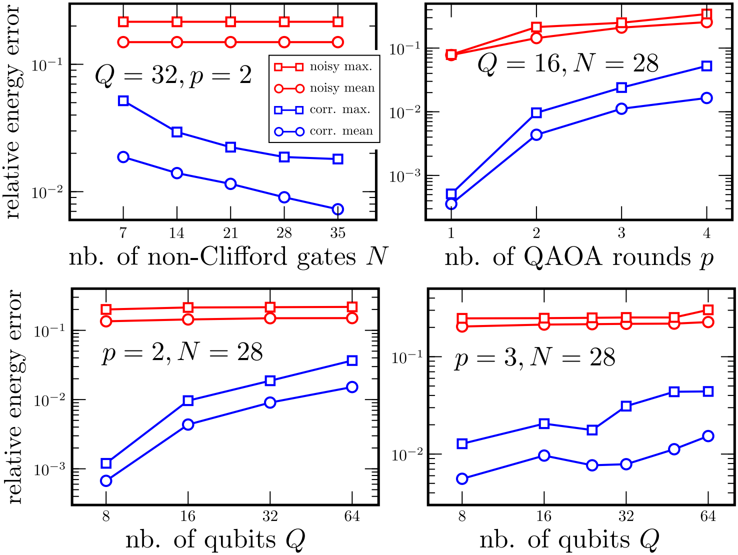
$$|\psi(\beta_1, \gamma_1, \dots, \beta_p, \gamma_p)\rangle = \prod_{j=p,p-1\dots,1} e^{i\beta_j H_2} e^{i\gamma_j H_1} (|+\rangle)^{\otimes Q}, \quad |+\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle).$$



- The QAOA is optimized with a noise model obtained by gate set tomography of IBM's Ourense quantum computer (L. Cincio, K. Rudinger, M. Sarovar, P. J. Coles, arXiv:2007.01210).
- Local minima of the optimization are simulated with IBM's Almaden quantum computer.
- A factor of 15 improvement obtained.



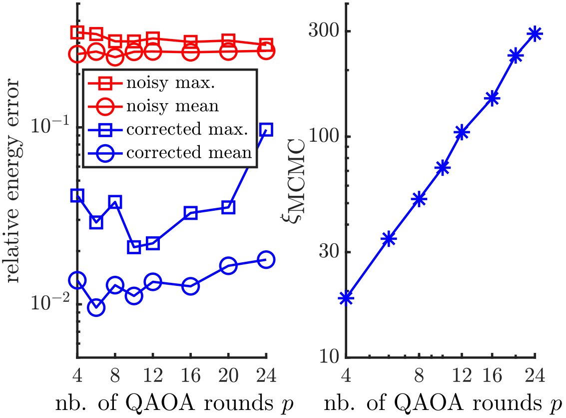
QAOA ground state simulation benchmark - scaling



At least a factor of 10 improvement obtained.

$$G^{\alpha} = \alpha G^{\text{noisy}} + (1-\alpha) G^{\text{exact}} \quad \alpha = \frac{4}{p}$$

$Q = 8, N = 28$

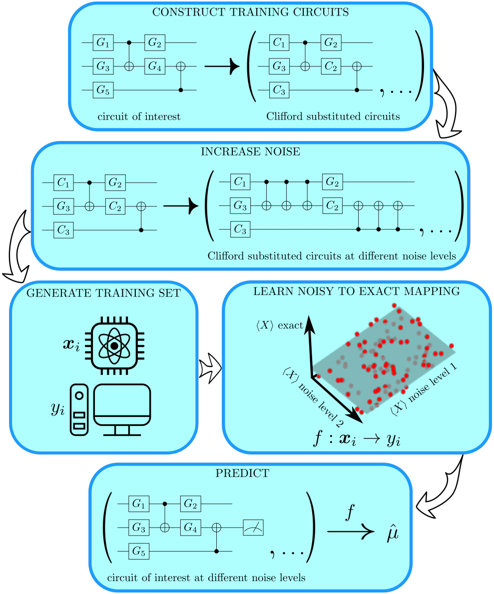


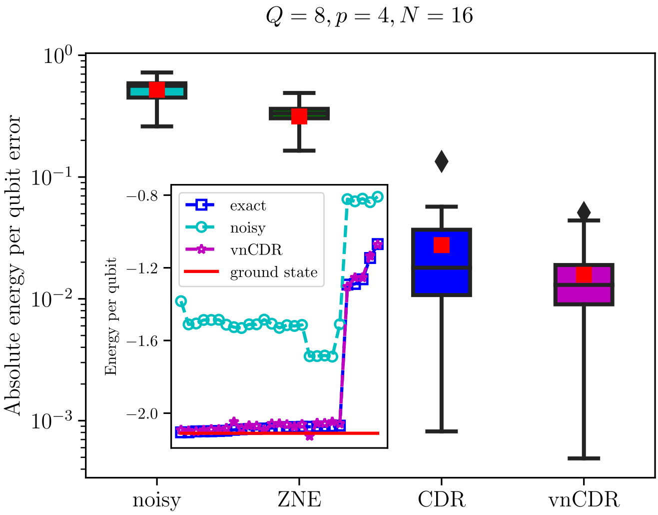
At least a factor of 10 improvement up to $p = 24$.

1. Choose training circuits as in the case of CDR.
2. Multiply noise level $j = 1, \ldots, n$ as in the case of Zero Noise Extrapolation (ZNE).
3. Construct a training set $\mathcal{T}_\psi = \{X^{\text{noisy},j}_{\phi_i}, X^{\text{exact}}_{\phi_i}\}$.
4. Learn a model for X^{exact}:

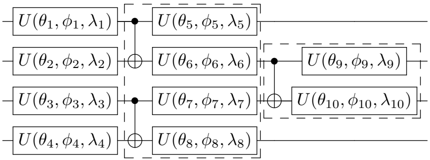
$$X^{\text{exact}} = \sum_j a_j X^{\text{noisy},j}.$$

5. Use the model to correct $X^{\text{noisy},j}_\psi$.

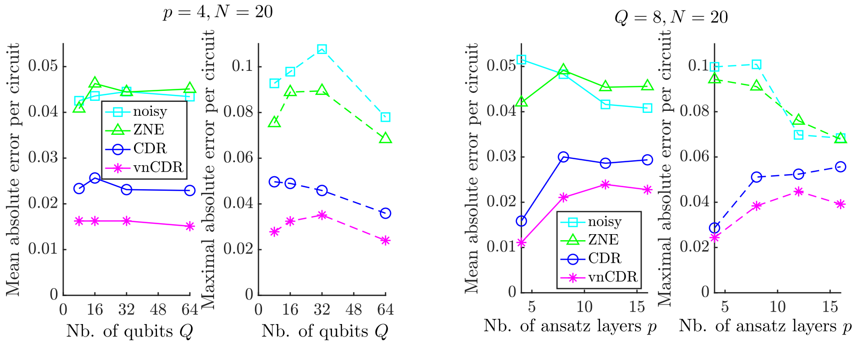




A factor of 33 improvement.



$$U(\theta,\phi,\lambda) = R_Z(\phi+\pi)PR_Z(\theta+\pi)PR_Z(\lambda)$$



Systematic improvement over ZNE.

Conclusions

- Error mitigation methods based on learning the noise effects from classically simulable near-Clifford circuits.
- vnCDR unifies CDR and ZNE.
- Good scaling with with number of qubits.
- A factor of 10 improvement for the 16-qubit hardware QAOA implementation.
- A factor of 10 improvement for the 64-qubit QAOA implementation with realistic noise.
- Systematic improvement over ZNE.