CSCI 4140
Quantum Annealers

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Introduction

- The most esoteric of the technologies that we will examine
- Also know the least amount about it
- The general approach is adiabatic quantum computing
- This appears to be quite powerful, but it’s theoretical, there are no implementation
- Quantum annealing is a special case, don’t know how powerful it is, but it has been implemented

Adiabatic Quantum Computing

- This quickly gets very theoretical, will just do a basic overview
- Based on the quantum Hamiltonian, an operator that represents the total energy in the system
- Start with a collection of superimposed random qubits, cooled to close to 0K
- Hamiltonian for this is well known, places the qubits in the ground energy state
- This is the starting point for our computation

Adiabatic Quantum Computing

- Next we formulate a Hamiltonian that corresponds to the solution to our problem, we want this to be the final start of our computation
- The idea is to slowly evolve the initial Hamiltonian to the final Hamiltonian keeping the entire system in the ground state during the whole process
- At the end of the final state is measured causing it to collapse, giving us a standard digital response
- The real problem is formulating the Hamiltonian for the solution

Quantum Annealing

- In quantum annealing we fix the form of the Hamiltonian, have one that can reasonably be implemented in hardware
- All the variable become binary, easier to map them onto qubits
- The complete Hamiltonian we will use is:

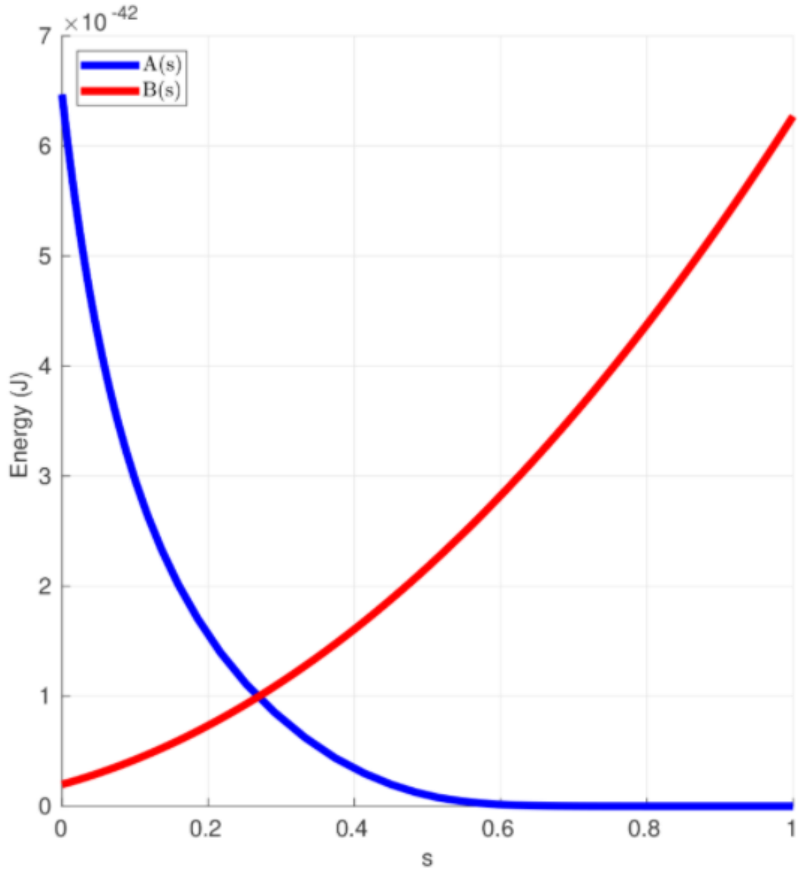
$$\mathcal{H}_{ising} = \underbrace{-\frac{A(s)}{2}\left(\sum_i \hat{\sigma}_x^{(i)}\right)}_{\text{Initial Hamiltonian}} + \underbrace{\frac{B(s)}{2}\left(\sum_i h_i \hat{\sigma}_z^{(i)} + \sum_{i>j} J_{i,j} \hat{\sigma}_z^{(i)} \hat{\sigma}_z^{(j)}\right)}_{\text{Final Hamiltonian}}$$

- Here $\hat{\sigma}_x$ and $\hat{\sigma}_z$ are the corresponding Pauli matrices

