Quantum Annealing, what is it?

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AtMol group meeting

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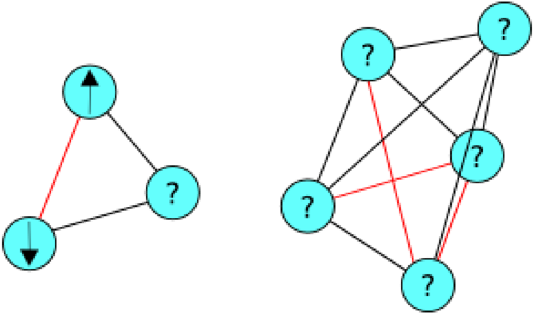
First what it isn't...

- It is not Universal Quantum computing!
- Instead aim is to find the lowest energy state of an Ising spin glass

$$H_{ISG} = \sum_{i} h_i \, \sigma_i^z + \sum_{i,j} J_{ij} \, \sigma_i^z \sigma_j^z$$



- But why does anyone want to do this...

(Why) do people care about this problem?

- Lockheed Martin and Google each spent ∼$10 million (US) on a machine to solve it (D-Wave)
- NP-complete problem, a hard problem which all problems can be mapped 'efficiently'[1] onto
- Want to solve hard problems faster using quantum mechanics ex. :
  - LM → verification & validation
  - Google → machine learning
  - NASA→schedule optimization

Will return to applications later

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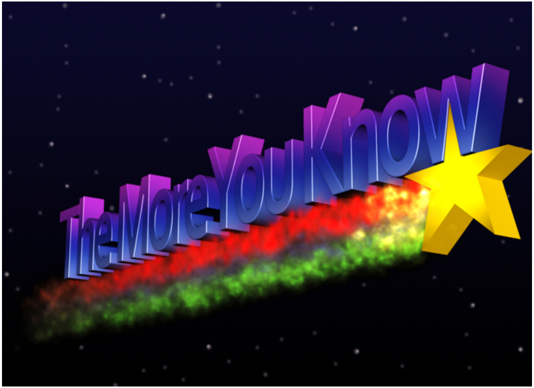
[1] Theorist definition of efficently, mapping scales polynomially with size

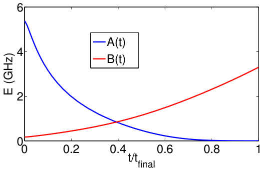
A quick, but important, technical note: (PSA to try to kill a common myth)

faster $\neq$ polynomial time

Problems will still be hard, but we can (maybe) do better using QM



Quantum Annealing



$$H = -A(t) \sum_i h_i \sigma_i^x + B(t) \left(\sum_i h_i \sigma_i^z + \sum_{i,j} J_{ij} \sigma_i^z \sigma_j^z \right)$$

$$[\sigma^z, \sigma^x] \neq 0 \;\therefore$$

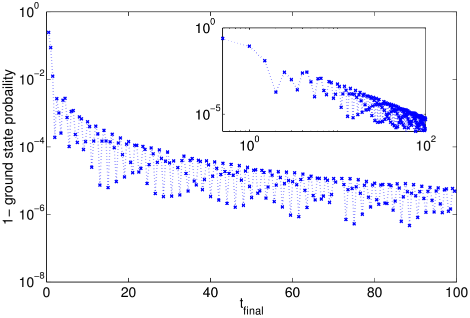
$A(t=0) \gg B(t=0) \rightarrow$independent classical spins

$A(t_{final}) \ll B(t_{final}) \rightarrow$classical Ising spin glass

$A(t) \approx B(t) \rightarrow$complicated quantum spin glass

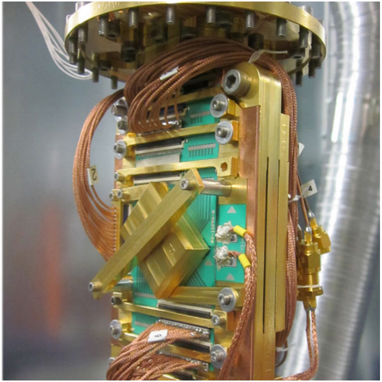
How does this work? (closed quantum system)

