Quantum Mechanics & Quantum Computation

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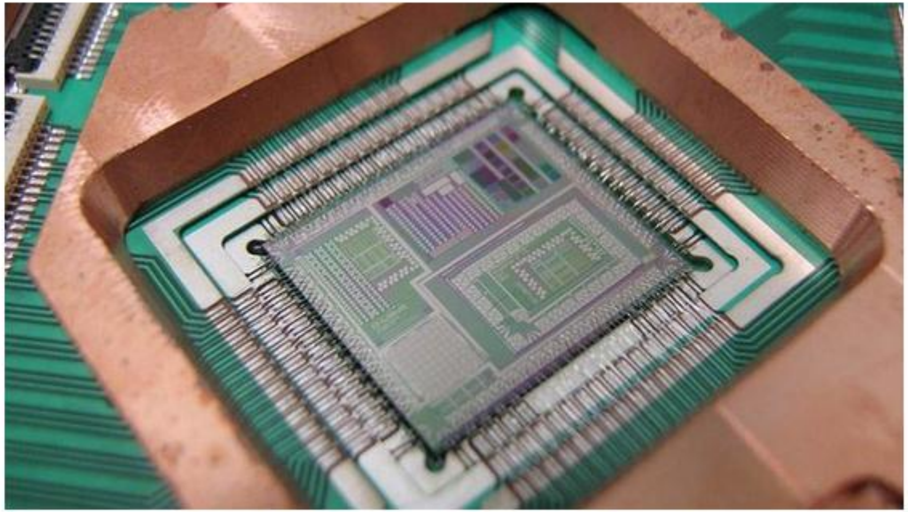
Lecture 16: Adiabatic Quantum Optimization

Intro

16 May 2013 Last updated at 07:54 ET

Nasa buys into 'quantum' computer

By Alex Mansfield
BBC Radio Science Unit



The machine does not fit the conventional concept of a quantum computer, but makes use of quantum effects

A $15m computer that uses "quantum physics" effects to boost its speed is to be installed at a Nasa facility.

Related Stories

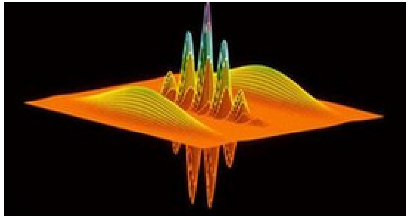
It will be shared by Google, Nasa, and other scientists, providing access to a machine said to be up to 3,600 times faster than conventional computers.

Quantum computing takes big leap
Limits of quantum world stretched
Quantum computer slips onto chips

Unlike standard machines, the D-Wave Two processor appears to make use of an effect called quantum tunnelling.

This allows it to reach solutions to certain types of mathematical problems in fractions of a second.

Effectively, it can try all possible solutions at the same time and then select the best.



Is quantum computing possible?

Google wants to use the facility at Nasa's Ames Research Center in California to find out how quantum computing might advance techniques of machine learning and artificial intelligence, including voice recognition.

University researchers will also get 20% of the time on the machine via the Universities Space Research Agency (USRA).

