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Quantum-Assisted Greedy Algorithms

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Introduction

- AI & Machine Learning
  - Synthetic/machine intelligence
  - Learning from experiences
- Quantum Computers (QC)
  - Quantum bit (qubit): superposition of many eigenstates
  - Quantum information processing: Entanglement & interference
  - Quantum computing: gate/circuit QC, adiabatic QC, measurement-based QC, …
- Quantum Machine Learning (QML)
  - QC can take ML models to the next level
  - quantum data
- Not always AI/ML is successful
  - Example: Compressive sensing
  - Greedy heuristics are among top candidates

Motivation: An Opportunity in NISQ ERA

Hybridizing

Greedy algorithms

- Making locally optimal choices to yield a globally optimum setting
- Most greedy algorithms fail to achieve the global optimum
- Greedy methods are efficient

NISQ Computers

- Can better approximate global optimums in certain domains (e.g., optimization)
- VQA/QA generally fail to attain global optimums

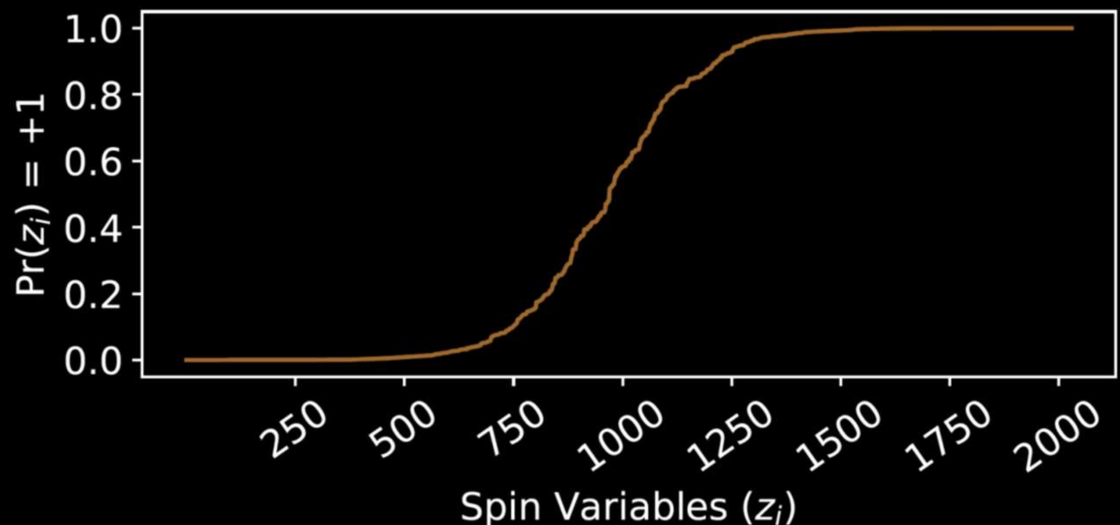
We can employ NISQ computers to make globally optimal choices at each iteration of a greedy algorithm

Quantum Annealers

- Quantum Annealers (QA)
  - Restricted adiabatic quantum computers
  - Single-instruction (quantum) computing machine
  - Sampling from the ground state of (Ising) Hamiltonians

$$\epsilon = \sum_{i=1}^{N} \boldsymbol{h}_i \boldsymbol{z}_i + \sum_{i=1}^{N} \sum_{j=i+1}^{N} J_{ij} \boldsymbol{z}_i \boldsymbol{z}_j$$

- Observation: Not all qubits are equal
- QAs can quickly recognize the region where global optima reside



Greedy Quantum Annealing (GQA)

$$\epsilon = \sum_{i=1}^{N} \boldsymbol{h}_i \boldsymbol{z}_i + \sum_{i=1}^{N} \sum_{j=i+1}^{N} J_{ij} \boldsymbol{z}_i \boldsymbol{z}_j$$