Quantum Annealing

- The h_i and the $J_{i,j}$ come from the problem to be solved
- The A(s) and B(s) are called the annealing schedule and typical values are shown on the next slide
- At the start of the process B(s) is close to 0 and A(s) is at its maximum value, this corresponds to the initial Hamiltonian, which is the start of the computation
- Over time A(s) decreases and B(s) increases, at the end we have reached our final Hamiltonian, which is the solution
- This takes on the order of 10msec to 100msec

Quantum Annealing



Quantum Annealing

- Since the process is statistical there is no guarantee that the end state will be the best solution
- The whole process is run multiple times, typically 100, and the best result is selected
- There are two main ways of formulating the Hamiltonian, we will just examine one of them
- They basically differ in the values assigned to the variables, which are still basically binary

Quantum Annealing

- The formulation we will examine is quadratic unconstrained binary optimization (QUBO)
- This is written in the following way, here $Q_{i,j}$ is an n x n matrix:

$$f(x) = \sum_{i} Q_{i,i} x_i + \sum_{i<j} Q_{i,j} x_i x_j$$

- The problem is to find the minimum value of f(x)
- There are a large number of important problems that can be formulated in this way

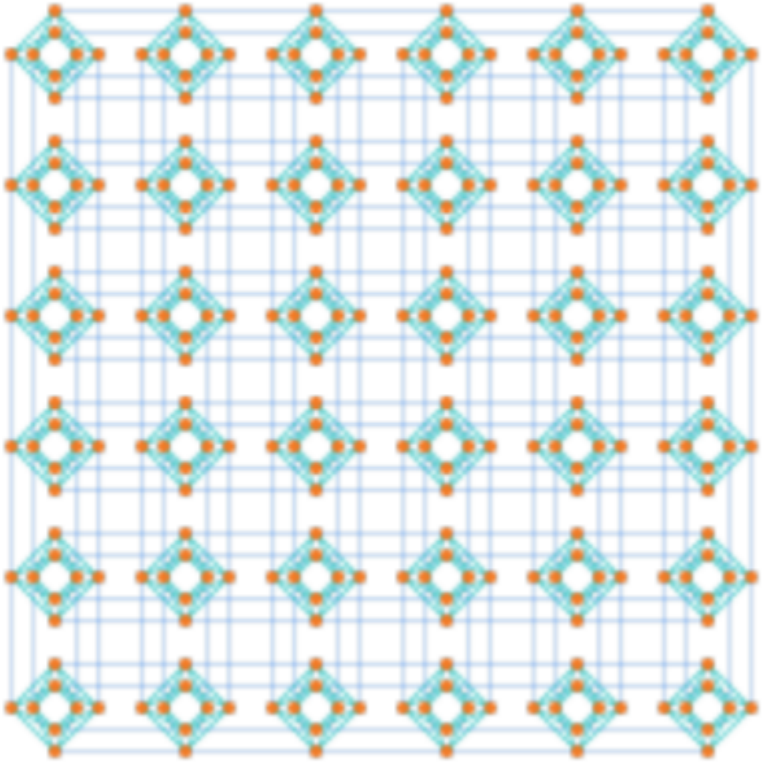
D-Wave

- D-Wave is a company in Vancouver that produces commercial quantum annealing computers, they have been selling them for about 8 years and have gone through several generations
- These are not universal quantum computers, they basically solve QUBO problems, which are an important class of problems
- If you have a spare $5M or so, you can buy one yourself
- Their latest generation has 5000 qubits, but we don’t have the same level of control over these qubits