Bits

MAY 16, 2013, 5:00 AM | 30 Comments

Google Buys a Quantum Computer

By QUENTIN HARDY

Kim Stallknecht for The New York Times

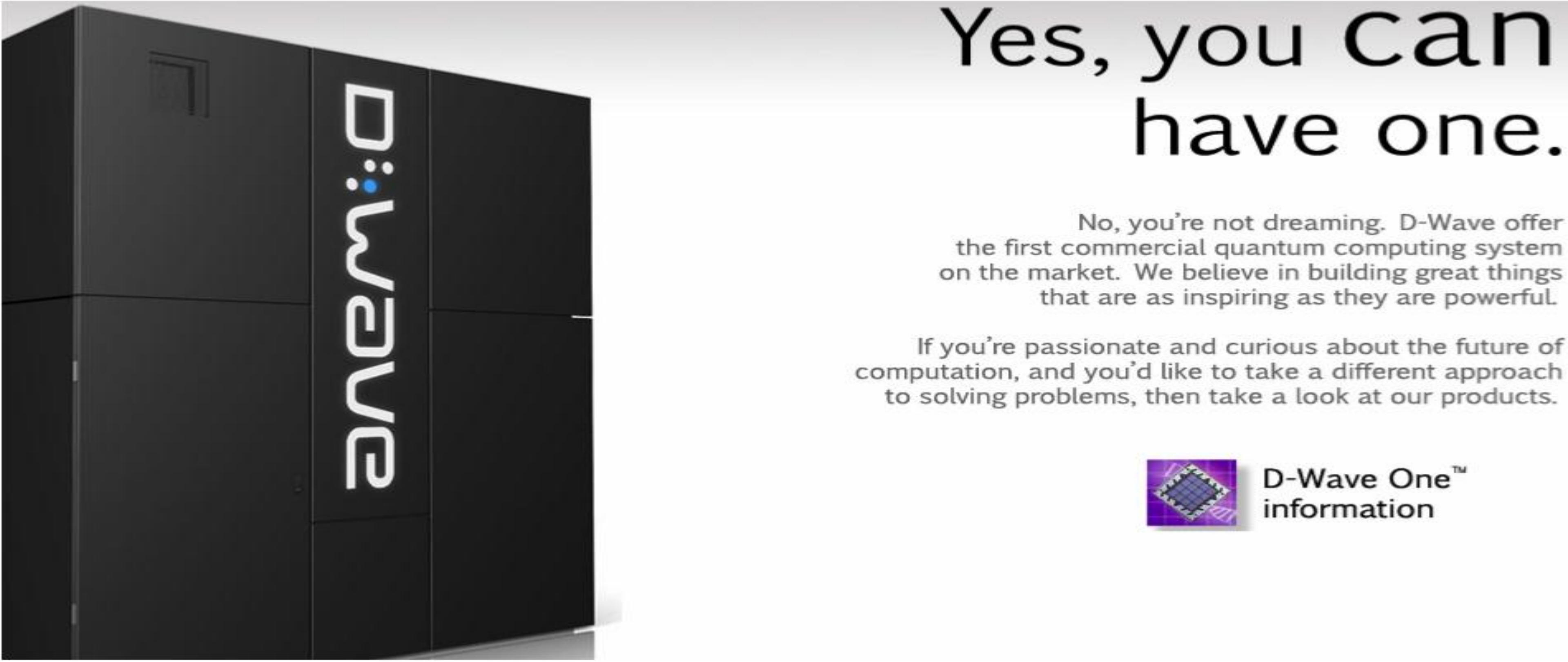
A quantum computer developed by D-Wave Systems.

Google and a corporation associated with NASA are forming a laboratory to study artificial intelligence by means of computers that use the unusual properties of quantum physics. Their quantum computer, which performs complex calculations thousands of times faster than existing supercomputers, is expected to be in active use in the third quarter of this year.

The Quantum Artificial Intelligence Lab, as the entity is called, will focus on machine learning, which is the way computers take note of patterns of information to improve their outputs. Personalized Internet search and predictions of traffic congestion based on GPS data are examples of machine learning. The field is particularly important for things like facial or voice recognition, biological behavior, or the management of very large and complex systems.

http://www.scottaaronson.com/blog/?p=1400

Testing a quantum computer



D-Wave sells first commercial quantum computer

June 1, 2011 by Lisa Zyga weblog

Enlarge

Dr. Geordie Rose, CTO and co-founder of D-Wave Systems, with the D-Wave One system. Image credit: D-Wave.

(PhysOrg.com) -- Last week, Burnaby, British Columbia-based company D-Wave Systems, Inc., announced that it sold its first commercial quantum computer. Global security company Lockheed Martin, based in Bethesda, Maryland, bought the quantum computer for a rumored $10 million, which includes maintenance and other services for several years.

Lockheed Martin communications manager Thad Madden said that the company spent a year reviewing the computer, called the D-Wave One, before purchasing it. The company plans to use the computer to build "cyber-physical systems," which integrate software with environmental sensors.

