Near-Future Quantum Advantages Beyond Speedup

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ASCR Workshop on Quantum Computing for Science
Topic 2: Quantum Algorithms for Applied Math and Linear Algebra

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white paper submitted jointly with **Daniel Lidar**

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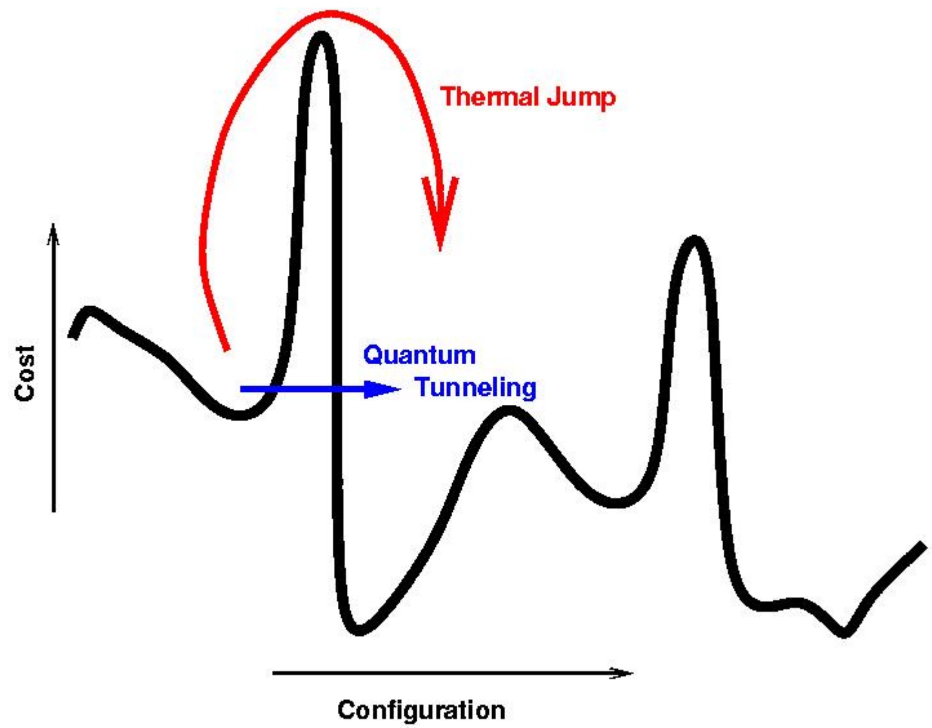
Outline

- background:
  quantum annealers and the search for speedup
- quantum advantages beyond speedup
- practical applications
- summary and conclusions

