ETH zürich

D-Wave Quantum Annealer

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A Different Quantum Device

- Physical quantum annealer (not a GMQC)
- Solves optimization problems (no algorithms)
- Commercial product
- Mature technology with large number of qubits (>1000)

Outline

Ising Spin Glass Problem

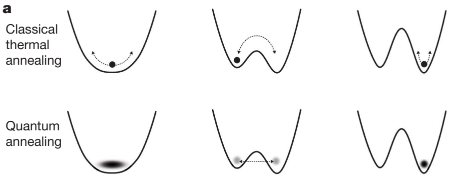
Ising spin glass Hamiltonian

$$H = -\sum_{i<j} J_{ij}\sigma_i^z\sigma_j^z - \sum_i h_i\sigma_i^z$$

- J_{ij}: couplings between spins
- h_i: local fields
- σ_i^α: Pauli matrix σ^α applied to spin i

Find the ground state of this Hamiltonian (NP Hard)

Quantum Annealing



- Start in coherent superposition
- Add time–dependent quantum fluctuations to Ising Hamiltonian

$$H(t) = -A(t) \sum_i \sigma_i^x + B(t) H_{\text{Ising}}$$

($A(t)$ decreases with increasing time, $B(t)$ increases)

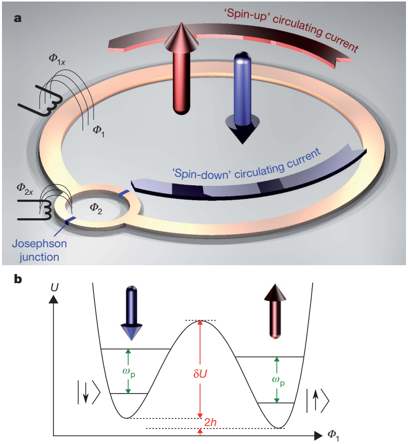
- Change A and B slowly; should remain in ground state
- Do not have to protect excited state from environment

Realizing a Quantum Annealer

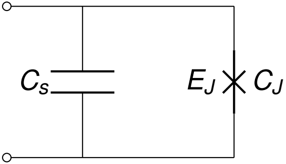
Does not map onto anything we have seen so far

We want something like the figure

- Spin states: Two rotating currents
- h_i: tunable well offset (Φ_{1x})
- Annealing: tunable barrier height (Φ_{2x})

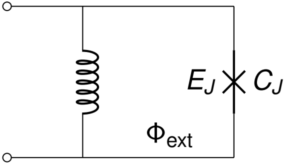


A New Type of Qubit



Transmon Qubit

- Capacitively shunted Josephson junction
- Relevant parameter: number of Cooper pairs on the island



Flux Qubit

- Inductively shunted Josephson junction
- Relevant parameter: magnetic flux (or phase)
- Persistent rotating currents

Hamiltonians

Charge Qubit

$$H_C = 4E_C(\hat{n} - n^x)^2 - E_J \cos(\varphi)$$

Flux Qubit

$$H_F = 4E_C n^2 - E_J \cos(\hat{\varphi}) + \frac{1}{2}E_L(\hat{\varphi} - \varphi^x)^2$$

- E_J: Josephson energy ($E_J = I_c\Phi_0/2\pi$)
- E_C: Coulomb energy ($E_C = e^2/2C_\Sigma$)
- E_L: Inductor energy ($E_L = \left(\frac{\Phi_0}{2\pi}\right)^2 \frac{1}{L}$)
- n^x, φ^x: external voltage or flux bias

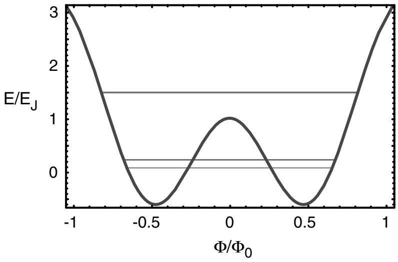
Shifted Cosine Potential

Fixed offset

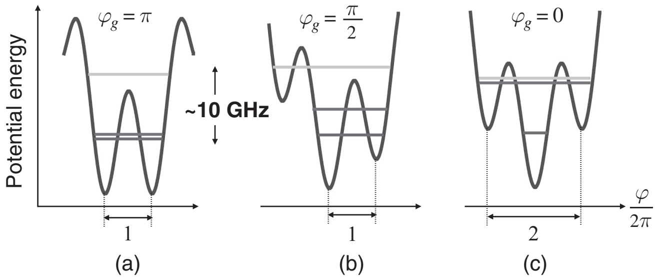
$$H_F = \boxed{4E_C n^2} - \boxed{E_J \cos(\hat{\varphi}) + \frac{1}{2}E_L(\hat{\varphi} - \varphi^x)^2}$$