- Adiabatic theorem of quantum mechanics
  - slow evolution keeps system in ground state
  - phase oscillations between ground and excited states faster then annealing rate → destructive interference

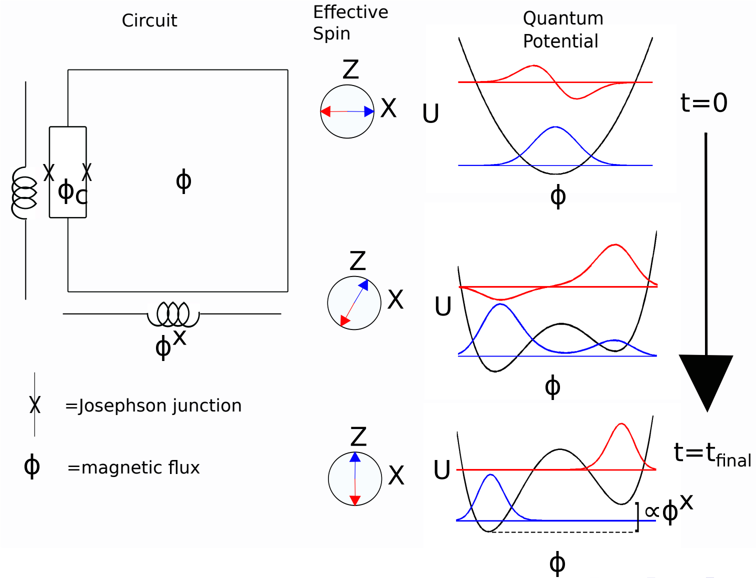


How does this work? (open quantum system)

- 2nd law of thermodynamics
  - Interference effects may be ruined by dephasing but...
  - themalizing at low T → high probability of finding lowest energy
  - Boltzmann distribution may be more useful then lowest energy state! (will come back to this)

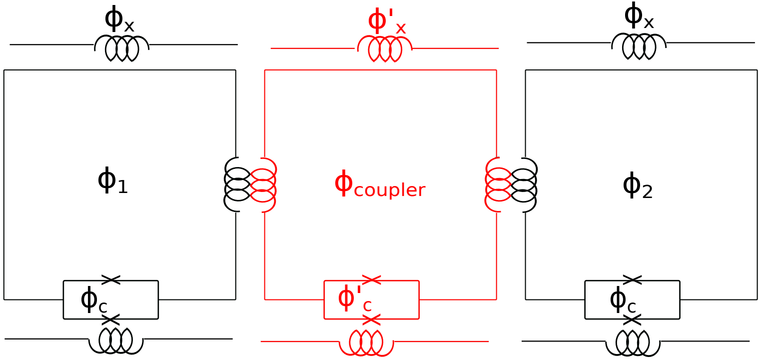


How to actually build an annealer: (D-Wave) artificial spin (aka qubit)



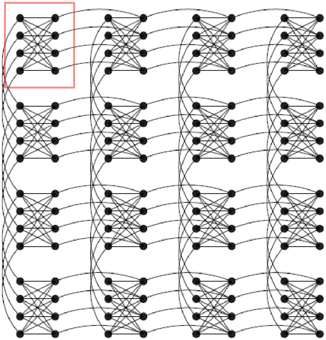
How to actually build an annealer: (D-Wave) coupler

1. Bias coupler circuit to monostable regime (ϕ'_c)
2. Inductively couple to two other qubits
    - Energy penalty function of total external flux (↓↑ and ↑↓ have same E)
    - Sign and magnitude controlled by ϕ'_x
3. Bias 'spins' so ↓↓ and ↑↑ state have the same energy (ϕ_x)



