Adiabatic Quantum Computation

at D-Wave Systems Inc.

Carson Holgate

Computer Science
Math
NCSU

MA 591 Special Topics in Quantum Computation

Outline

Outline

Adiabatic Theorem

Max Born and Vladimir Fock (1928)

A physical system remains in its instantaneous eigenstate if a given perturbation is acting on it slowly enough and if there is a gap between the eigenvalue and the rest of the Hamiltonian's spectrum.

Outline

Application

- Quantum systems evolve according to the Schrödinger equation.

$$i\frac{d}{dt}|\psi(t)\rangle = \mathcal{H}(t)|\psi(t)\rangle$$

- Start with $|\psi(0)\rangle$ as the ground state of $\mathcal{H}(0)$.
- If there is a non-zero gap between $|\psi(0)\rangle$ and the next lowest energy level as long as $\mathcal{H}(t)$ varies slowly enough (i.e. little energy is added to the system) $|\psi(t)\rangle$ will remain close to the instantaneous ground state of $\mathcal{H}(t)$.

Application

- Quantum systems evolve according to the Schrödinger equation.

$$i\frac{d}{dt}|\psi(t)\rangle = \mathcal{H}(t)|\psi(t)\rangle$$

- Start with $|\psi(0)\rangle$ as the ground state of $\mathcal{H}(0)$.
- If there is a non-zero gap between $|\psi(0)\rangle$ and the next lowest energy level as long as $\mathcal{H}(t)$ varies slowly enough (i.e. little energy is added to the system) $|\psi(t)\rangle$ will remain close to the instantaneous ground state of $\mathcal{H}(t)$.

Application

- Quantum systems evolve according to the Schrödinger equation.

$$i\frac{d}{dt}|\psi(t)\rangle = \mathcal{H}(t)|\psi(t)\rangle$$

- Start with $|\psi(0)\rangle$ as the ground state of $\mathcal{H}(0)$.
- If there is a non-zero gap between $|\psi(0)\rangle$ and the next lowest energy level as long as $\mathcal{H}(t)$ varies slowly enough (i.e. little energy is added to the system) $|\psi(t)\rangle$ will remain close to the instantaneous ground state of $\mathcal{H}(t)$.

The Magic

- Encode the solution in the ground state of a problem Hamiltonian $\mathcal{H}_P$.
  - Specifying $\mathcal{H}_P$ is easy but finding its ground state is difficult.
- Choose an initial Hamiltonian $\mathcal{H}_B$ whose ground state is easy to find.
- Construct the system:

$$\mathcal{H}(t) = (1 - t/T)\mathcal{H}_B + (t/T)\mathcal{H}_P$$

Where T is a parameter to control the rate at which $\mathcal{H}(t)$ varies. Normalized to $\tilde{\mathcal{H}}(s), 0 \leq s \leq 1$:

$$\tilde{\mathcal{H}}(s) = (1 - s)\mathcal{H}_B + s\mathcal{H}_P$$

The Magic

- Encode the solution in the ground state of a problem Hamiltonian $\mathcal{H}_P$.
  - Specifying $\mathcal{H}_P$ is easy but finding its ground state is difficult.
- Choose an initial Hamiltonian $\mathcal{H}_B$ whose ground state is easy to find.
- Construct the system:

$$\mathcal{H}(t) = (1 - t/T)\mathcal{H}_B + (t/T)\mathcal{H}_P$$

Where T is a parameter to control the rate at which $\mathcal{H}(t)$ varies. Normalized to $\tilde{\mathcal{H}}(s), 0 \leq s \leq 1$:

$$\tilde{\mathcal{H}}(s) = (1 - s)\mathcal{H}_B + s\mathcal{H}_P$$

The Magic

- Encode the solution in the ground state of a problem Hamiltonian $\mathcal{H}_P$.
  - Specifying $\mathcal{H}_P$ is easy but finding its ground state is difficult.
- Choose an initial Hamiltonian $\mathcal{H}_B$ whose ground state is easy to find.
- Construct the system:

$$\mathcal{H}(t) = (1 - t/T)\mathcal{H}_B + (t/T)\mathcal{H}_P$$

Where T is a parameter to control the rate at which $\mathcal{H}(t)$ varies. Normalized to $\tilde{\mathcal{H}}(s), 0 \leq s \leq 1$:

$$\tilde{\mathcal{H}}(s) = (1 - s)\mathcal{H}_B + s\mathcal{H}_P$$

The Magic

- Encode the solution in the ground state of a problem Hamiltonian $\mathcal{H}_P$.
  - Specifying $\mathcal{H}_P$ is easy but finding its ground state is difficult.
- Choose an initial Hamiltonian $\mathcal{H}_B$ whose ground state is easy to find.
- Construct the system:

$$\mathcal{H}(t) = (1 - t/T)\mathcal{H}_B + (t/T)\mathcal{H}_P$$

Where T is a parameter to control the rate at which $\mathcal{H}(t)$ varies. Normalized to $\tilde{\mathcal{H}}(s), 0 \leq s \leq 1$:

$$\tilde{\mathcal{H}}(s) = (1 - s)\mathcal{H}_B + s\mathcal{H}_P$$

Outline

History

- Founded in 1999 by:
  - Haig Farris
  - Geordie Rose (CTO)
  - Bob Wiens (former CFO)
  - Alexandre Zagoskin (Chief Scientist)
- Started as an off-shoot of the University of British Columbia funding academic research in quantum computing.
- Currently located in Burnaby, British Columbia.

Goals

- Find low cost solutions to Quadratic Unconstrained Binary Optimization (QUBO) problems.
  - arXiv:quant-ph/0001106v1 3-SAT
  - NPC controversy
- Equivalent to finding low energy states of classical Ising Hamiltonian:

$$\mathcal{H} = \sum_i h_i \sigma_{zi} + \sum_{ij} J_{ij} \sigma_{zi} \sigma_{zj}$$

- Find a reasonable way to do it

Goals

- Find low cost solutions to Quadratic Unconstrained Binary Optimization (QUBO) problems.
  - arXiv:quant-ph/0001106v1 3-SAT
  - NPC controversy
- Equivalent to finding low energy states of classical Ising Hamiltonian:

$$\mathcal{H} = \sum_i h_i \sigma_{zi} + \sum_{ij} J_{ij} \sigma_{zi} \sigma_{zj}$$

- Find a reasonable way to do it

Goals

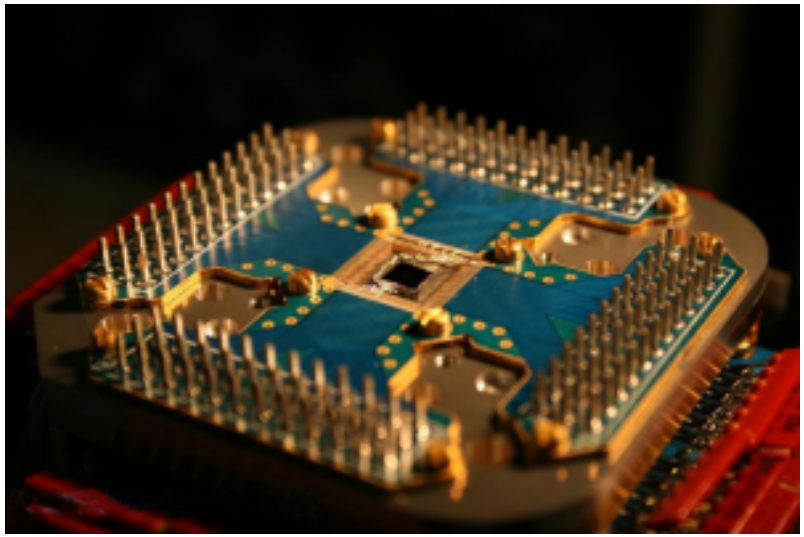
- Find low cost solutions to Quadratic Unconstrained Binary Optimization (QUBO) problems.
  - arXiv:quant-ph/0001106v1 3-SAT
  - NPC controversy
- Equivalent to finding low energy states of classical Ising Hamiltonian:

$$\mathcal{H} = \sum_i h_i \sigma_{zi} + \sum_{ij} J_{ij} \sigma_{zi} \sigma_{zj}$$