Background

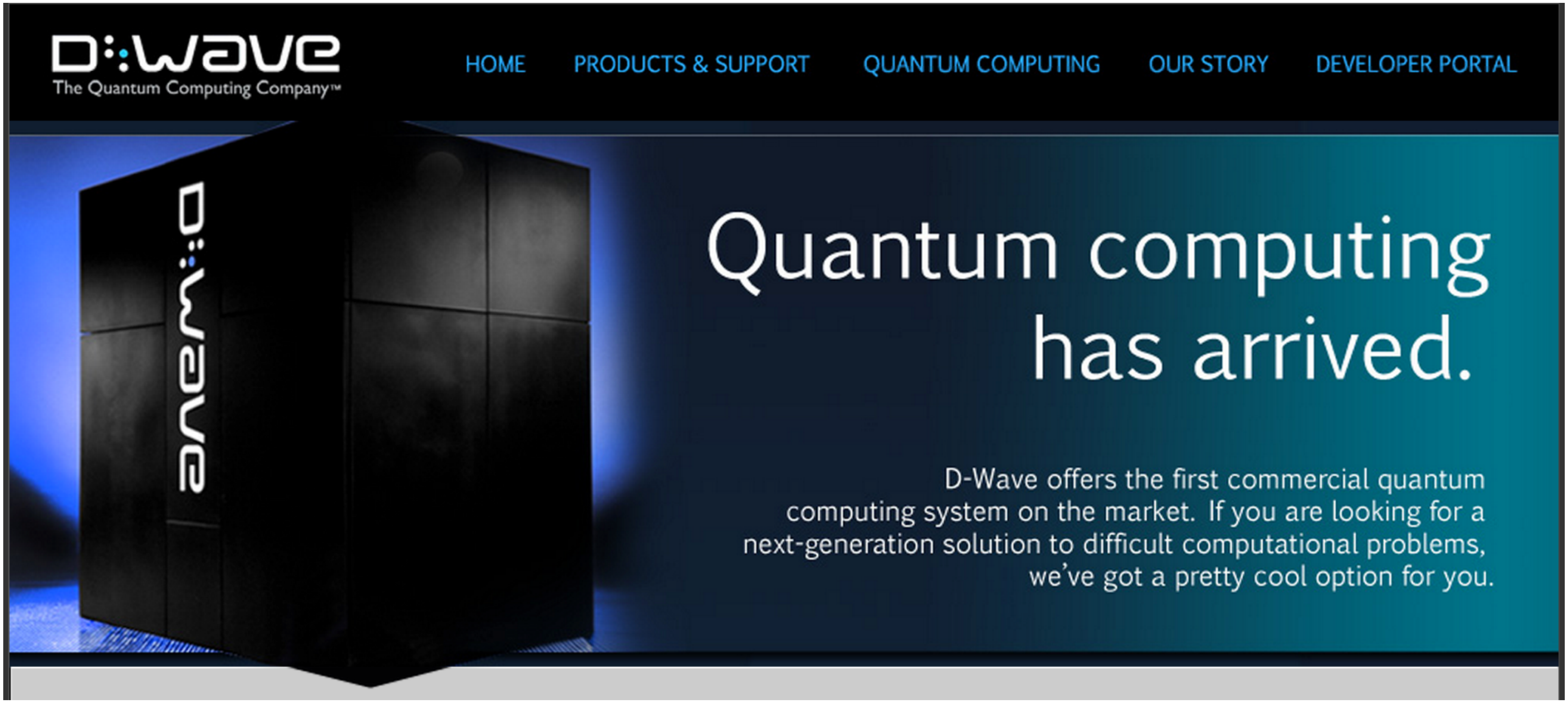
Introduction

- simulated (thermal) annealing: an optimization technique based on gradually reducing thermal fluctuations to find the minimizing configuration of a given cost function. used mainly for problems where the search space is discrete, e.g., combinatorial optimization problems with many local minima. thermal fluctuations are used to escape local minima.
- quantum annealing: an optimization technique based on gradually reducing the magnitude of quantum fluctuations to find global minima, presumably uses quantum tunneling to traverse energy barriers.



Introduction

- in 2011, D-Wave Systems Inc. have declared:

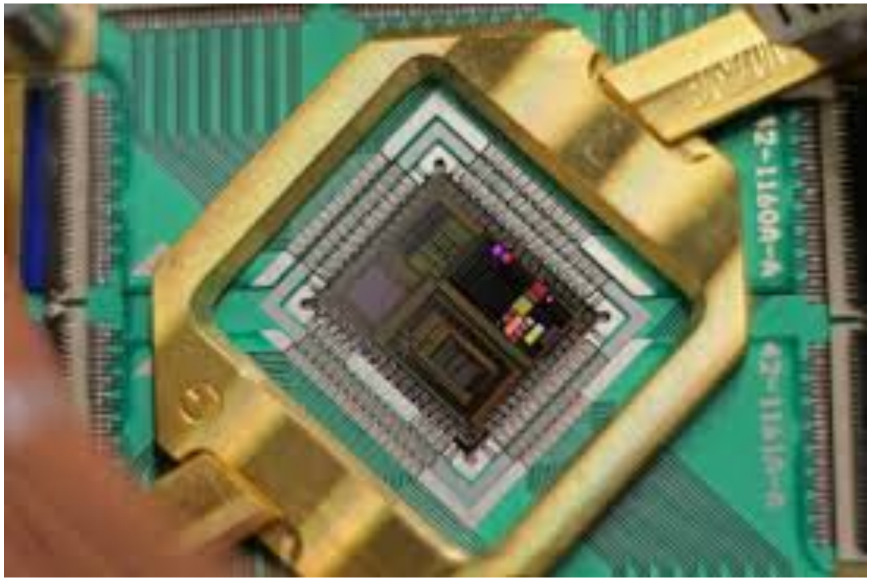


- but has it?

The D-Wave Two Chip

- dealing with the D-Wave device has taught us quite a bit.
- it has raised fundamental questions that extend far beyond the chip itself.
- e.g., how do we properly benchmarking non-universal quantum devices?
- how do we characterize, detect and measure the "quantumness" or "classicality" of experimental devices?

these questions
will be valid for any near-
future quantum device



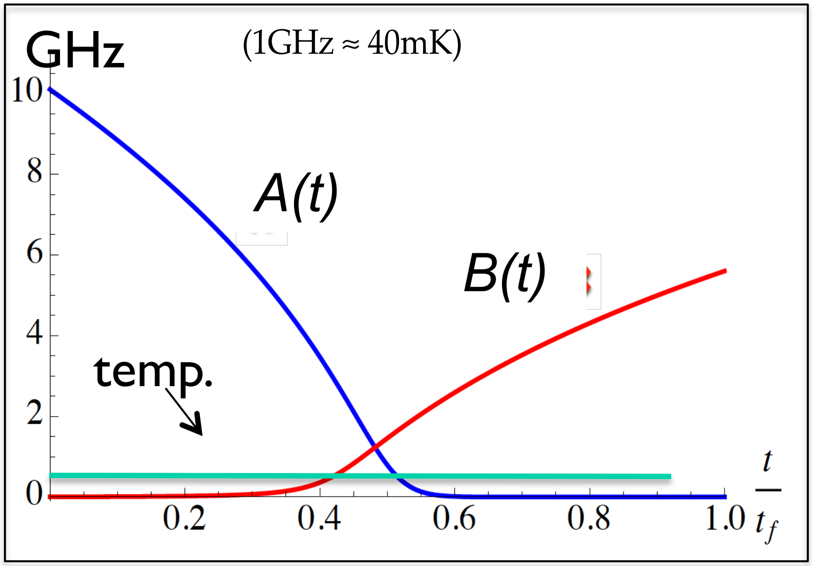
The D-Wave Two Chip

- the D-Wave chip is (presumably) a quantum annealing optimizer evolving according to:

$$\boxed{H = A(t)H_d + B(t)\ H_p}$$

- *A(t)* and *B(t)* specify the annealing schedule. anneal times are $\in [20\mu s, 20ms]$
- H_d is a transverse-field Hamiltonian (source of quantum fluctuations).
- "problem Hamiltonian" (classical cost function to be minimized):

$$\boxed{H_p = \sum_{\langle i,j \rangle} J_{ij} S_i S_j + \sum_i h_i S_i}$$

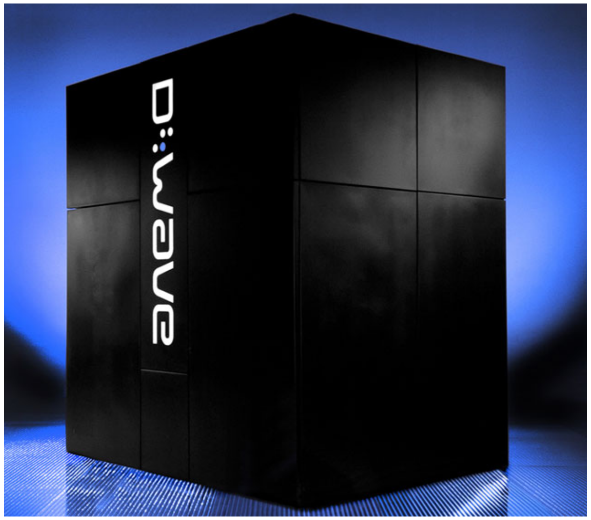


The D-Wave Two Chip

but how quantum is it?

