Open-System Adiabatic Quantum Annealing

Bob Lucas
USC – Lockheed Martin Quantum Computing Center
April 29, 2015
Need More Capability?

Exploit a New Phenomenon
D-Wave Quantum Annealer

Massive Scaling
Tianhe-2 (3M cores)

Application Specific Systems
D.E. Shaw Research Anton
Quantum Annealing = Thermal Annealing ++

- Probability to overcome barrier: $e^{-\beta \Delta E}$
- Easy to jump: $\beta \Delta E \ll 1$
- Hard to jump: $\beta \Delta E \gg 1$

- Probability to tunnel through barrier: $e^{-x\sqrt{\Delta E}}$
- Easy to tunnel: $x^2 \Delta E \ll 1$
- Hard to tunnel: $x^2 \Delta E \gg 1$
Adiabatic Quantum Annealing

Problem: find the ground state of

\[ H_{\text{Ising}} = \sum_j h_j \sigma_j^z + \sum_{(i,j)\in E} J_{ij} \sigma_i^z \sigma_j^z \]

Shown by Barahona (1982) to be NP-hard in 2D, \( J_{ij} = \pm, \ h_j \neq 0 \).

Use adiabatic interpolation from transverse field (Farhi et al., 2000)

\[ H(t) = A(t) \sum_j \sigma_j^x + B(t) H_{\text{Ising}} \]

Program \( \{h_i\}, \{J_{ij}\} \)

Graph Embedding implemented on DW-1 via Chimera graph retains NP-hardness (V. Choi, 2010)
USC Research Foci

Quantum signatures
Is it behaving like an open-system, adiabatic quantum annealer?

Entanglement
Is it unambiguously a quantum machine?

Computational advantage
Is it faster, or better by some other metric?

Applications
What human problems might it solve?
Witness for Entanglement

Collaboration with D-Wave
Only they can take the measurements needed

Separable States

\[ \rho \]

\[ Z \]

Lanting, et.al, PRX 4, 021001 2014
Quantum Annealing vs. Simulated Annealing

Benchmarks with 2-range glasses without fields

D-Wave 2 vs. Nvidia Kepler GPU (USC & ETH)
Hard problems motivated by satisfiability

Random walk to create frustrated loops that respect a planted solution

Frustration

Itay Hen, Performance of D-Wave Two on Problems with Planted Solutions, AQC 2014
Hard problems for multiple heuristics

- “at least once with 99% chance” – a comparison.
- Universal peak in hardness.
Performance on hard problems

- "average time to solution" scaling results.

Graphs showing the relationship between $N_{loops}/N_{qubits}$ and average time to solution for different values of $N_{loops}/N_{qubits}$.
Another Way to Add Value
Finding Different Solutions

![Graphs showing probability distribution over ordered ground states for DW1 and SSSV, and DW1 and SQA.]
Open Research Problems

Why does the D-Wave even work?
It's an open system

How much quantum speedup will there be?
Any? If so, on what problems?

What applications will it ultimately solve?
We've had half a century to find competing heuristics

How should you program it?
Specifically excluded from recent research programs

What should the topology be?
Reduce critical scaling limitation

Other adiabatic quantum systems will face these.
These questions are all bigger than just D-Wave