Economist.com

Quantum computing

Orion's belter

Feb 15th 2007 | VANCOUVER

From *The Economist* print edition

The world's first practical quantum computer is unveiled

AS CALIFORNIA is to the United States, so British Columbia is to Canada. Both are about as far south-west as you can go on their respective mainlands. Both have high-tech aspirations. And, although the Fraser Valley does not yet have quite the cachet of Silicon Valley, it may be about to steal a march on its southern neighbour. For, on February 13th, D-Wave Systems, a firm based in Burnaby, near Vancouver, announced the existence of the world's first practical quantum computer.

Economist.com

Quantum computing

Orion's belter

Feb 15th 2007 | VANCOUVER

From *The Economist* print edition

Quantum computers provide a neat shortcut to solving a range of mathematical tasks known as NP-complete problems. They do so by encoding all possible permutations in the form of a small number of “qubits”. In a normal computer, bits of digital information are either 0 or 1. In a quantum computer these normal bits are replaced by a “superposition” (the qubit) of both 0 and 1 that is unique to the ambiguous world of quantum mechanics. Qubits have already been created in the laboratory using photons (the particles of which light is composed), ions and certain sorts of atomic nuclei. By a process known as entanglement, two qubits can encode four different values simultaneously (00, 01, 10 and 11). Four qubits can represent 16 values, and so on. That means huge calculations can be done using a manageable number of qubits. In principle, by putting a set of entangled qubits into a suitably tuned magnetic field, the optimal solution to a given NP-complete problem can be found in one shot.

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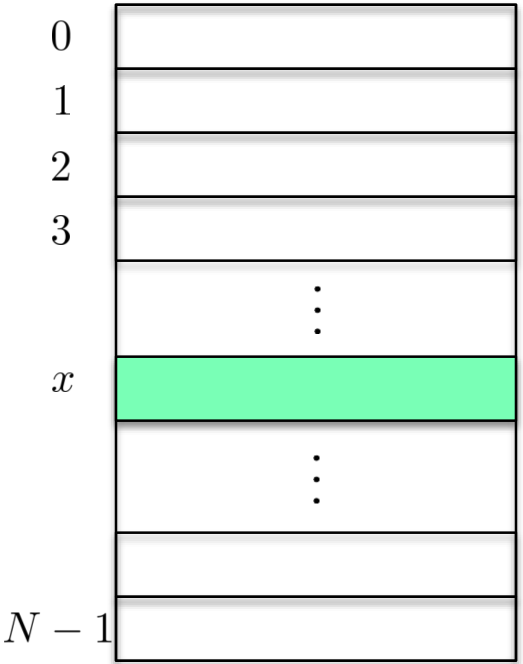
NP-hard optimization problems

Unstructured search

"Digital haystack"



N = 2ⁿ

NP-Complete Problems:

Satisfiability:

Finding a solution to an NP-complete problem can be viewed as a search problem.

$$f(x_1, \dots, x_n) = \underbrace{(x_1 \vee \neg x_2 \vee x_3)}_{c_1} \wedge \underbrace{(x_2 \vee \neg x_5 \vee x_6)}_{c_2} \wedge \cdots \wedge c_m.$$

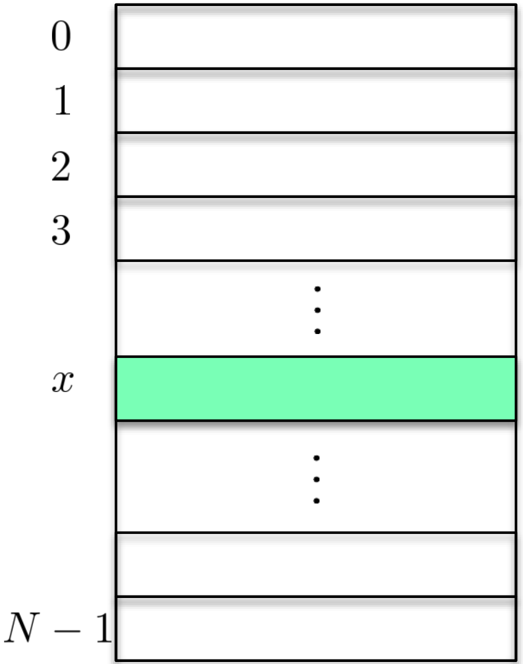
Is there a configuration of $x_1, x_2, \cdots$ that satisfy the above formula?