- recent compelling evidence by Lanting et al. (PRX, April 2014) that entanglement exists and can be indirectly detected midway through the run, using "probe" qubits.
- unpublished preliminary results suggesting that the classical models do not reproduce the quantum signature (but Master Equation quantum simulations do).

can this "quantumness" be harnessed to do something useful?

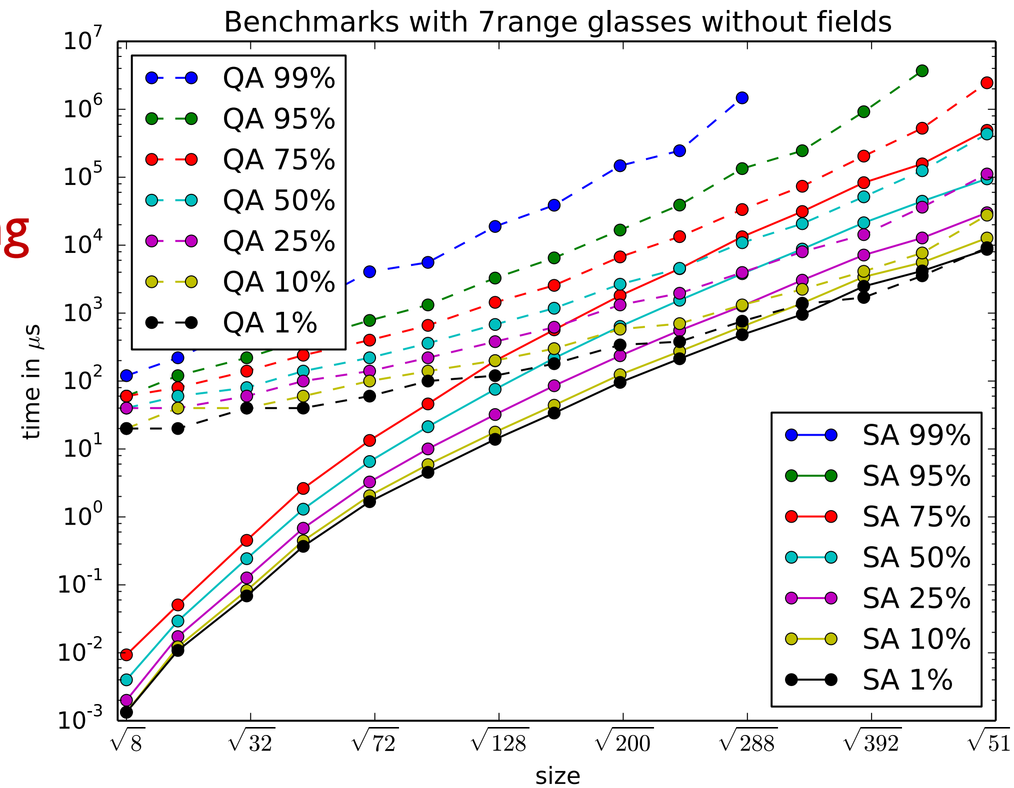


Benchmarking so far

- benchmarking tests have been inconclusive so far.

- random MAX 2-SAT instances on the Chimera:
  - S. Santra et al., "MAX 2-SAT with up to 108 qubits" (New J. Phys., 2014).

- random Ising models (no fields $h_i = 0, J_{ij} = \pm 1$ or similar):
  - S. Boixo, et al., "Quantum Annealing With More Than One Hundred Qubits", (Nature Phys., 2014).
  - T. F. Rønnow et al., "Defining and detecting quantum speedup"., (Science, 2014).