- Let $\boldsymbol{z}^*$ be the ground state of H
- We aim to find $\tilde{\boldsymbol{z}}$ such that

$$\|\boldsymbol{z}^* - \tilde{\boldsymbol{z}}\|_2^2 \to 0$$

or

$$\|\boldsymbol{H}(\boldsymbol{z}^*) - \boldsymbol{H}(\tilde{\boldsymbol{z}})\|_2^2 \to 0$$

- We start with $\tilde{z} = \{\}$
- On each episode
  - GQA samples from the ground state of H
  - We look at spins as random variables with Bernoulli distribution; we use sample set to estimate its parameters
  - GQA contracts spins with high certainty

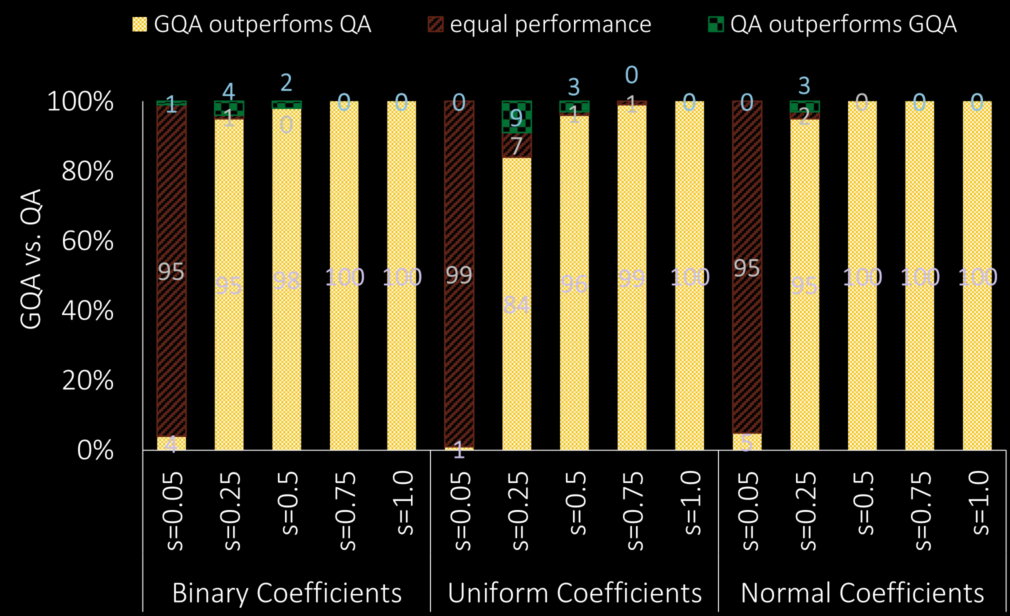
Input: H, θ
Output: $\tilde{\mathrm{z}}$
$\tilde{\mathrm{z}} \leftarrow \{\}$
$H^t \leftarrow H$
do
  $H^{t+1} \leftarrow H^t$
  $Z \leftarrow \{\mathrm{z}^1, \mathrm{z}^2, \cdots, \mathrm{z}^n\} = \arg\min_{\mathrm{z}} H^t$
  for $i \leftarrow 1$ **to** N **do**
    if $u(\mathrm{z}_i) \leq \theta$ **then**
      $\tilde{\mathrm{z}}_i \leftarrow \mathrm{sgn}\left(\sum_{j=1}^{n} \mathrm{z}_i^j\right)$
      $H_{\mathrm{h}_i}^{t+1} \leftarrow 0$
      for $j \leftarrow 1$ **to** N **do**
        if $J_{ij} \in H^{t+1}$ **then**
          $H_{\mathrm{h}_j}^{t+1} \leftarrow H_{\mathrm{h}_j}^{t+1} + J_{ij}\tilde{\mathrm{z}}_i$
          $H_{J_{ij}}^{t+1} \leftarrow 0$
        end
        if $J_{ji} \in H^{t+1}$ **then**
          $H_{\mathrm{h}_j}^{t+1} \leftarrow H_{\mathrm{h}_j}^{t+1} + J_{ji}\tilde{\mathrm{z}}_i$
          $H_{J_{ji}}^{t+1} \leftarrow 0$
        end
      end
    end
  end
while $H^{t+1} \neq H^t$
if $|\tilde{\mathrm{z}}| < N$ **then**
  $\tilde{\mathrm{z}} \leftarrow \tilde{\mathrm{z}} \cup \mathrm{MQC}(Z)$
end