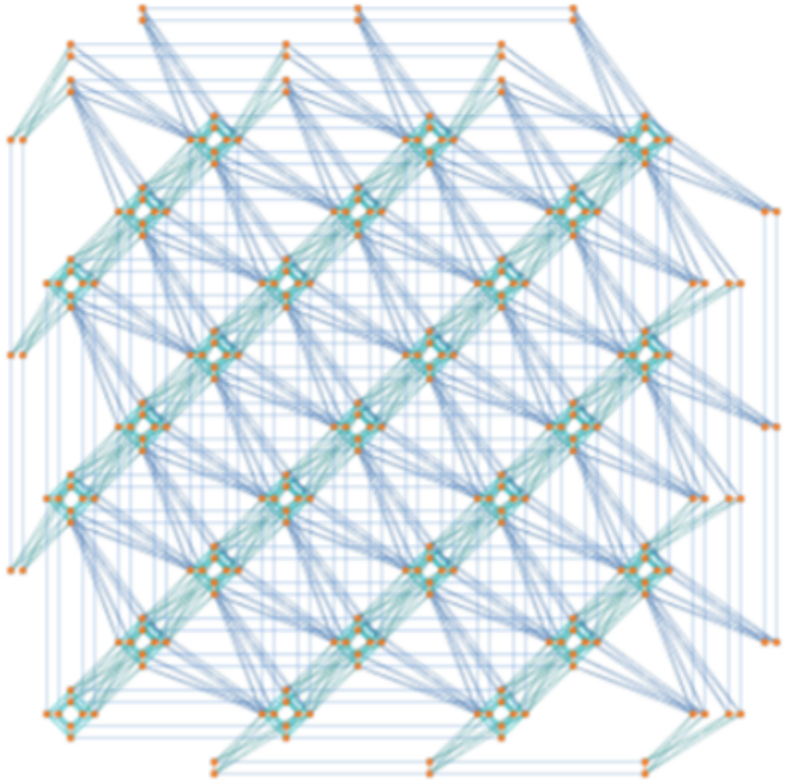
D-Wave

- For a complete quantum annealer, all the qubits need to be connected, this isn’t the case with the D-Wave system, this is almost impossible to implement
- Instead there is limited connections between qubits
- In addition, there is noise in their systems, D-Wave uses a form of replication code called chaining, link together a chain of physical qubits to form a logical qubit
- The connections between qubits are called couplers
- The two recent architectures are Chimera and Pegasus