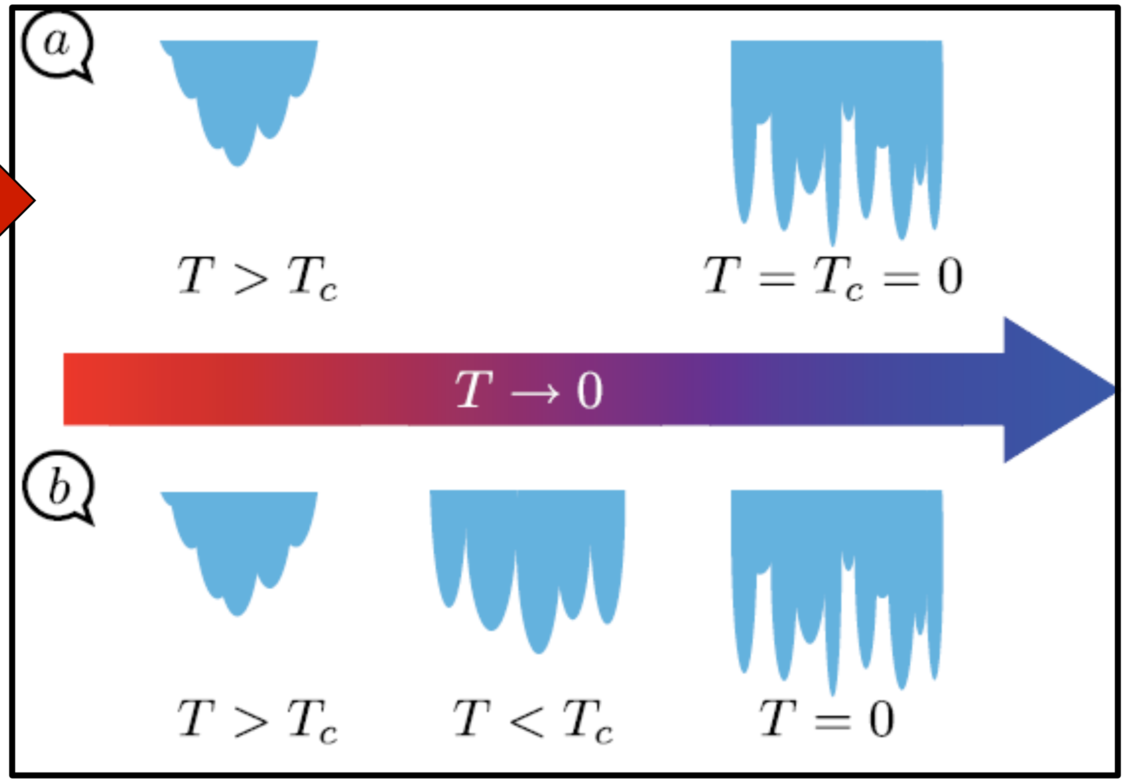


- no evidence for speedup so far.

Benchmarking so far

- possible issues with benchmarking problems tested so far (i.e., random couplings $J = \pm 1, \pm 2$, or spin-glass benchmarks):
- problems tested so far may have been too easy (Katzgraber, Hamze, and Andrist, PRX, April, 2014):
  - a large number of ground states.
  - classical phase transition to a spin glass occurs at $T = 0$.

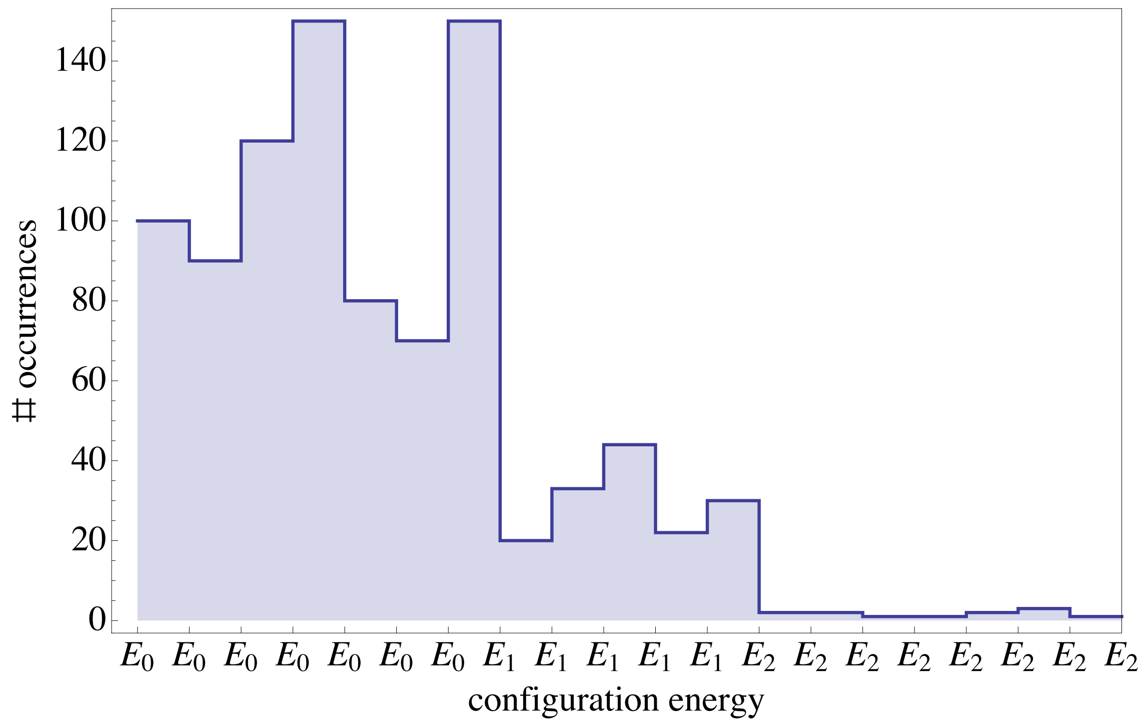
better benchmarks are needed!