There are 2^n possible configurations.

max # satisfied clauses. optimization problem.

Unstructured search

"Digital haystack"



Quantum

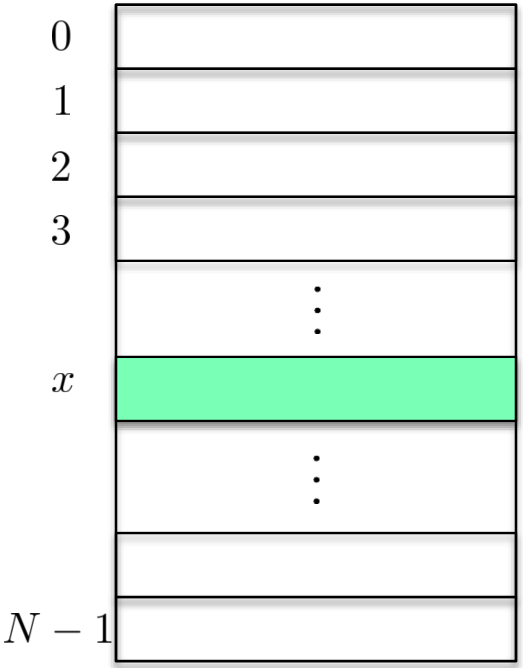
Grover's Algorithm: $O(\sqrt{N})$ time.

$N = 2^n$

$\sqrt{N} = \sqrt{2^n} = 2^{n/2}$

Unstructured search

"Digital haystack"



Theorem: Any quantum algorithm must take at least √N time.

"

$2^{n/2}$ time.

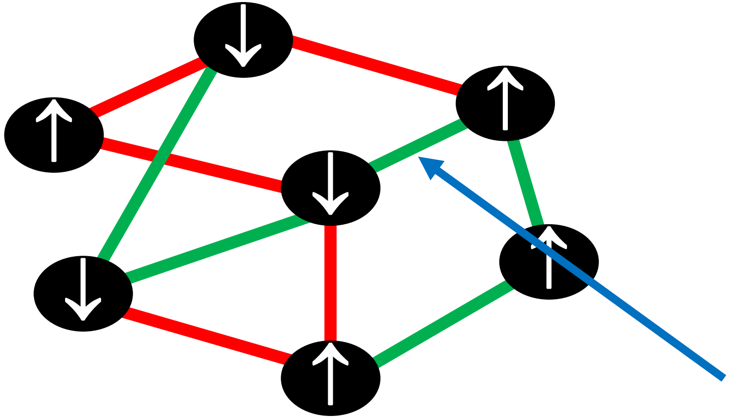
[Farhi, Goldstone, Gutman, Sipser. Science 2001]
Framework of adiabatic quantum optimization.
Simulations on small examples seemed to show polynomial time for random instances of 3SAT.

http://arxiv.org/pdf/quant-ph/0001106v1.pdf

Isn't this ruled out by previous lowerbound? $\geq 2^{n/2}$

Not necessarily. But it does mean that any quantum algorithm must use the structure of the problem.

Ground State Solutions



Which ↑↓ spin distribution minimizes the number of red edges with similar spins and green edges with opposite spins?

(1 violation.)

1) A combinatorial minimization problem.
2) A lowest energy question for magnetic materials.

The ground state of the magnet is the solution to our optimization problem.

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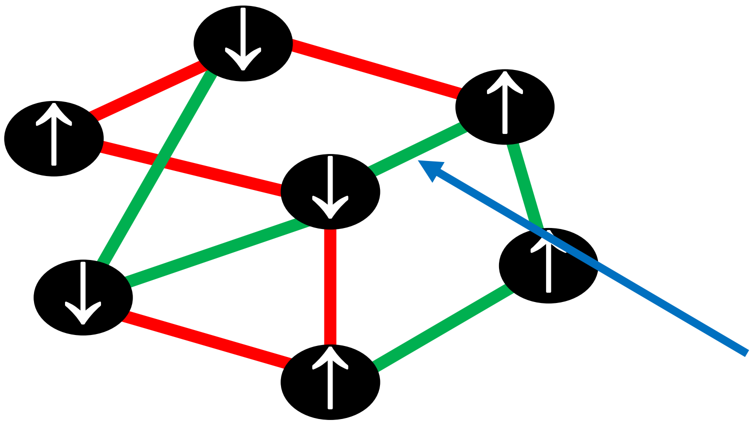
Adiabatic Quantum Optimization

Ground State Solutions



Which ↑↓ spin configuration minimizes the number of red edges with similar spins and green edges with opposite spins?