D-Wave



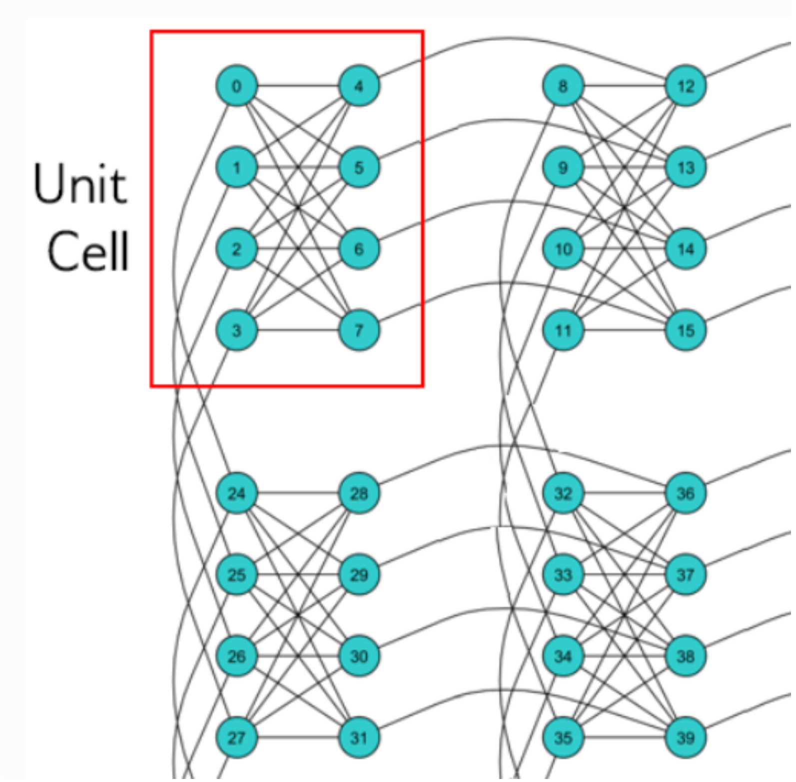
Chimera



Pegasus

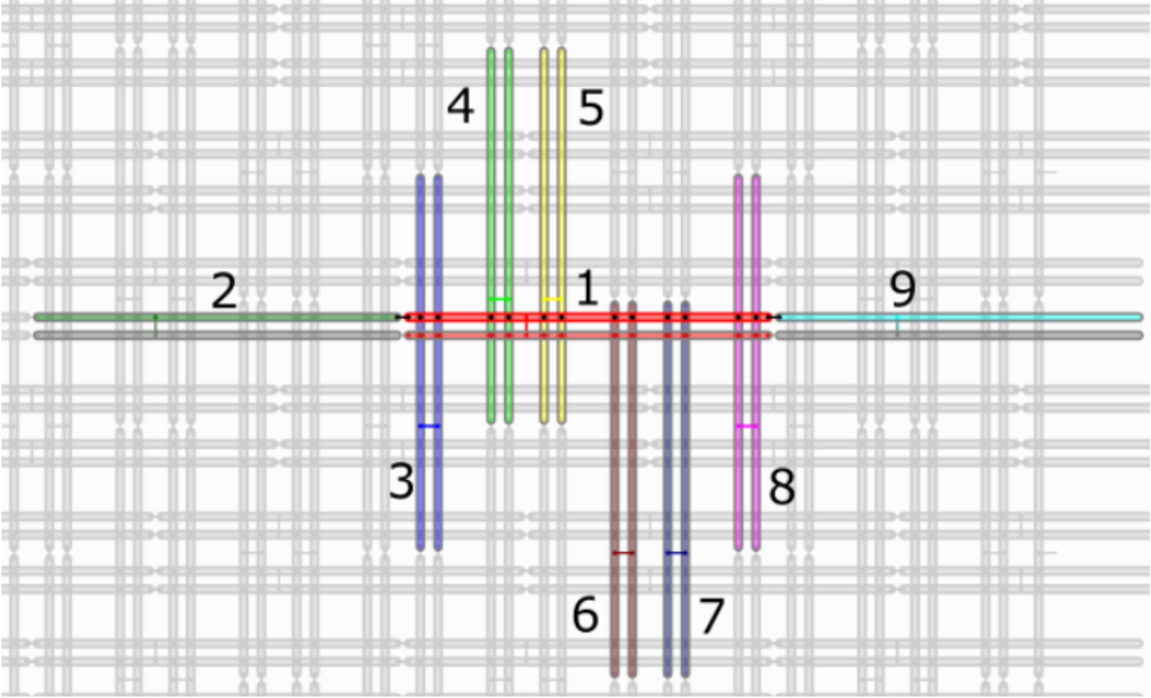
D-Wave

- In the case of Chimera, each qubit is connected to 6 other qubits, 4 in its local cell, and 2 in neighbouring cells



D-Wave

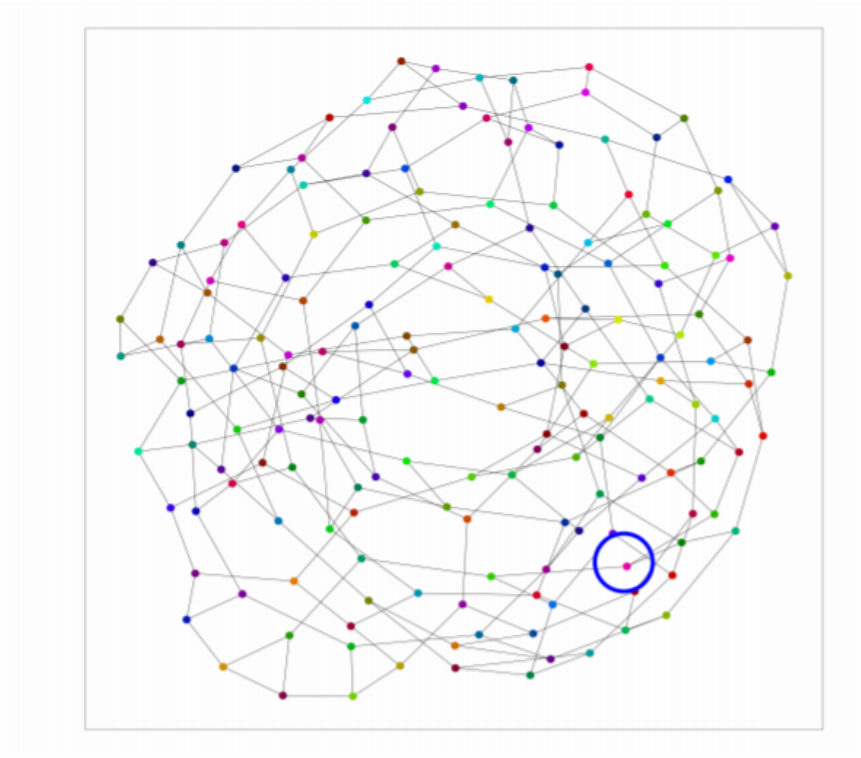
- For Pegasus, each qubit is connected to 15 other qubits in a more general way