Interesting physics

$\varphi^x = \pi$



Tunable Potential Minima

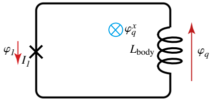


- Changing φ^x ($\equiv \varphi_g$) shifts cosine relative to quadratic; changes the shape of the potential
- Flux qubit can change well offset (h_i in Ising Hamiltonian) through biasing external flux
- Changing E_J could turn cosine on and off (tunable barrier)

RF–SQUID

- Simple flux qubit (a) also known as RF–SQUID
- Shifts well offset through φ_q^x
- Need many identical qubits for quantum computer
- Hard to make uniform Josephson junctions (exponential dependence on oxide thickness)
- Want to change E_J *in situ*

(a)



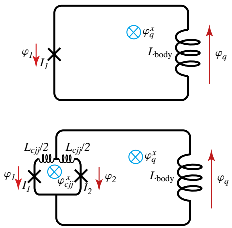
Compound Josephson Junction

- CJJ (b) replaces JJ with SQUID
- Two Josephson junctions that behave as single tunable junction
- Tunes I_c (E_J) through extra external flux term φ^x_{cjj}
- If these junctions are asymmetric, we get complicated interdependence

$$\cos(\varphi^x_q) \mapsto \cos(\varphi^x_q - \varphi^x_{q0}(\varphi^x_{cjj}))$$

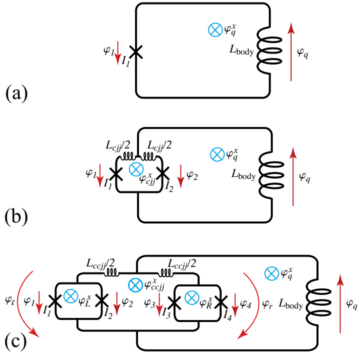
(a)

(b)



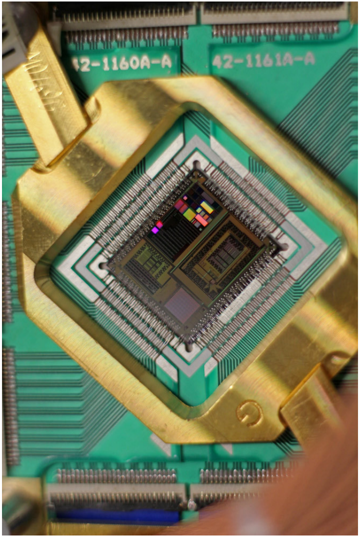
Compound–Compound Josephson Junction

- CCJJ (c) replaces each JJ in CJJ with a SQUID
- Tunes barrier height via φ^x_{ccjj}, just like CJJ
- Balances left and right loops with static flux offsets (φ^x_L and φ^x_R)



From Qubit to Quantum Processor

- Big difference between CCJJ and processor
- Still need coupling, readout, and tuning
- Utility of the flux qubit (tunable inductive coupling)
- Interesting aspects of commercial engineering



So Far

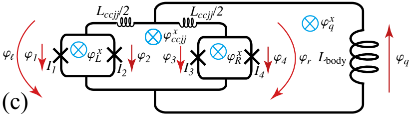
We want a processor that can anneal an Ising spin glass. Currently, we have a qubit that can control the following:

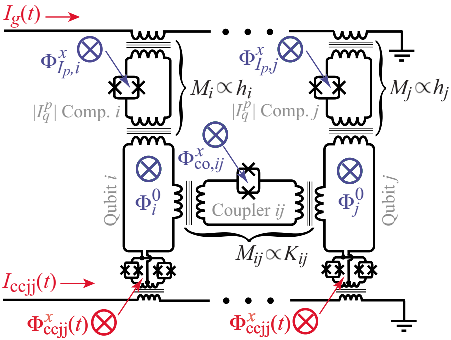
$$H(t) = \underbrace{\boxed{-A(t)\sum_i \sigma_i^x}}_{\text{Barrier Height } (\varphi^x_{ccjj})} - B(t)\left[\sum_{i<j} J_{ij}\sigma_i^z\sigma_j^z + \underbrace{\boxed{\sum_i h_i\sigma_i^z}}_{\text{Well Offset } (\varphi^x_q)}\right]$$

We need to add couplings J_{ij}

Coupling and Tuning

- Top portion: Well offset control (φ_q^x); single control line plus individual couplers
- Middle: qubits and qubit inductive couplers (J_{ij})
- Bottom: Barrier height control (φ_{ccjj}^x)
- Not shown: *L* tuner, to homogenize inductance between qubits
- All individual offsets stored in *Permanent Magnetic Memory*





