Theory/Algorithms Session

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Recent Developments in Quantum Algorithms

Thermalization

Learning

Streaming Algorithms

Miscellanea

Thermalization

- Classical algorithmic building block: *Markov chain Monte Carlo*

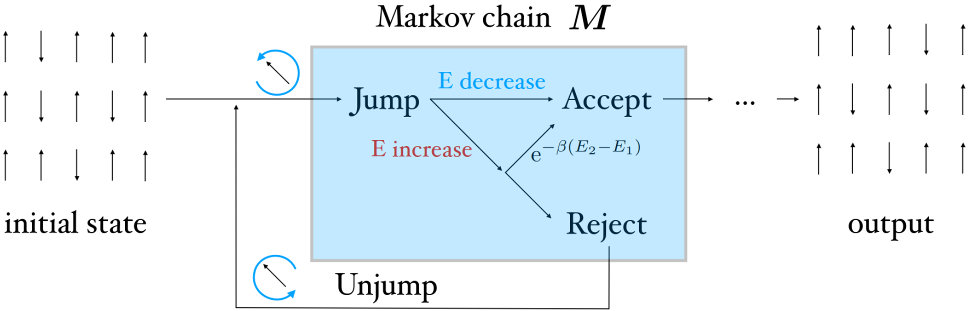
Algorithm (MCMC)

Given $E(z)$, *sample from the distribution*

$$p_\beta(z) \propto \exp(-\beta E(z)).$$

Thermalization

- Typical method (Metropolis–Hastings)



- Efficient per update, but not necessarily efficient mixing time

Thermalization

- Quantum analog:

Algorithm (Gibbs state preparation)

Given H, prepare

$$\rho_\beta \propto \exp\left(-\beta H\right).$$

- Hard due to *energy-time uncertainty*; spectrum of H might take exponential time to resolve

Thermalization

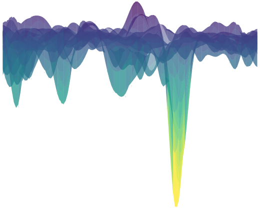
- Recent results: can get around this by approximating with a "smoothed" H
    - C.-F. Chen et al., *Quantum thermal state preparation*, arXiv:2303.18224 [quant-ph]
- **Key building block:** repeated "weak measurement" of chosen jump operators
- Can show rapid mixing in certain cases
    - C. Rouzé et al., *Efficient thermalization and universal quantum computing with quantum Gibbs samplers*, arXiv:2403.12691 [quant-ph]
    - A. Bakshi et al., *High-temperature Gibbs states are unentangled and efficiently preparable*, arXiv:2403.16850 [quant-ph]

Learning

- Quantum neural networks (QNNs): given parameterized quantum circuit $U(\boldsymbol{\theta})$, optimize:

$$f(\boldsymbol{\theta}) = \langle\psi_0| U_{\boldsymbol{\theta}}^{\dagger} H U_{\boldsymbol{\theta}} |\psi_0\rangle$$

- Exponential quantum advantage (generically) seems impossible due to issues in training
  - M. Cerezo et al., *Does provable absence of barren plateaus imply classical simulability? or, why we need to rethink variational quantum computing*, `arXiv:2312.09121 [quant-ph]`

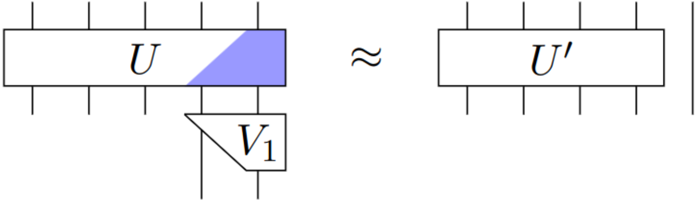


Learning

- Recent hope: *tailored learning algorithms* and *restricted QNNs*
  - H.-Y. Huang et al., *Learning shallow quantum circuits*, arXiv:2401.10095 [quant-ph]
  - E. R. Anschuetz and X. Gao, *Arbitrary polynomial separations in trainable quantum machine learning*, arXiv:2402.08606 [quant-ph]

Learning

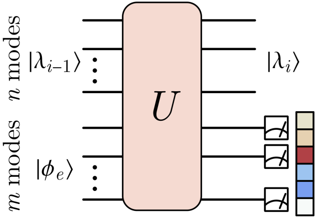
- H.-Y. Huang et al., *Learning shallow quantum circuits*, arXiv:2401.10095 [quant-ph]:
    - Disentangle one qubit at a time, “sew together” in intelligent way to deal with ambiguity in choice of V_i



- **Pros:** Exponentially hard to sample from classically!
- **Cons:** Only works specifically for learning shallow-depth quantum circuits; gives garbage if learning generic data

Learning

- E. R. Anschuetz and X. Gao, *Arbitrary polynomial separations in trainable quantum machine learning*, `arXiv:2402.08606 [quant-ph]`:
  - Construct QNNs out of *nonuniversal* resources



- **Pros:** Restricted gate set so easier to implement; “set-and-forget” learning via gradient descent
- **Cons:** Only proven separation on quantum-inspired data sets; no separation during training

Streaming Algorithms

- Previous slide an example of a *streaming algorithm*
- Other examples:
    - J. Kallaugher, "A quantum advantage for a natural streaming problem", FOCS 2021
    - J. Kallaugher et al., *Exponential quantum space advantage for approximating maximum directed cut in the streaming model*, arXiv:`2311.14123 [quant-ph]`
- Quantum advantage in *communication complexity*, though not necessarily computationally efficient

Miscellanea

- Separation between noisy 3D QNC_0 and AC_0
    - L. Caha et al., *A colossal advantage: 3D-local noisy shallow quantum circuits defeat unbounded fan-in classical circuits*, arXiv:2312.09209 [quant-ph]
- Learning advantage given access to conjugate states
    - R. King et al., *Exponential learning advantages with conjugate states and minimal quantum memory*, arXiv:2403.03469 [quant-ph]
- Fast quantum scramblers
    - T. Metger et al., *Simple constructions of linear-depth t-designs and pseudorandom unitaries*, arXiv:2404.12647 [quant-ph]

Themes

- Thermalization: what can we do with it?
- Quantum machine learning: are there other bespoke learning algorithms?
- Showcasing quantum advantage beyond BQP vs. BPP