How to actually build an annealer: hardware graph

- Ideally want fully connected
- Not realistic in practice
- Non-planar graphs support hard problems ex: Chimera graph[2]



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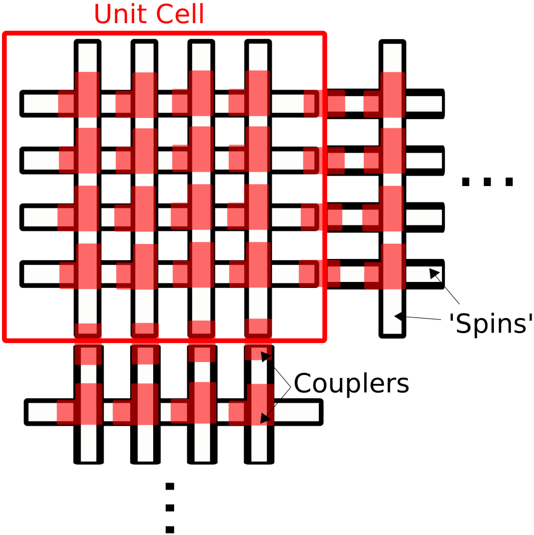
[2] Note that a fully connected graph can be mapped to a chimera with 'minor embedding'

How to actually build a chimera: D-Wave layout

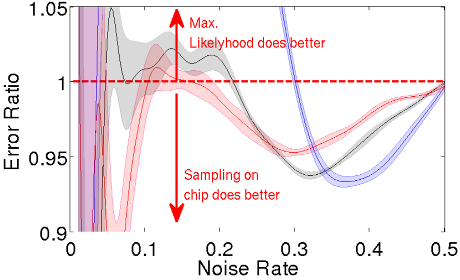


So you have a quantum annealer, what do you do with it?

1. Benchmark it - very hard
    1.1 Even difficult to make hard problems, random chimeras are 'easy'
    1.2 What do you compare it with?
    1.3 Likely application dependent
2. Come up with new applications
    2.1 Find new optimization problems which map well
    2.2 Thermal sampling
3. Try to make it better
    3.1 Better hardware graphs
    3.2 Reduce noise etc...
4. Do physics
    4.1 Incredibly complex quantum system with lots of tuning knobs

Thermal Sampling, why is this useful?

- Graph isomorphism - isomorphic graphs have the same spectrum
- Boltzmann machines- train neural networks with 'thermal like' activation rules
- Maximum entropy Bayesian inference- ex. message decoding

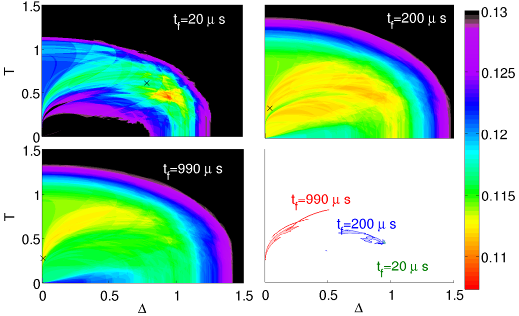


Max.
Likelyhood does better

Sampling on
chip does better

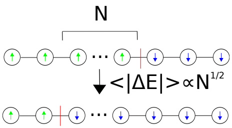
Physics study 1

- Freezing in mid evolution dynamics
- Plot of difference from exact diagonalization (ED) result

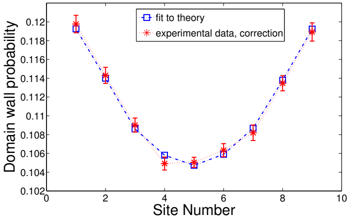


Physics study 2

- Order-by-disorder effect on domain walls
  - control error in fields creates effective correlated noise for forced domain wall



- Correlation in noise leads to counter-intuitive U shaped domain wall distribution



Acknowledgements

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- Experimental data taken on Lockheed Martin D-Wave chip at University of Southern California Information Science Institute
- References: please ask after if you are interested