Single Flux Quantum Readout

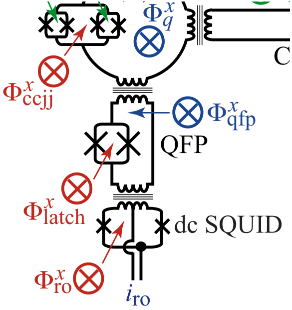
Quantum Flux Parametron

RF–SQUID

- Locks the final qubit state based on external control
- Insulates qubit from readout measurement

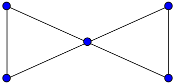
DC–SQUID

- Sensitive flux detector
- Reads state of QFP
- Produces unwanted microwave signals

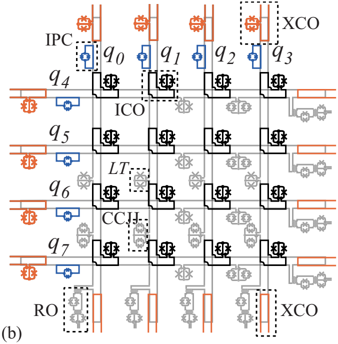


Medium Connectivity

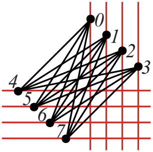
- Eight qubits in a block
- Each qubit attached to four interblock qubits and two extrablock qubits (red)
- Bipartite complete connectivity graph $K_{4,4}$
- Nonplanar (NP–Hard Ising)



Planar graph



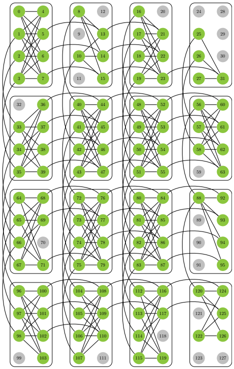
(b)



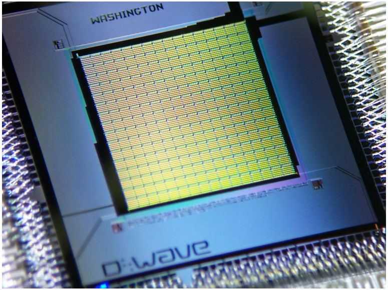
(c)

Larger Connectivity

Tile the blocks of qubits

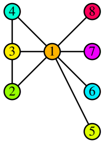


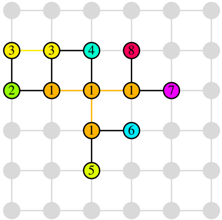
“Chimera” graph



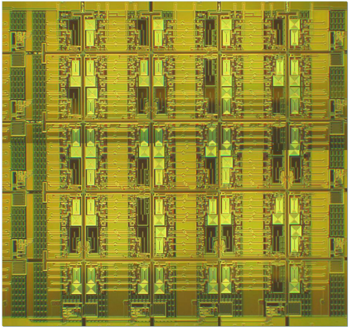
Connectivity Generality

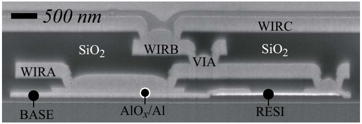
- Does this connectivity limit the problems we can solve?
- No, as long as each qubit is connected to at least three others
- Map the logical connectivity (left) onto physical qubits (right)
- Ferromagnetic coupling binds logical qubit
- Can affect annealing times





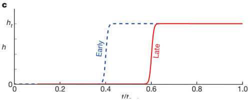
Physical Construction



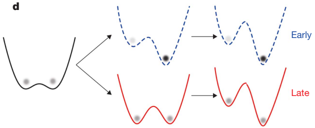


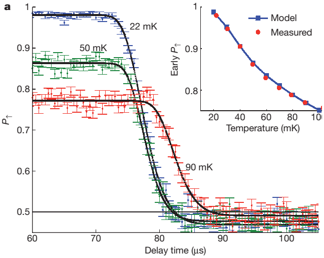
- Multilayer Nb superconducting IC process
- Extremely low noise despite dense, complex circuitry
- Superconducting boxes around each qubit
- Top: Optical image, qubits, PMM visible
- Bottom: SEM image, wiring layers visible

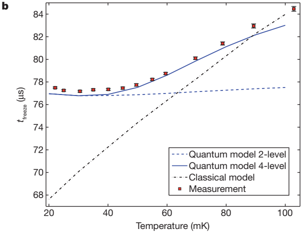
Quantum Bit Properties



- Start annealing
- Apply well offset term suddenly
- Measure probability of system reaching the ground state
- Calculated freezing time
- Look at temperature dependence

