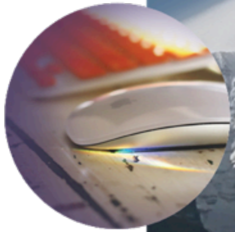
HETEROGENEOUS QUANTUM COMPUTING FOR SATELLITE OPTIMIZATION

GIDEON BASS

BOOZ ALLEN HAMILTON

September 2017



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AGENDA

+ Quantum Annealing in the field
+ Problem Statement
+ Results
+ Conclusions

QUANTUM ANNEALING HAS MANY REAL-WORLD APPLICATIONS

HOWEVER MOST RESEARCH HAS BEEN THEORETICAL

On the readiness of quantum optimization machines for industrial applications

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...monstrate that quantum annealing and, in particular, quantum anneal-
...the potential to outperform current classical optimization algorithms
...he benchmarking of these devices has been controversial. Initially,
...however, these were quickly shown to be not well suited to detect
...chmarking shifted to carefully crafted synthetic problems designed

Traffic flow optimization using a quantum annealer

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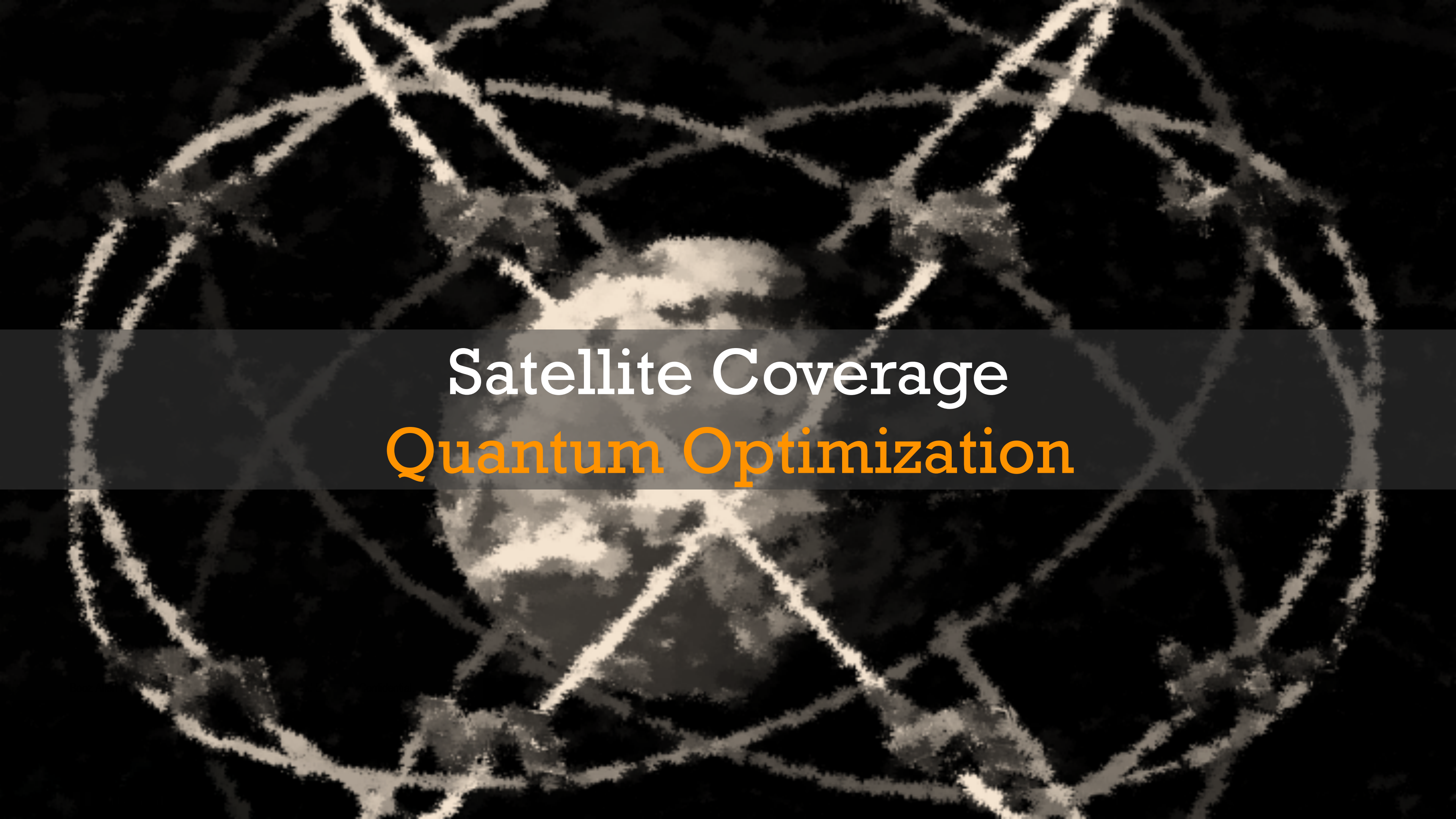
Abstract