- Find a reasonable way to do it

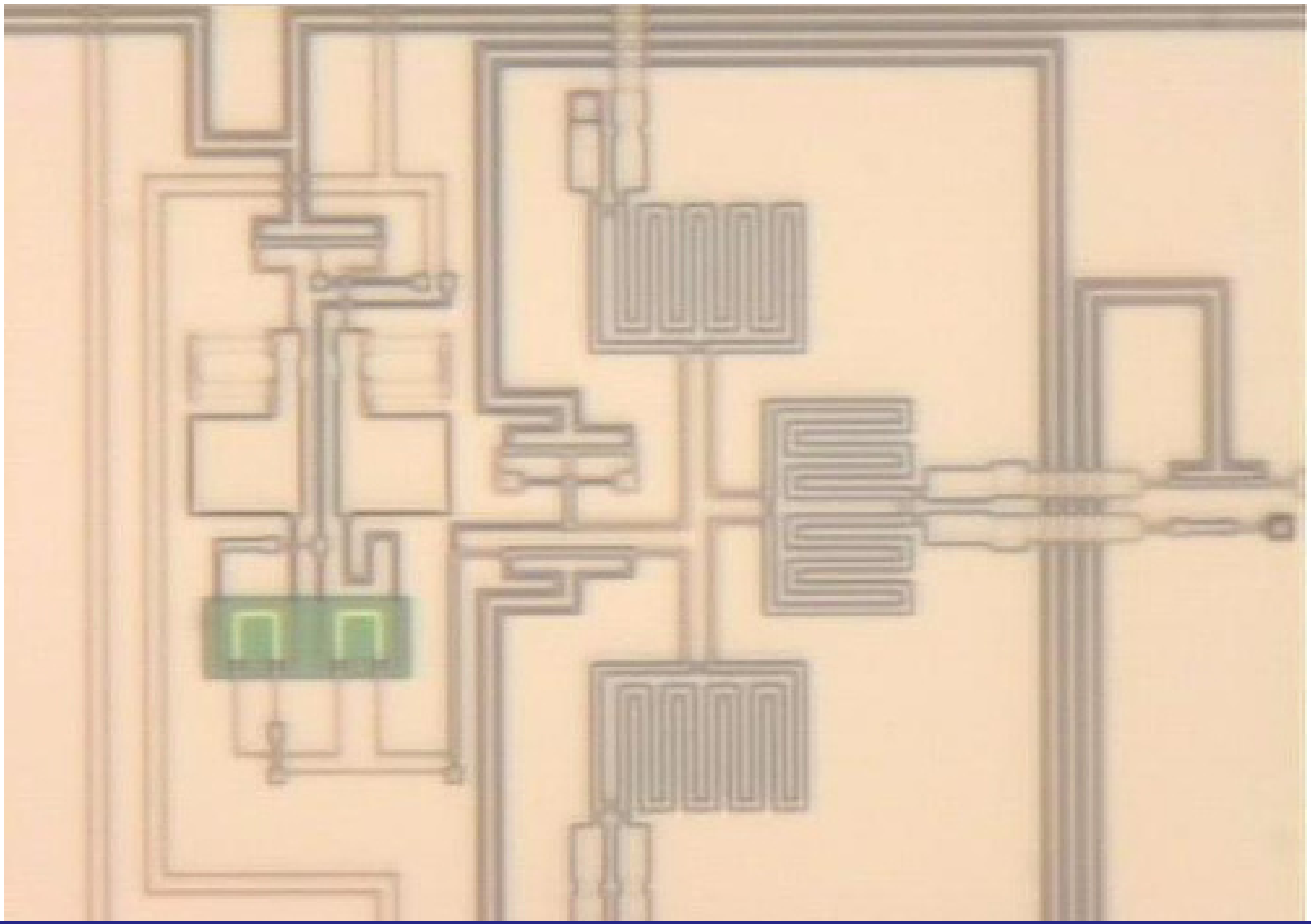
Outline

Infrastructure

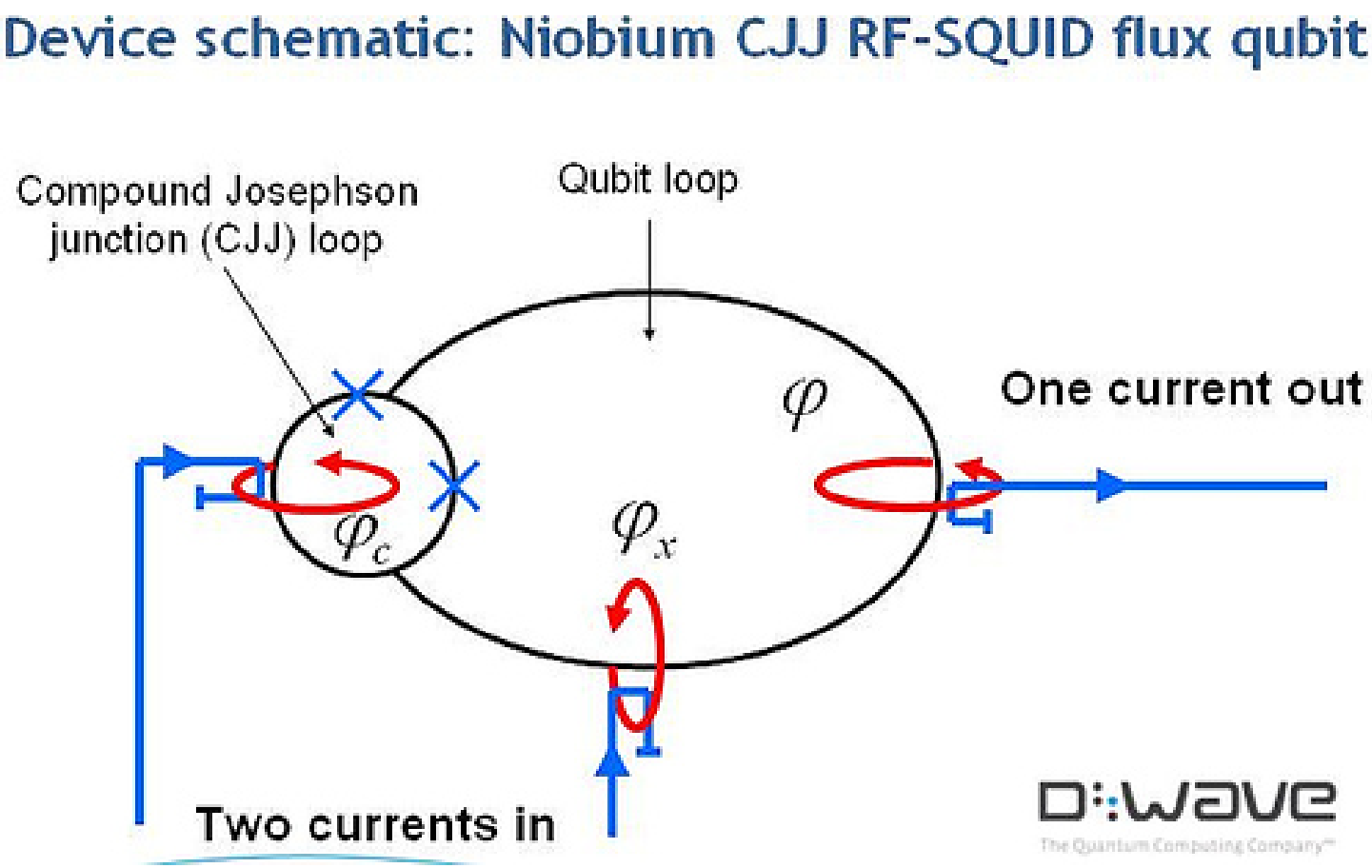


- Superconducting metals operating at ultra low temperatures
- Manufactured with existing fabrication techniques

