Quantum Inspired

EE599-001 & EE699-010, Spring 2026

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Why?

- Quantum computers might be much faster to solve various problems, but are they?
  - The disappointing scale of NISQ hardware
  - What are the basic quantum operations?
  - The search for quantum supremacy

- Quantum computing is re-thinking some basic assumptions of computing… maybe re-thinking conventional computation is good too?

# Quantum-Inspired (QI) Algorithms

- Quantum algorithms operate on entangled superpositions, often using interference and amplitude amplification...

- Can approximate quantum qubit operations by linear algebra on exponentially large vectors
- QI exploits structure (e.g., sparsity or sampling) to achieve sub-linear or poly-log runtime
- Is quantum speedup obtained if conventional code adopts a quantum algorithm's approach?

Quantum Supremacy

- Quantum supremacy is measured against an *assumed* classical "hardness" of the *problem*

- Converting a quantum algorithm into code that can execute conventionally, "*dequantization*," doesn't invalidate; it clarifies where quantum advantage lies

- Understanding QI algorithms provides better insight into future quantum hardware claims

A Benchmark Problem

- Solving a jigsaw puzzle was proposed as a benchmark

- Each piece has 4 edges with uniquely numbered shapes

- Use *any algorithm* to match piece edges with same number

- A variant of this is **Quantum Awesomeness**, intended to show quantum supremacy
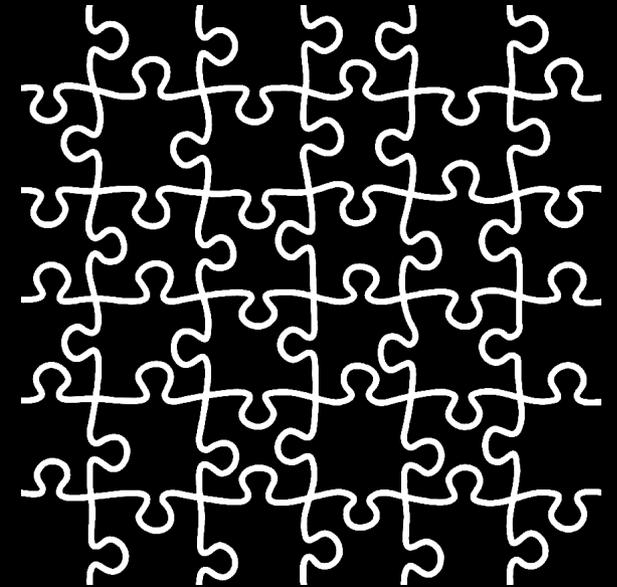
A Problematic Benchmark

- Solving a jigsaw puzzle was proposed as a benchmark

- Each piece has 4 edges with uniquely numbered shapes

- Use *any algorithm* to match piece edges with same number

- Hashing on a conventional machine, n-piece puzzle is solved in O(1) time and ~O(n) effort
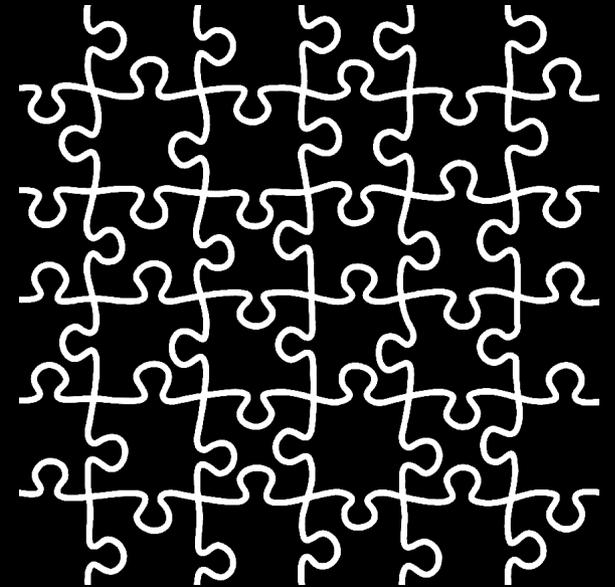
QRAM: Quantum RAM

- QRAM model: O(1) quantum query for any amplitude within a superposed vector
  - Think Grover's algorithm…
  - Initialize a superposition with a vector?

- Analogous to SIMD parallel vector indexing, where each PE$_{iproc}$ accesses a[f(iproc)]…
TMC CM implemented by $\Sigma((j==iproc)*a[j])$

- The hard part for quantum is initializing a[], not indexing (which is basically Grover's alg.)