Quantum annealing algorithms belong to the class of meta-heuristic tools, applicable for solving binary optimization problems. Hardware implementations of quantum annealing, such as the quantum processing units (QPUs) produced by D-Wave Systems, have been subject to multiple analyses in research, with the aim of characterizing the technology's usefulness for optimization and sampling tasks. In this paper, we present a real-world application that uses quantum technologies. Specifically, we show how to map certain parts of a real-world traffic flow optimization problem to be suitable for quantum annealing. We show that time-critical optimization tasks, such as continuous redistribution of position data for cars in dense road networks, are suitable candidates for quantum computing. Due to the limited size and connectivity

Satellite Coverage

Quantum Optimization

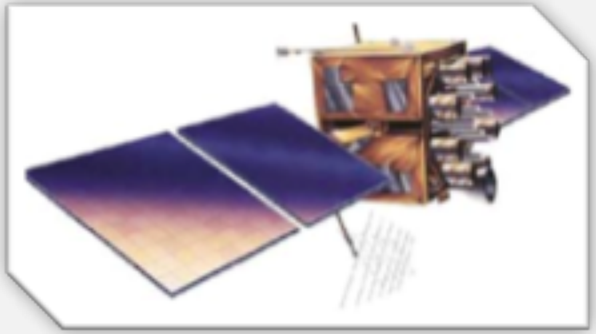


SATELLITE COVERAGE OPTIMIZATION

Summary: Group satellite together in such a way as to maximize coverage.

Data: For any possible grouping of satellites, a coverage percentage

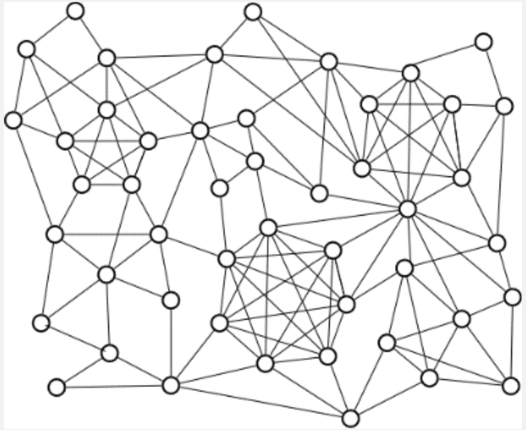
Goal: Assign each of N satellites to k groups, such that total mean coverage is maximized



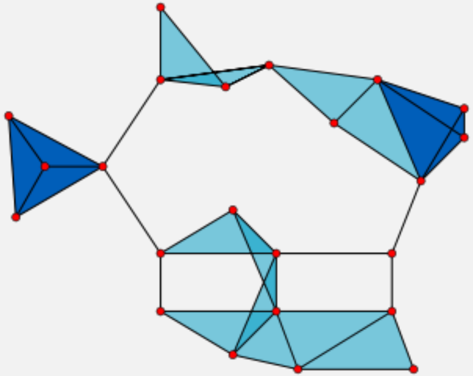
+ Satellites change position and **require constant re-optimization**
+ **Brute force solving is out of the question**; even trivial subsets of the satellites form too many combinations to check.
+ Quantum technology offers a promise to **perform combinatorial optimization much faster**, while yielding better coverage outcomes.