Quantum advantages beyond speedup

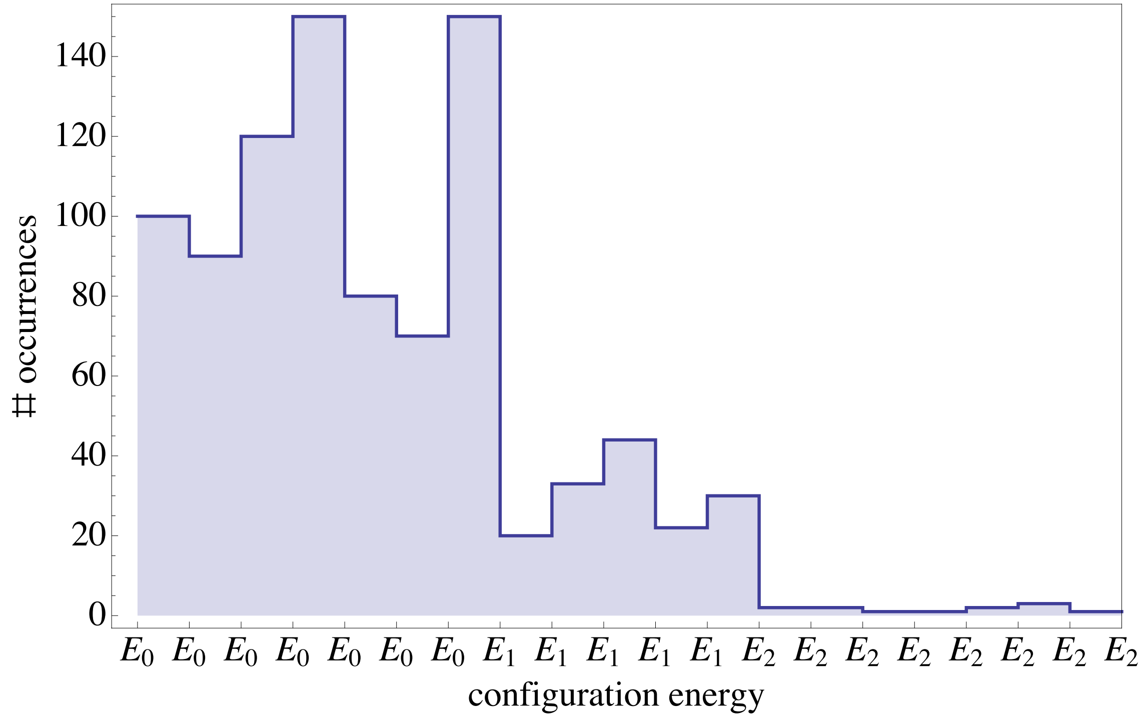
Quantum Annealers as Samplers

- quantum annealing optimizers produce more than just hit/miss answers (leading eventually to "success probabilities").
- quantum annealers produce distributions of configurations (some of which are valid optimal solutions, others are not).
- outcomes contain additional valuable information that may not be easily accessible classically.
- this "quantitative difference" may be exploited.



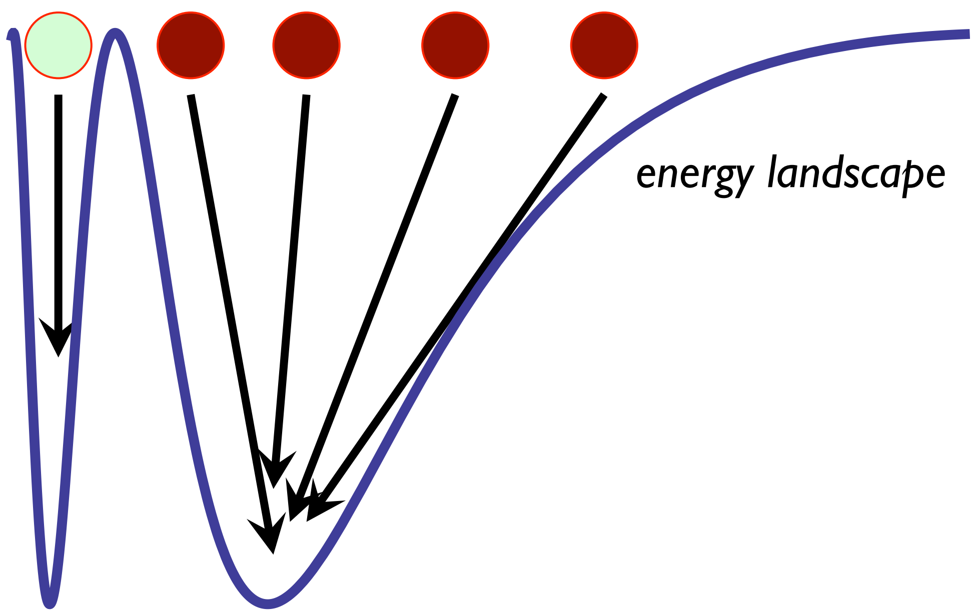
Quantum Annealers as Samplers

- quantum computers are apparently good at sampling.
  - most notably: Shor's QFT (used in almost all non-blackbox quantum algorithms that are superior to the best classical ones).
  - also, boson sampling (Aaronson & Arkhipov).
- quantum annealers are samplers. no reason to believe they always generate "classically-easy" distributions.
- this property may be used in a variety of ways.