1 violation

1) An NP-hard optimization problem.
2) Minimum energy configuration for a magnetic material.

The ground state of the magnet is the solution to the optimization problem.

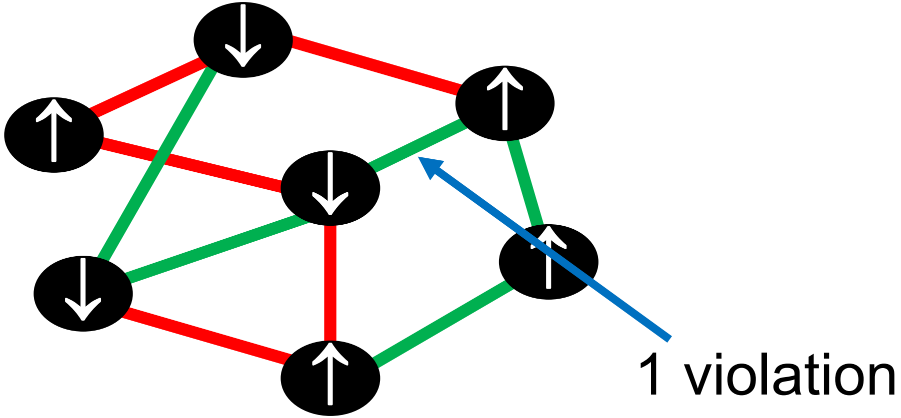
Ground State Solutions

↑ 1

↓ 0

n spins

configuration ⟷ n bit string $\underline{\underline{x}} \in \{0,1\}^n$.



Energy of x = $f(x)$.

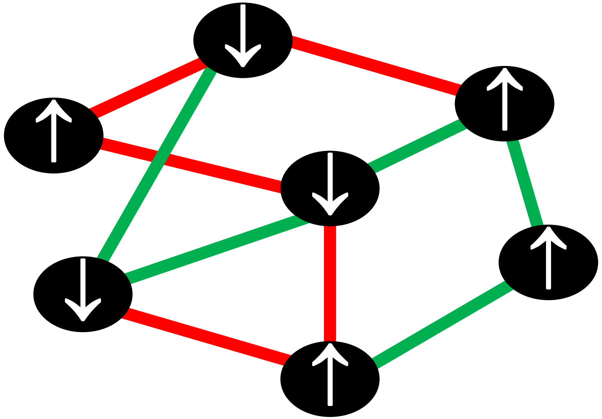
$$H = \underbrace{\begin{bmatrix} f(00\cdots0) & & & & 0 \\ & \ddots & & & \\ & & f(x) & & \\ & & & \ddots & \\ 0 & & & & f(11\cdots1) \end{bmatrix}}_{2^n \times 2^n}$$

$$H = \underline{\underline{H_1}} + H_2 + \cdots + H_m \qquad m \text{ edges}$$

$$\begin{bmatrix} 0 & & & 0 \\ & 1 & & \\ & & 1 & \\ 0 & & & 0 \end{bmatrix} \otimes I$$

Adiabatic Quantum Optimization

$H_0 \longrightarrow H_f$

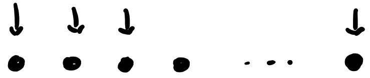


$$|\psi_0\rangle = \frac{1}{2^{n/2}} \sum_{x \in \{0,1\}^n} |x\rangle$$

$|\psi_f\rangle$

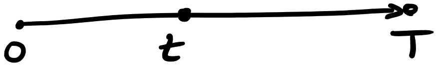
Known ground state

output



$\left(\frac{1}{\sqrt{2}}|0\rangle + \frac{1}{\sqrt{2}}|1\rangle\right)$

$$\begin{pmatrix} 1 & -1 \\ -1 & 1 \end{pmatrix} = I - X$$



$$H_t = \left(1 - \frac{t}{T}\right) H_0 + \frac{t}{T} H_f$$

Adiabatic Thm

T large enough

- How fast? $T = \frac{1}{Min_t \, g(t)^2}$ where g(t) is the difference between 2 smallest eigenvalues of H(t)