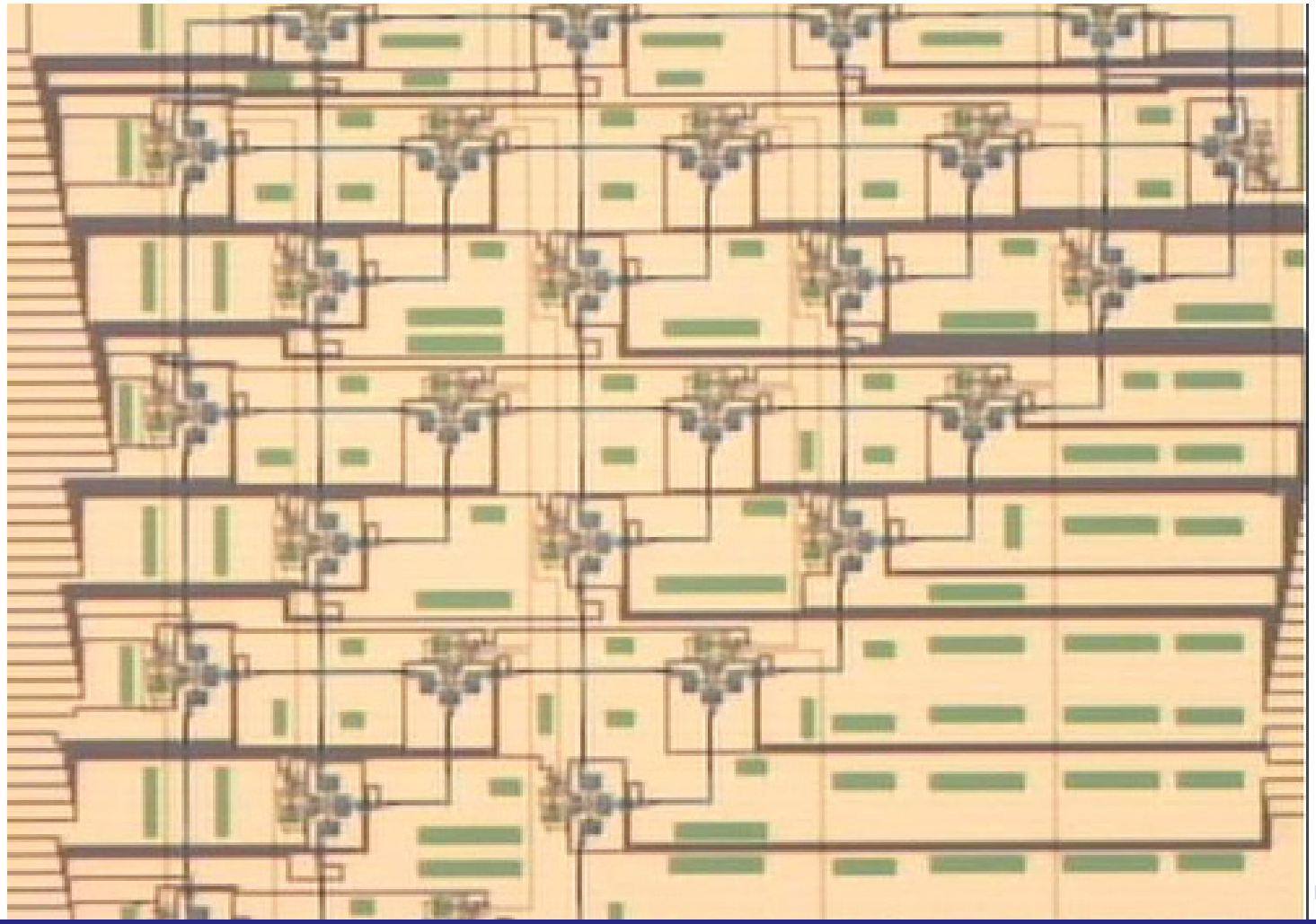
The Qubit



Schematic

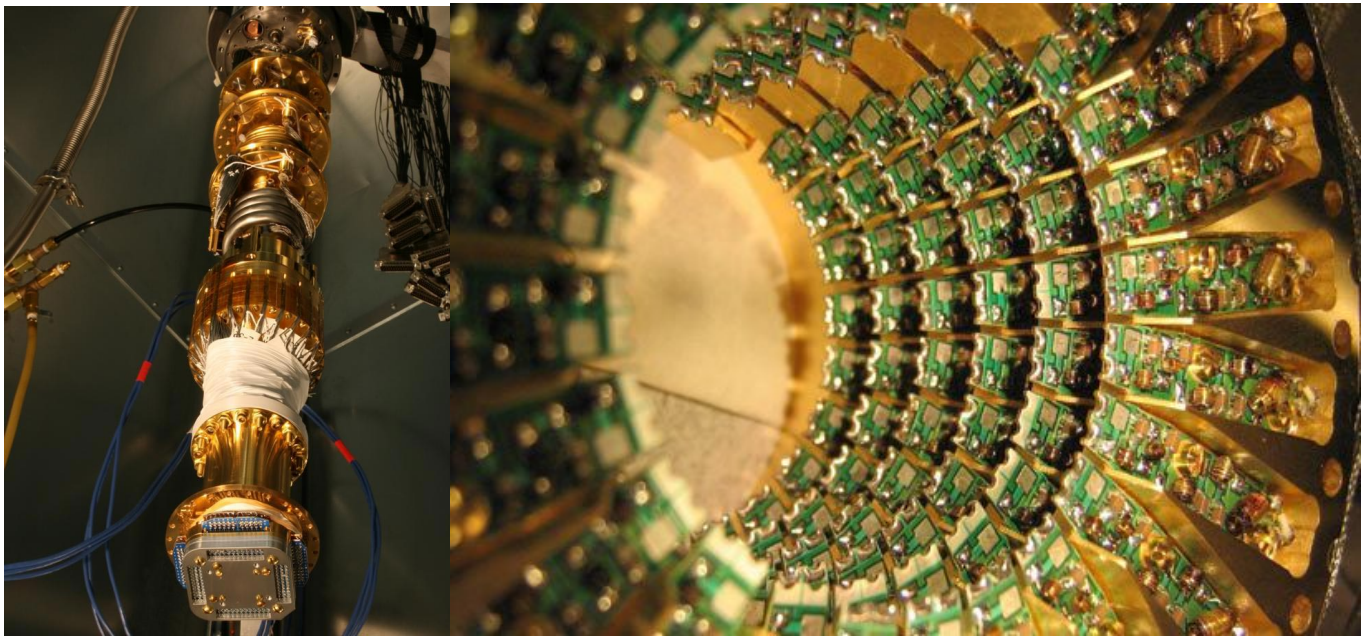

Device schematic: Niobium CJJ RF-SQUID flux qubit
Compound Josephson junction (CJJ) loop
Qubit loop
One current out
Two currents in
φ
φ_c
φ_x
D-Wave
The Quantum Computing Company

System



Outline

Orion



- 16 qubit System
  - www.apps.dwavesys.com
  - Orion web services API

Google's Interest

- Image matching
  - Google Goggles
  - Face Recognition
- Machine learning
  - Recognizing cars

Outline

DiVincenzo

1. A scalable physical system with well characterized qubits
2. The ability to initialize state
3. Long relevant decoherence times
4. Universal set of quantum gates
5. The ability to measure specific qubits

DiVincenzo

1. A scalable physical system with well characterized qubits
2. The ability to initialize state
3. Long relevant decoherence times
4. Universal set of quantum gates
5. The ability to measure specific qubits

DiVincenzo

1. A scalable physical system with well characterized qubits
2. The ability to initialize state
3. Long relevant decoherence times
4. Universal set of quantum gates
5. The ability to measure specific qubits

DiVincenzo

1. A scalable physical system with well characterized qubits
2. The ability to initialize state
3. Long relevant decoherence times
4. Universal set of quantum gates
5. The ability to measure specific qubits

DiVincenzo

1. A scalable physical system with well characterized qubits
2. The ability to initialize state
3. Long relevant decoherence times
4. Universal set of quantum gates
5. The ability to measure specific qubits

Outline

P == NP?

- QUBO $\supset$ P
- Goldstone, Gutmann, and Sipser adiabatic algorithmic solution for 3-SAT
- Aharonov, van Dam, et al. adiabatic quantum computation is equivalent to standard quantum computation (NMR)
- Problems with simulated annealing
  - QUBO solutions are only NP-Hard

P == NP?

- QUBO $\supset$ P