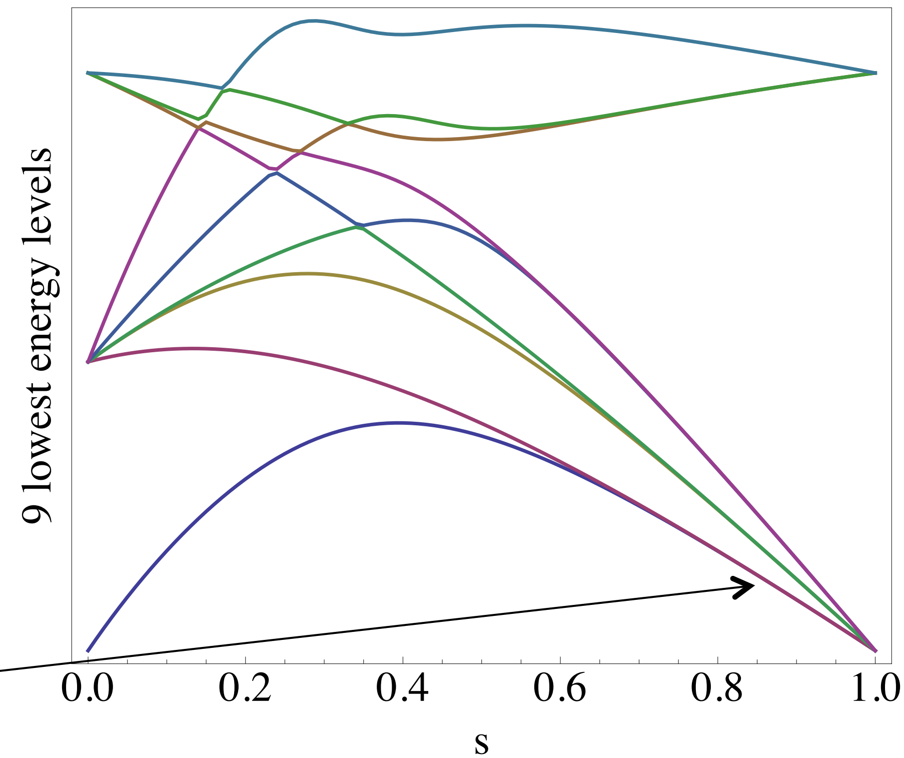
Quantum Annealers as Samplers

- consider an optimization problem with a degenerate ground subspace.
- a thermal annealer functioning as a solver, will sample the solution space, favoring some solutions over others (unless it has already equilibrated).
- some configurations may be "classically-suppressed".
- when looking at time-to-minimal energy, this does not matter.
- in other cases, it does. for example, when the problem at hand requires finding all solutions.



Quantum Annealers as Samplers

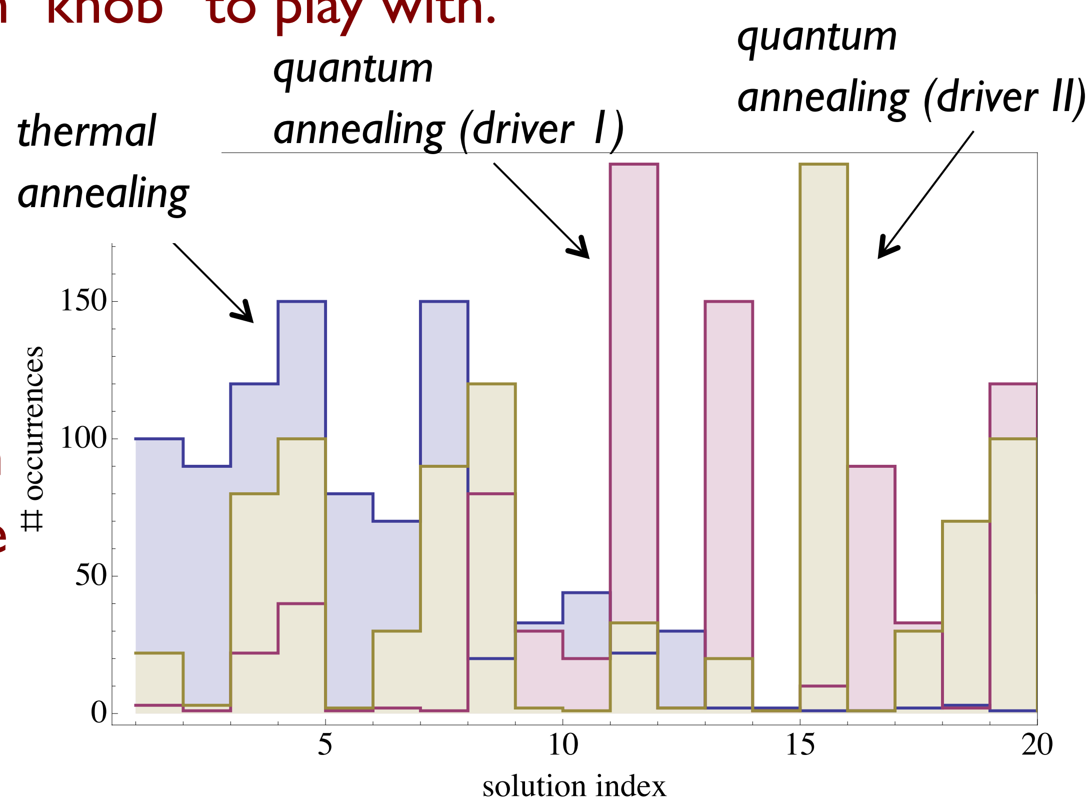
- when solving optimization problems, quantum annealers sample the classical solution space.
- under appropriate conditions, the annealer would choose one specific quantum ground state (as ensured by the adiabatic theorem).
- the amplitudes of the various classical states correspond to a "quantum probability distribution" over solution states, that is different than the classical distribution given by simulated annealing.



classically-degenerate ground subspace but one specific quantum ground state.

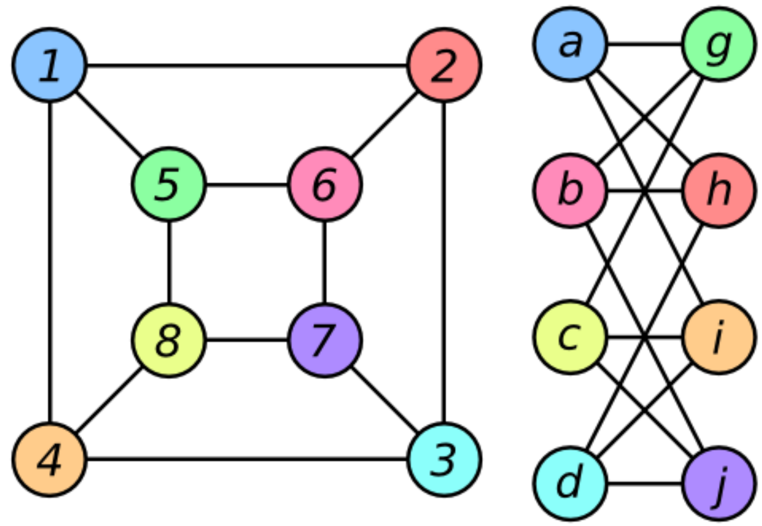
The "extra knob"

- the final "quantum distribution" over classical ground states is not only generally different than the classical one, but also depends on the choice of the initial (driver) Hamiltonian (or intermediate ones).
- this gives us an extra quantum "knob" to play with.
- e.g., what happens if the driver Hamiltonian is non-stoquastic?
- if classically-suppressed states are found by a quantum annealer, this would constitute as a "qualitative" advantage.