$H(t) = \left(1 - \frac{t}{T}\right) H_0 + \frac{t}{T} H_f$

$g(t) = E_1^{(t)} - E_0^{(t)}$

gap

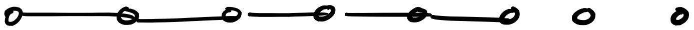
Farhi et al 2001 : Simulated on small instances

- Adiabatic optimization gives quadratic speedup for search,
  http://arxiv.org/pdf/quant-ph/0107015v1.pdf
  http://arxiv.org/pdf/quant-ph/0206003v1.pdf

NP optimization problem

$H(t) = (1 - \frac{t}{T}) H_0 + \frac{t}{T} H_f$

- Exponential time for NP-complete problems including max 2SAT:
  http://ww2.chemistry.gatech.edu/~brown/QICS08/reichardt-adiabatic.pdf



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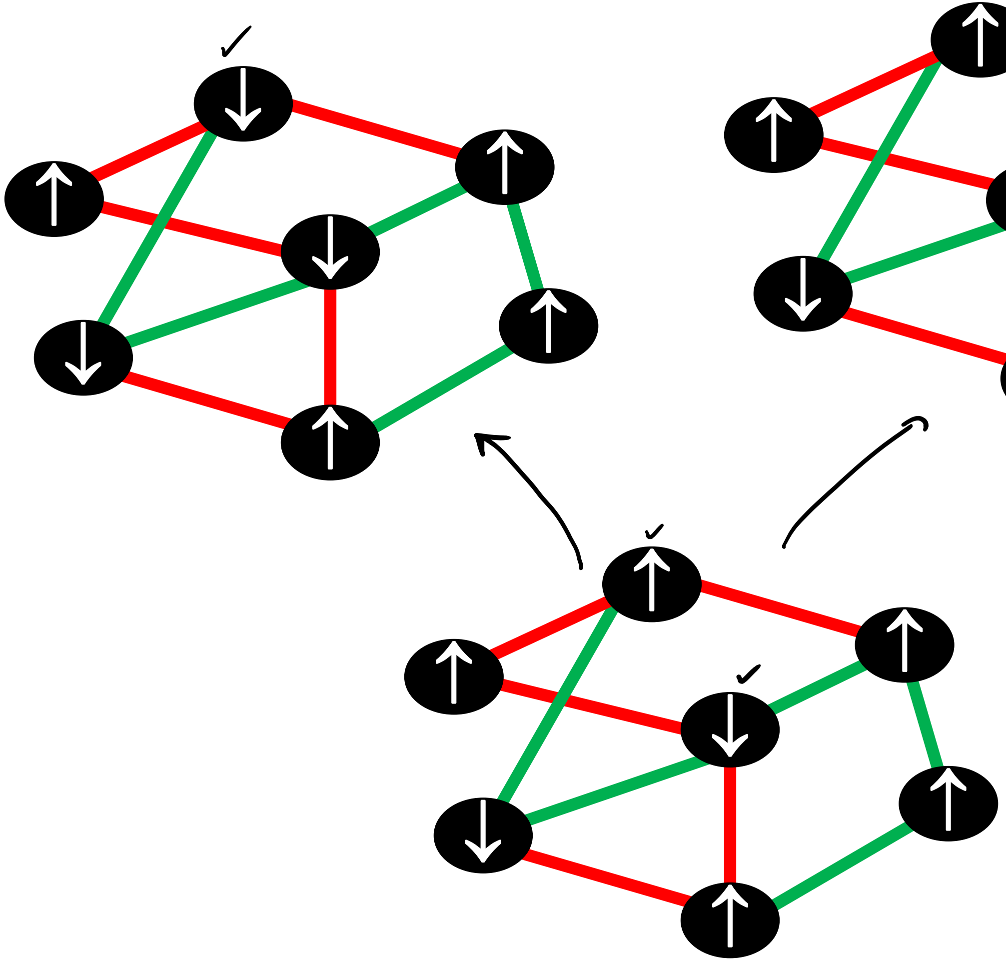
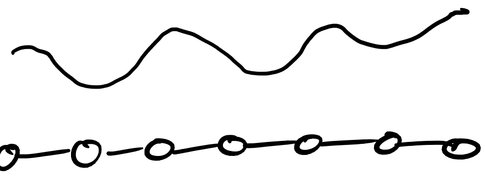
Local Optima, Simulated Annealing & Tunneling