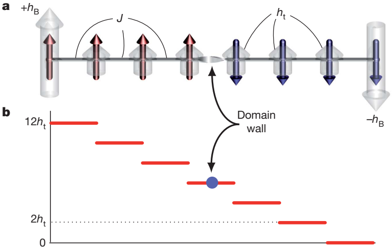


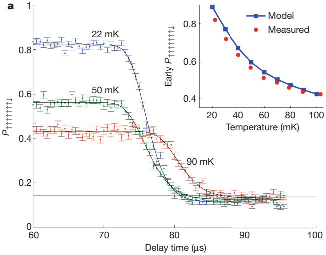


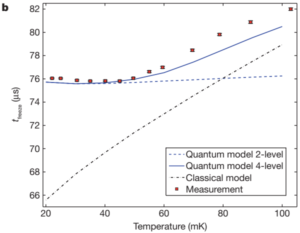


Quantum Bit Properties

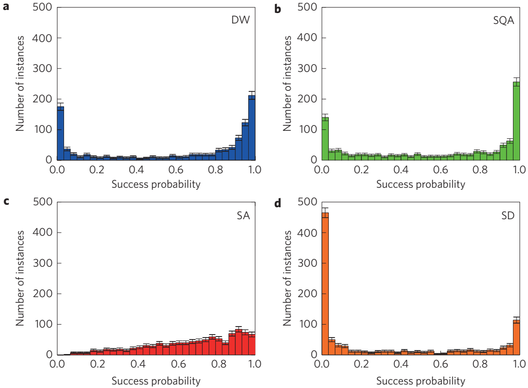
- Look at eight qubits
- Frustrated Ising spin chain
- Same results







Verification of Quantum Annealing



Histograms of solution success probabilities of D-Wave, Simulated Quantum Annealing, Simulated Annealing, and Spin Dynamics

Future Directions

- Possibility of optimizing the problem layout for the chimera connectivity
- Increase number of qubits
- Expand possible Hamiltonians (Adiabatic quantum optimization for general Hamiltonians is universal, maps to GMQC)

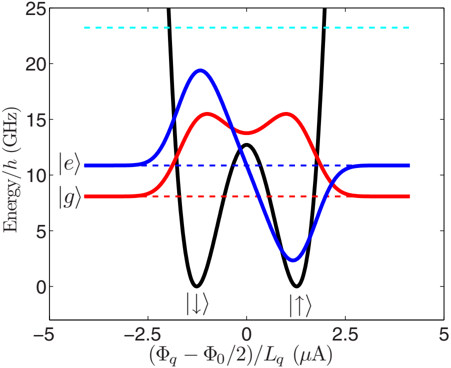
Conclusions

- D-Wave has built a functioning quantum annealer
- Scalable to large numbers of qubits
- Extremely well–engineered qubits and infrastructure
- Speedup has not been robustly demonstrated
- Questions about how quantum the device is (may be thermal annealer for certain problems)

References

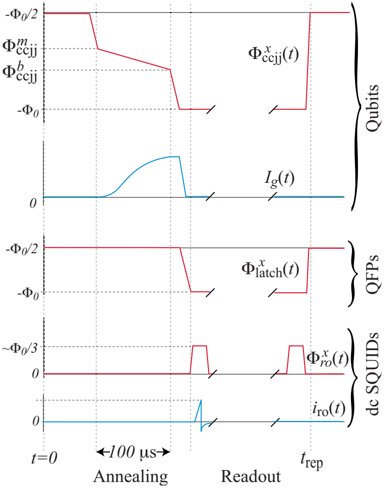
- S. Boixo *et. al.*, *Evidence for quantum annealing with more than one hundred qubits*, Nature Physics **10**, 218-224 (2014)
- V. Choi, *Minor–embedding in adiabatic quantum computation: I. The parameter setting problem*, Journal of Quantum Information Processing **7**, 193-209 (2008)
- R. Harris *et. al.*, *Experimental investigation of an eight–qubit unit cell in a superconducting optimization processor*, Physical Review B **82**, 024511 (2010)
- R. Harris *et. al.*, *Experimental demonstration of a robust and scalable flux qubit*, Physical Review B **81**, 134510 (2010)
- M. W. Johnson *et. al.*, *Quantum annealing with manufactured spins*, Nature **473**, 194-198 (2011)

Basis



- $|e\rangle$ and $|g\rangle$ are energy eigenstates of the Hamiltonian
- Long coherence times, but not ideal for qubit interactions
- Use persistent current basis

Time Trace and Control Signals



Phase and Flux

Second Josephson equation

$$V = \frac{\hbar}{2e} \frac{\partial \delta}{\partial t}$$

Faraday's law of induction

$$\mathcal{E} = -\frac{\partial \Phi}{\partial t}$$

So, we get

$$\varphi = 2\pi \frac{\Phi}{\Phi_0}$$