THE WEIGHTED K-CLIQUE PROBLEM

+ This problem can be reformulated as a graph problem, called the **k-clique problem**



+ Each potential group of satellites in a sub-constellation can be considered a node on a graph
  - Each node is given a weight equal to the coverage provided
  - If both sub-constellation use the same satellite, the nodes are unconnected
  - The goal is thus to find the k nodes with the highest total weight that are all mutually connected (a "clique")



+ This problem can then be expressed as a QUBO, and sent to the quantum computer

DESIGNING THE QUBO

Constraints:

1. Choose only nodes that are connected
2. Maximize the sum of coverages for each group chosen
3. Choose a number of qubits equal to the number of available satellites

Each (logical) qubit represents a potential grouping of satellites

Connections represent a grouping that is non-overlapping (does not use the same satellite in multiple groups)

$$H = \sum_{i<j} 2(w_i + w_j)$$

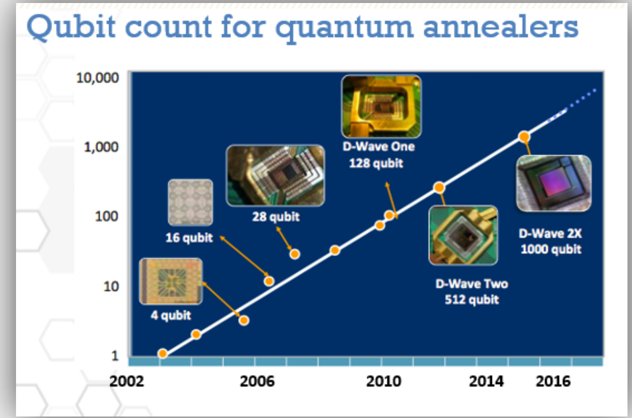
$$H = \sum_{i} -Aw_i x_i$$

$$H = W\left(\sum_i x_i - 8\right)^2 = 64W - \sum_i 8W x_i + \sum_{i<j} x_i x_j$$