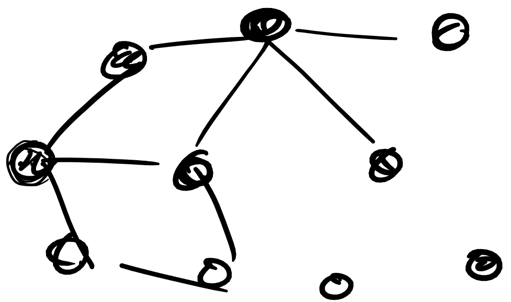
Energy Landscape

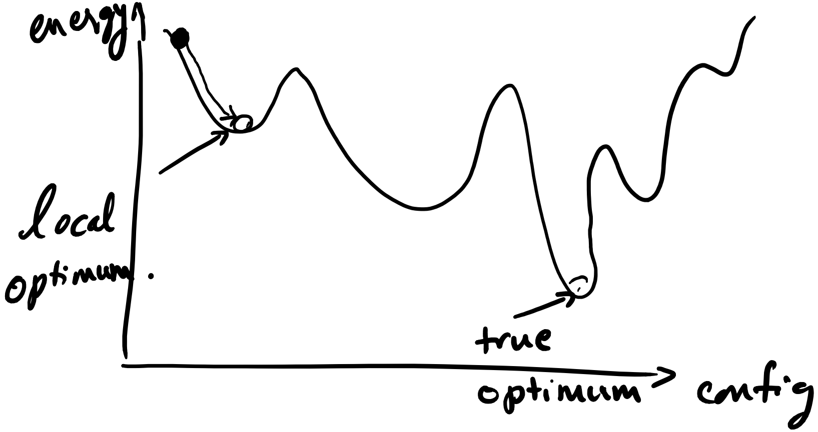




n spins

2^n configurations.





Simulated annealing.

T temp.

Start at high temperature

↓ reduce temp.

$T = 0$.

$\sigma \longleftrightarrow E(\sigma)$.

$\sigma' \longleftrightarrow E(\sigma')$.

If $E(\sigma') \leq E(\sigma)$ move to σ'

If $E(\sigma') > E(\sigma)$ move to σ' with prob $e^{-\frac{E(\sigma') - E(\sigma)}{T}}$

$P(\sigma) \propto e^{-E(\sigma)/T}$ } Gibbs distribution.

$T \to \infty$ Uniform distribution.

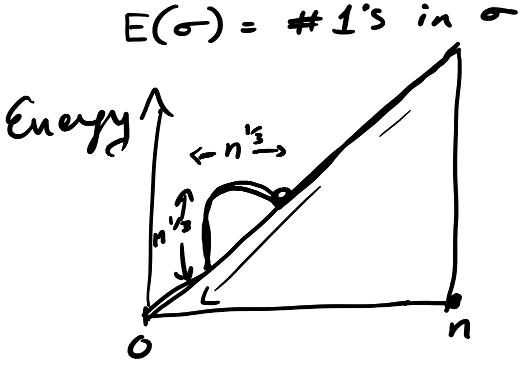
$T \to 0$ $P(\sigma_{min}) \to 1$.

Hard Instances for AQO ⟷ gap is exponentially small

local optima

Simulated annealing ⟷ AQO.