Example: deciding graph isomorphism

- the graph isomorphism problem: are two graphs the same upon permuting the indices?



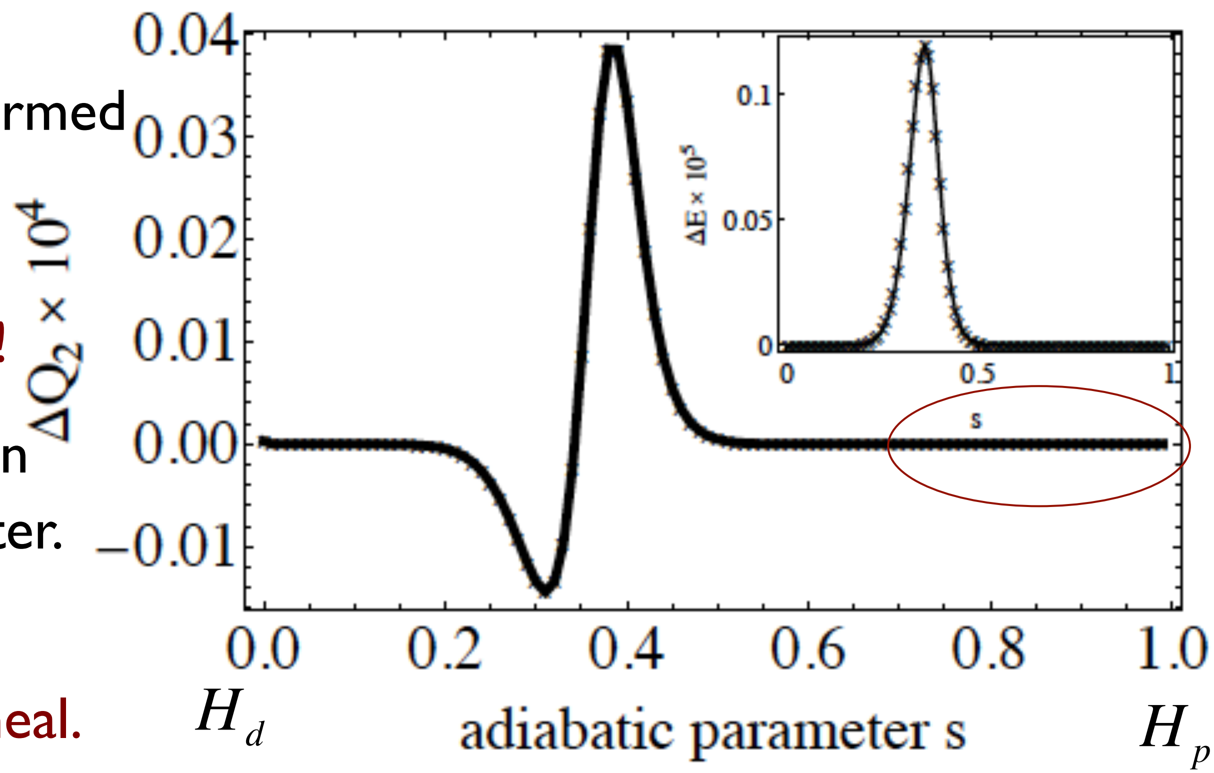
- using quantum annealers: define an Ising cost function (say, an antiferromagnet) on the two graphs then, run an adiabatic algorithm with say, an initial transverse-field driver on the two cost functions separately (Hen & Young, 2012).

- perform certain measurements during the annealing process.

- different expectation values would mean non-isomorphic graphs.

Example: deciding graph isomorphism

- some non-isomorphic graphs have the same classical (final) spectrum. (referred to as "co-Ising", Vinci et al., 2014).
- in a way, they are "classically indistinguishable".
- when quantum measurements are performed midway thru the anneal, the quantum process tells them apart!
- figure shows difference in spin-glass order parameter.
- differences vanish at the (classical) end of the anneal.



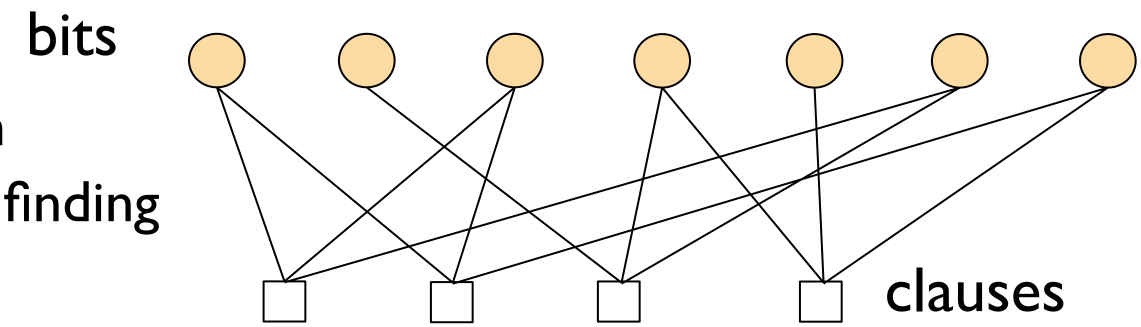
Practical applications

Quantum vs classical distributions

- thermal annealing (generic classical algorithms) generates a distribution of states. Bolzmann-Gibbs if equilibrated, something else if not.
- quantum annealing would generate in general a different distribution of configurations.
- if quantum annealers produce distributions that are difficult to produce classically, this may be used to solve certain problems.
- when does this matter?