Quantum Recommendation Systems & Linear Algebra

- **Kerenidis & Prakash (2016)** exponentially faster quantum recommendation systems
  - Sparse user-product preference mxn matrix
  - Quantum samples k-rank approximation in O(poly(k,1/ε)*polylog(mn)) for small k
  - Classical is $\Omega(mn)$
  - Prime example of practical quantum advantage for machine learning

Tang's Dequantization

- **Tang (2018)** proved polynomially-slower conventional version of Kerenidis & Prakash
  - Tree "sample-and-query" (SQ), not QRAM
  - Does ℓ^2-norm importance sampling
  - Also $O(\text{poly}(k,1/\varepsilon)*\text{polylog}(mn))$ for small k
  - Quantum speedup required better input data than the classical algorithm was given

Generalized Classical SQ

- **Tang (2018)** generalizes to low-rank approximation of any matrix by score sampling
  - Importance of each row/col to top-k
  - Sample rows proportional to ℓ^2-norm to approx. SVD (singular value decomposition)
  - Many quantum linear algebra algorithms dequantized using similar methods… e.g., for machine learning

The HHL Algorithm

- **Harrow, Hassidim, & Lloyd (2009)** presented quantum solution of linear systems of equations
  - Quantum time $O(\log(n) * K^2/\varepsilon)$, K condition no.
  - Classical is $O(n * poly(K))$
  - However, quantum output is $|x\rangle$, so it takes at least $O(n)$ repeats to measure

Classical HHL Alternatives

- Various new classical algorithms converge on solutions exponentially quickly
  - **Randomized Kaczmarz (2007)** iteratively projects onto hyperplanes
  - Stochastic gradient descent for least-squares systems converge in $O(n*\log(1/\varepsilon)/\lambda min)$

- HHL works for sparse and well-conditioned; for those, classical iterative solvers compete

Classical HHL-Inspired

- Various dequantizations of linear algebra that is used in HHL applications
  - Quantum singular value transformation (QSVT) unifies HHL, phase estimation, and amplitude amplification
  - Chebyshev expansions approximating matrix functions as polynomials behave similarly
  - Solutions with poly-log solution sparsity have polynomial slowdown using conventional

Grover's Search

- Unstructured search on *N* items in $O(\sqrt{N})$ quantum queries vs. $O(N)$ conventional
  - Uses amplitude amplification
  - Quadratic speedup is "real" because $O(N)$ bound is tight, but it isn't exponential

- Structure is easily imposed in conventional searches…

Quantum Annealing

- Quantum annealing can be exponnetially faster than conventional simulated annealing
  - Simulated Quantum Annealing (SQA) mimics quantum tunneling in a Monte Carlo method
  - Competitive wth D-Wave hardware QA

- An example of quantum thinking giving speedup rather than quantum HW...

QAOA and Tensor Networks

- Quantum Approximate Opimization Algorithm (QAOA) is a hybrid combinatorial optimization algorithm for NISQ; e.g., QUBO, MaxCut
  - p alternating cost and mixer Hamiltonians; QAOA at depth p has $2p$ free parameters optimized classically
  - Tensor network contraction simulates QAOA circuits for low entanglement cases
  - For MaxCut on planar/sparse graphs, **Goemans and Williamson SDP (1995)** is faster than QAOA

qPCA

- Quantum Principal Component Analysis (qPCA) by **Lloyd, Mohseni, and Rebentrost (2013)**
  - qPCA is O(log n) vs. classical PCA is O(n^2)
  - Tang's dequantization with SQ-oracle with sampling PCA is also O(log n)
  - qPCA only wins when classical sampling is not efficient (e.g., at higher ranks)

Boson Sampling

- **Aaronson and Arkhipov (2011)** proposed Boson sampling model of linear optical net
  - Requires #P-complete matrix permanents (#P-complete means $O(n^2 2^n)$)
  - Classical approximate simulators compete for small photon counts
  - Classical **tensor network GBS (2024)** basically shows quantum results obscured by noise...

RCS

- Google claimed Sycamore achieved quantum supremacy in 2019 with RCS
  - Original claim: ~10K years on supercomputer
  - 2021 estimate reduced to days on a cluster; then IBM did a classical simulation…

- RCS is still faster on a quantum system, but it isn't really doing anything useful except as a metric of quantum hardware quality

Other Quantum Inspired

- Various Monte Carlo stochastic simulations use amplitude weights or other quantum properties
- Various graph walk algorithms, e.g., **this**
- Quantum Natural Language Processing (QNLP) mapping compositional distributional semantics into tensor networks

Things Without Classical Approxmations

- Quantum chemsitry: Variational Quantum Eigensolver (VQE) and quantum phase estimation at scale
- Factoring: Shor's algorithm still wins
- Quantum error correction: fault-tolerant quantum computation with constant overhead
- Quantum communication: teleportation and entanglement-based protocols

What Does This Mean?

- Quantum advantage mostly comes from
  - Stochastic algorithms
  - Quantum concepts in classical algorithms
  - Exponential work done with single operations on entangled superpositions

- Data access model is often the limiting factor

- **Are quantum phenomena necessary** to efficiently operate on entangled superpositions?