- Can tunnel through local optima in certain special circumstances:
  http://ww2.chemistry.gatech.edu/~brown/QICS08/reichardt-adiabatic.pdf



- Anderson localization based arguments that it typically gets stuck in local optima:
  http://arxiv.org/pdf/0912.0746.pdf

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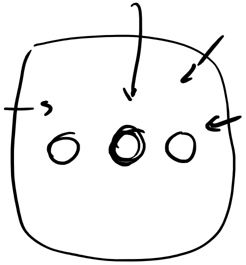
D-Wave + Project

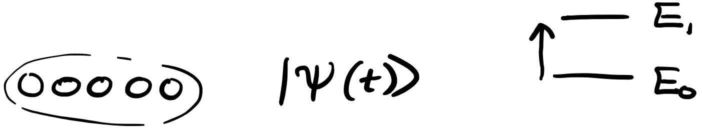
Decoherence:



QAC ≈ quantum circuits.

QAO

$H(t)$



* Restricted quantum computer
* Evidence

D-Wave

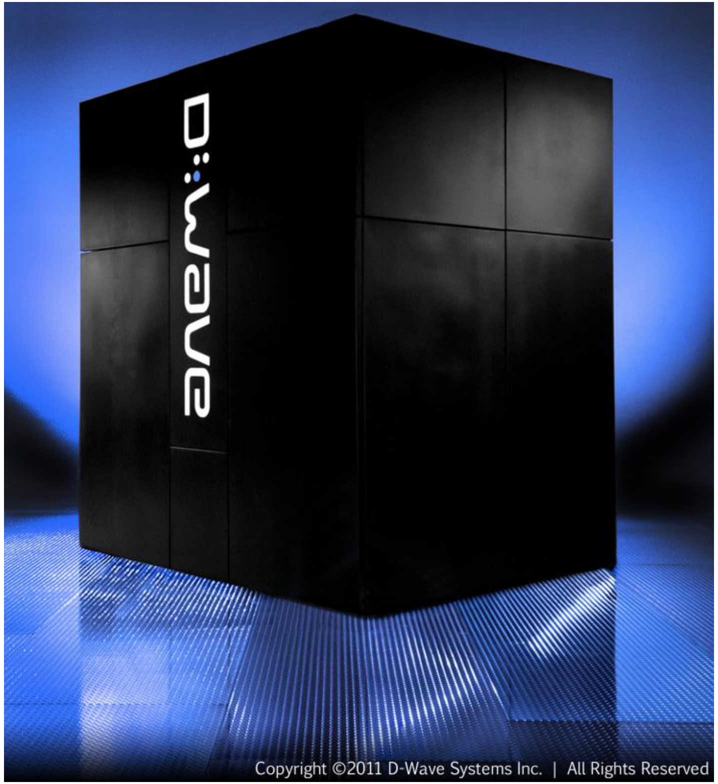
D-Wave One (2011) : 128 qubits

D-Wave Two (2013) : 512 qubits

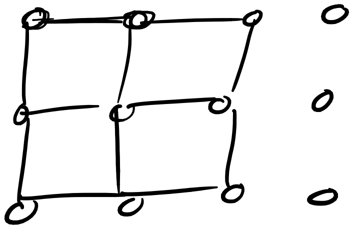
Quantum annealing vs QAO

environment

finite temp.



Programmable coupling between qubits



Time per annealing run ~ microseconds

Decoherence time of qubits appears to be much shorter.

Opaque

Experimental Evaluation of an Adiabatic Quantum System for Combinatorial Optimization, McGeoch and Wang, 2013, http://graphics8.nytimes.com/packages/pdf/business/quantum-study.pdf

DWave 3600 times faster.

http://www.scottaaronson.com/blog/?p=1400

Quantum annealing with more than one hundred qubits, Boixo et al., 2013, http://arxiv.org/abs/1304.4595

Indirect Evidence of entanglement – quantum behavior.

Classical signature of quantum annealing, Smolin & Smith http://arxiv.org/pdf/1305.4904v1.pdf

So far there seem to be few prospects for speedup versus classical computers

Some indication that there might be entanglement, although the jury is still out.

The Hamiltonians that the D-Wave machine can implement are a restricted class called Stoquastic Hamiltonians. There is a classical heuristic called quantum Monte Carlo that works very well in practice in simulating such Hamiltonians.