GQA: Results

$$\epsilon = \sum_{i=1}^{N} \boldsymbol{h}_i \boldsymbol{z}_i + \sum_{i=1}^{N} \sum_{j=i+1}^{N} J_{ij} \boldsymbol{z}_i \boldsymbol{z}_j$$

Benchmarking: Random Problems

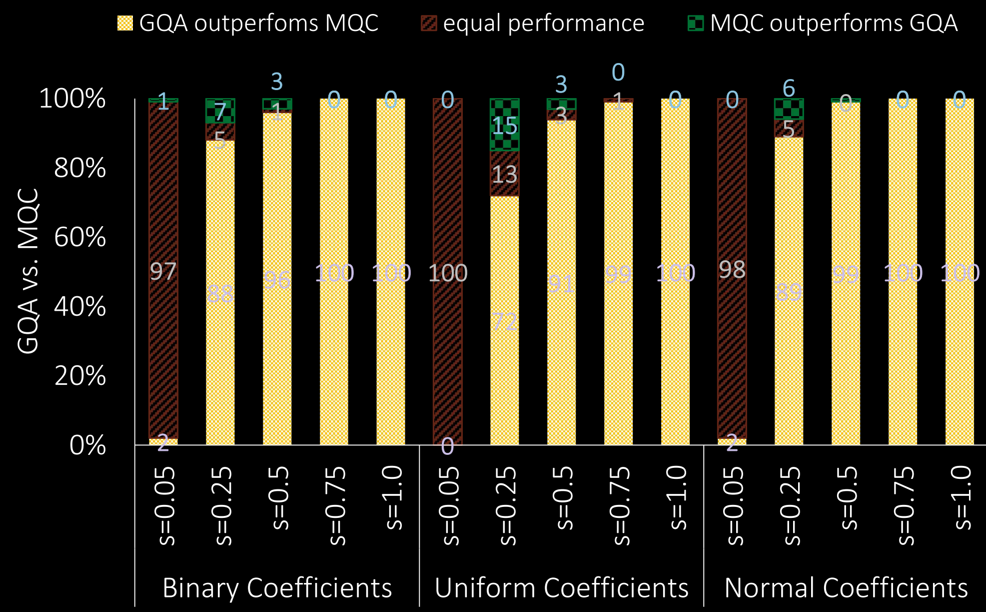
- Random coefficients
  - Binary {-1,+1}
  - Uniform [-1,+1]
  - Normal N(0,1)
- Varying sparsity rate (s)
- Baseline: QA



GQA: Results…

$$\epsilon = \sum_{i=1}^{N} \boldsymbol{h}_i \boldsymbol{z}_i + \sum_{i=1}^{N} \sum_{j=i+1}^{N} J_{ij} \boldsymbol{z}_i \boldsymbol{z}_j$$

- Multi-Qubit Correction (MQC)
  - A novel postprocessing policy for QAs
- Observations
  - For Chimera-like problems, performance of GQA approaches to the performance of MQC
  - For clique-like problems, GQA demonstrates better performance



Summary

- Quantum Computers
  - We are in NISQ era
  - NISQ computers can better approximate optimum solutions in certain domains
- Greedy Algorithms
  - The best (or the only) option in some real-world applications
  - Generally fail in finding global optima
- Quantum-Assisted Greedy Algorithms
  - Leveraging NISQ computers for boosting the performance of greedy algorithms
- Greedy Quantum Annealers
  - A greedy scheme for finding the ground state of (Ising) Hamiltonians

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Thank you