- Goldstone, Gutmann, and Sipser adiabatic algorithmic solution for 3-SAT
- Aharonov, van Dam, et al. adiabatic quantum computation is equivalent to standard quantum computation (NMR)
- Problems with simulated annealing
  - QUBO solutions are only NP-Hard

P == NP?

- QUBO $\supset$ P
- Goldstone, Gutmann, and Sipser adiabatic algorithmic solution for 3-SAT
- Aharonov, van Dam, et al. adiabatic quantum computation is equivalent to standard quantum computation (NMR)
- Problems with simulated annealing
  - QUBO solutions are only NP-Hard

Summary

- Adiabatic quantum computation is feasible because of long decoherence times.
- Systems can be built with existing manufacturing techniques.
- The Chimera C4 chip has been demonstrated successfully.
- The actual quantum nature of the system is controversial.

- Outlook
  - D-Wave has yet to produce a fully entangled system due to bus connectivity issues.
  - The backend of Orion is still a simulation but should be up and running soon.

More Resources I


D. Aharonov, W. vanDam, J. Kempe, Z. Landau, S. Lloyd, O. Regev
Adiabatic Quantum Computation is Equivalent to Standard Quantum Computation.
arXiv:quant-ph/0405098v2,2005.


D. DiVincenzo.
The Physical Implementation of Quantum Computation.
arXiv:quant-ph/0002077v3,2000.


E. Farhi, J. Goldstone, S. Gutmann, M. Sipser
Quantum Computation by Adiabatic Evolution.
arXiv:quant-ph/0001106v1,2000.

More Resources II


R. Harris et al.
Experimental Demonstration of a Robust and Scalable Flux Qubit
arXiv:0909.4321v1 [cond-mat.supr-con],2009.


H. Neven
Machine Learning with Quantum Algorithms
http://googleresearch.blogspot.com/2009/12/machine-learning-with-quantum.html,2009.


G. Rose
rose.blog
http://dwave.wordpress.com/

More Resources III


H. Neven, G. Rose
Google Tech Talks: Quantum Computing
http://www.youtube.com/watch?v=I56UugZ8DIfeature = channel, 2007.


D-Wave Systems Inc.
http://www.dwavesys.com/