Quantum-assisted ALLSAT

- in many practical areas, problems may be reduced to satisfiability -type problems in which the goal is to find all or as many satisfying assignments as possible.



factor graph of a SAT problem

- in validation and verification (V&V,) this corresponds to finding "valuable" bugs.

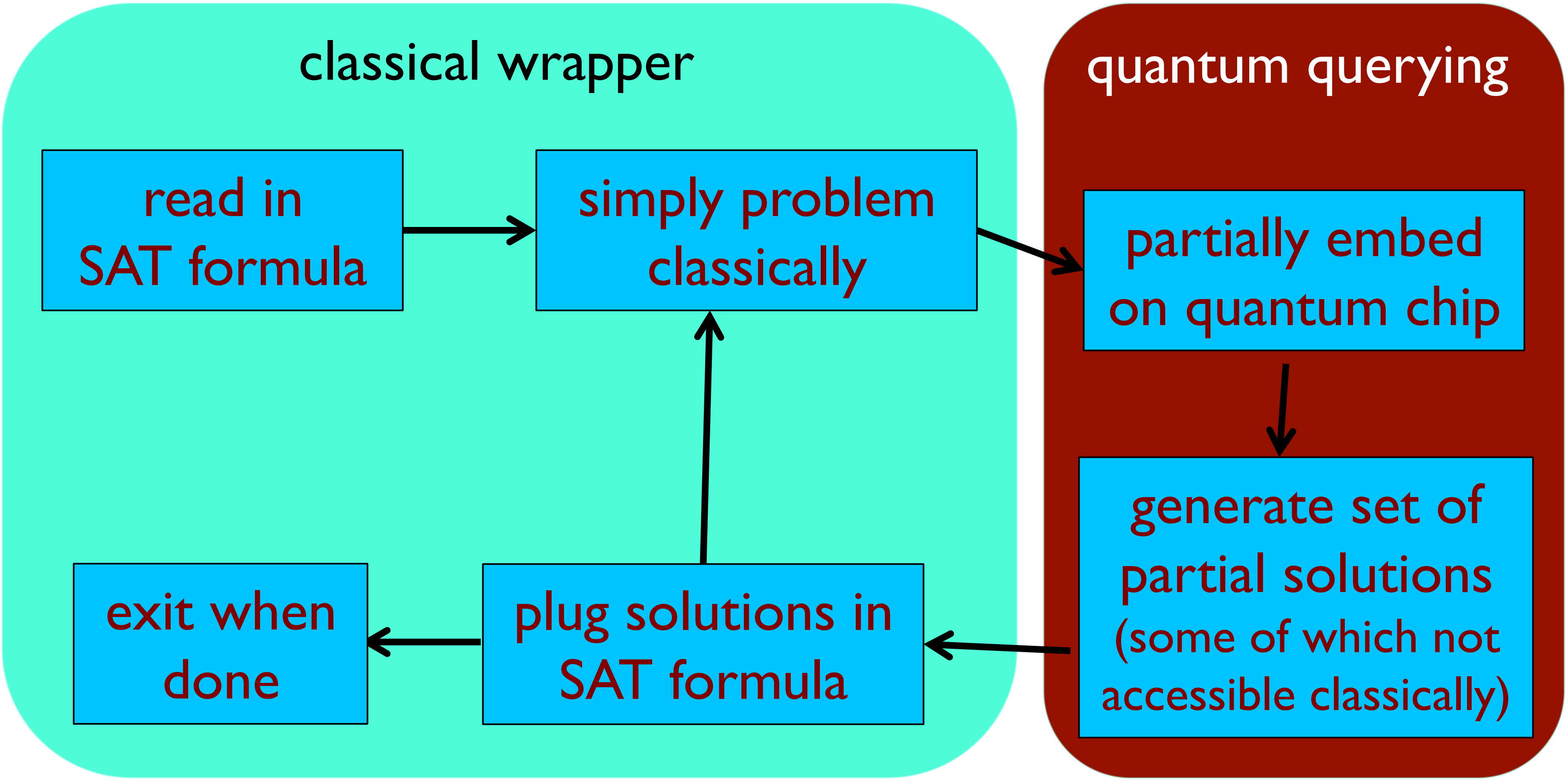
- in planning and scheduling problems, this corresponds to finding a valid plan/schedule.

- quantum annealers can produce "classically-hidden" or "classically-suppressed" assignments or solutions.

- when joined with classical solvers, the resultant set of solutions will be larger and may be viewed as "qualitatively superior".

Quantum-assisted ALLSAT

- a possible hybrid quantum-classical algorithm would be:



Summary and conclusions

Summary and conclusions

- quantum annealers may provide advantages that extend beyond the usual "speedup question" (i.e., time to minimum energy).
- the "quantum annealers as samplers" road has not yet been extensively explored.
- provides a better utilization of current/near-future capabilities because more information produced by the device is exploited than just success probabilities.
- may be viewed as providing potential "qualitative enhancements": more solutions than classical alone.
  - as samplers of distributions that are classically hard to generate.
  - as "counters" or ALLSAT solvers.
- of considerable practical importance.

Thank You!

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