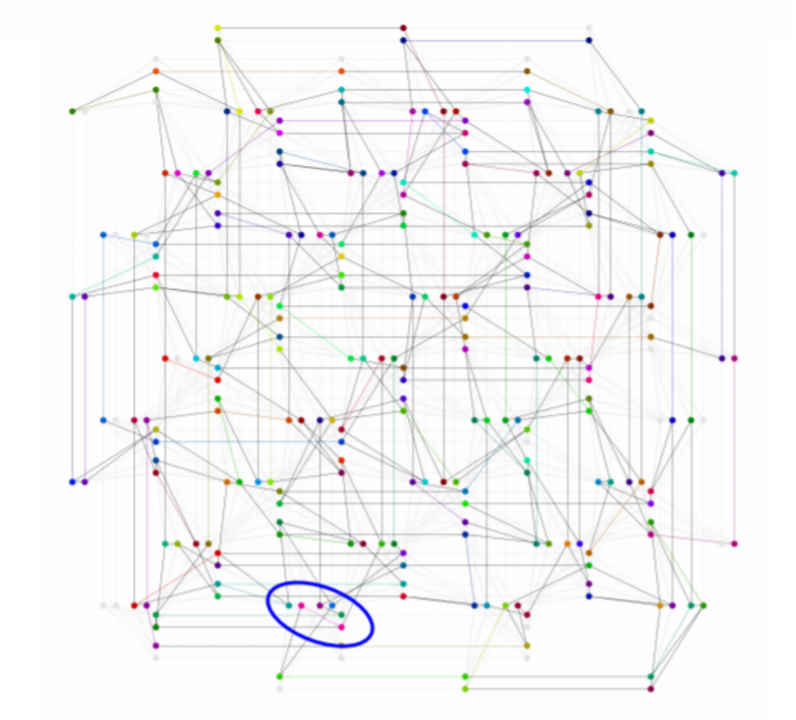
D-Wave

- The main issue with programming is mapping the graph for the problem, defined by the Q matrix onto the available qubits
- The problem graph may have more connectivity than the hardware graph, which makes this mapping more difficult
- This could result in a large number of wasted qubits
- With the 5000 qubits in Pegasus, chains are at least 5 qubits long, so 1000 possible graph nodes, but the problem structure could reduce this to a few hundred or less

D-Wave



Problem Graph



Physical Graph

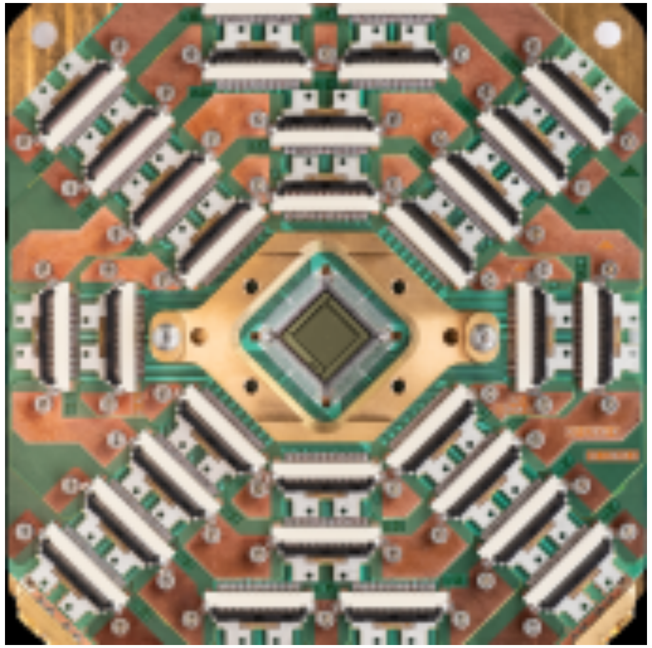
D-Wave

- There is no information on how the qubits are implemented, there is little technical information, besides what’s needed for programming
- One the problems with this approach is the large number of parameters that need to be tuned for each application
- The documentation gives some guidance, but there appears to be a process of fine tuning required to get a final solution
- They have a programmer’s guide on just setting and tuning the parameters

D-Wave

- D-Wave provide a programming system called Ocean for developing applications for there hardware
- They have a number of visualization that assist with debugging and parameter tuning
- They have computers on the net, which you can access for a fee, there is a small amount of free time

D-Wave



Summary

- Of the four major approaches this is the least popular, not a lot is known about it
- It is quite complicated mathematically
- D-Wave produces commercial systems that have been used to solve real world problems, unfortunately they are quite secretive
- I don’t believe a number of the claims that they make, they provide no justification for them