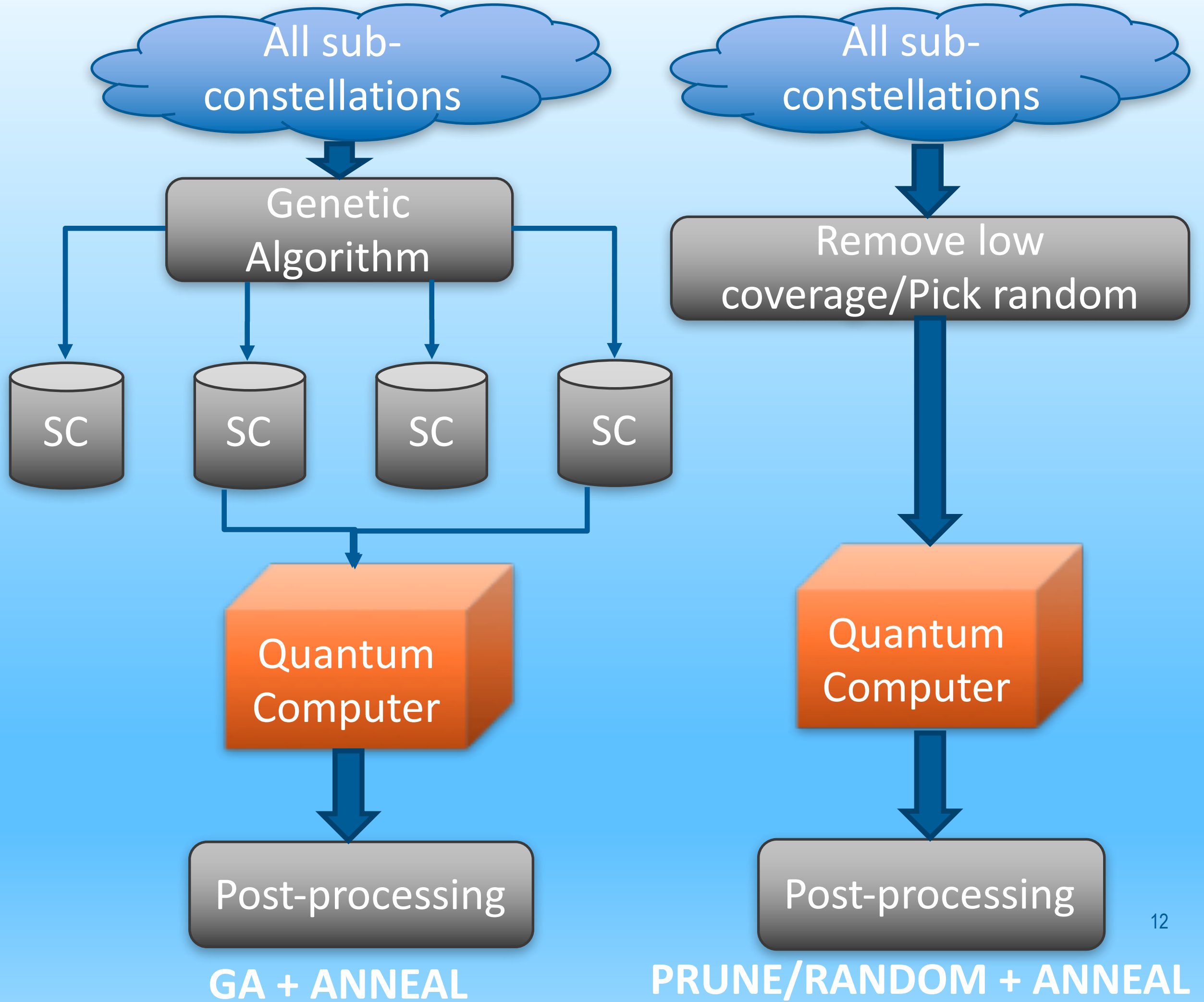
W is the qubit maximum weight

QUANTUM HARDWARE IS RAPIDLY MATURING

- This satellite optimization problem is **a prime candidate for a quantum approach** when used in concert with classical computing resources.
- The application to satellites could be **the first major quantum success** when applied to a real-world full-scale problem.
- However, with current numbers, we would still need 10^4-10^5 qubits to fully embed this problem
- Thus, we created a heterogeneous approach that combines classical processing and quantum annealing



HETEROGENEOUS TECHNIQUES: TWO APPROACHES

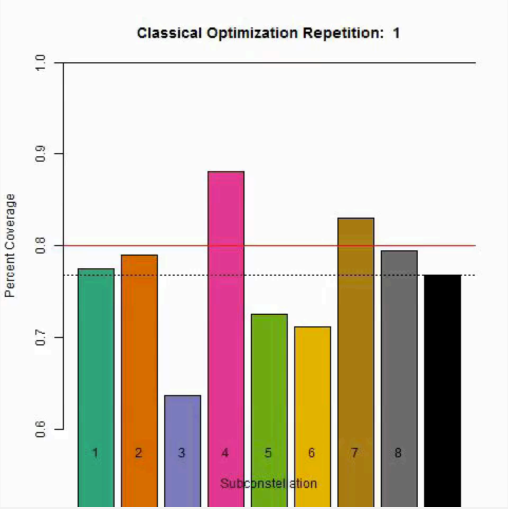


HETEROGENEOUS COMPUTING MODELS

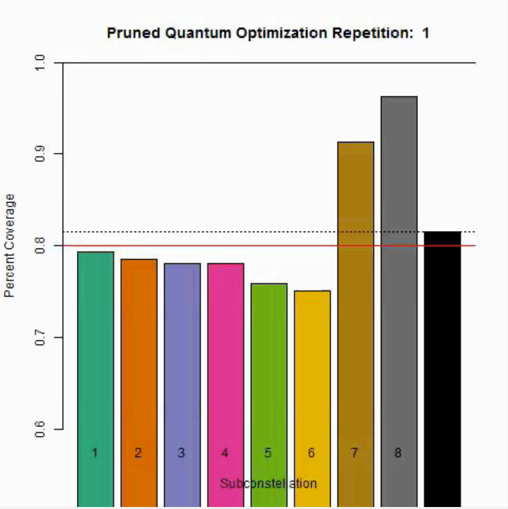
Method	Pros	Cons
Classical Heuristics	Can provide fairly good results. Can be run on classical machine.	Cannot be run on current QA devices, no quantum speed-up, scaling uncertain
GA pre-processing	Searches full decision space, produces solid results	Middle of the road performance and speed, many parameters to tune
Prune and Anneal	Very good results in good time, most similar to existing technique	Does not explore full solution space, requires domain knowledge

RESULTS COMPARISON: QUANTUM SIMULATOR

- An 80% coverage(red) is the minimum acceptable average.
- The eight colored bars represent individual sets, black bar (and dotted line) is overall average
- **Quantum approach is faster** and finds **a significantly better results**

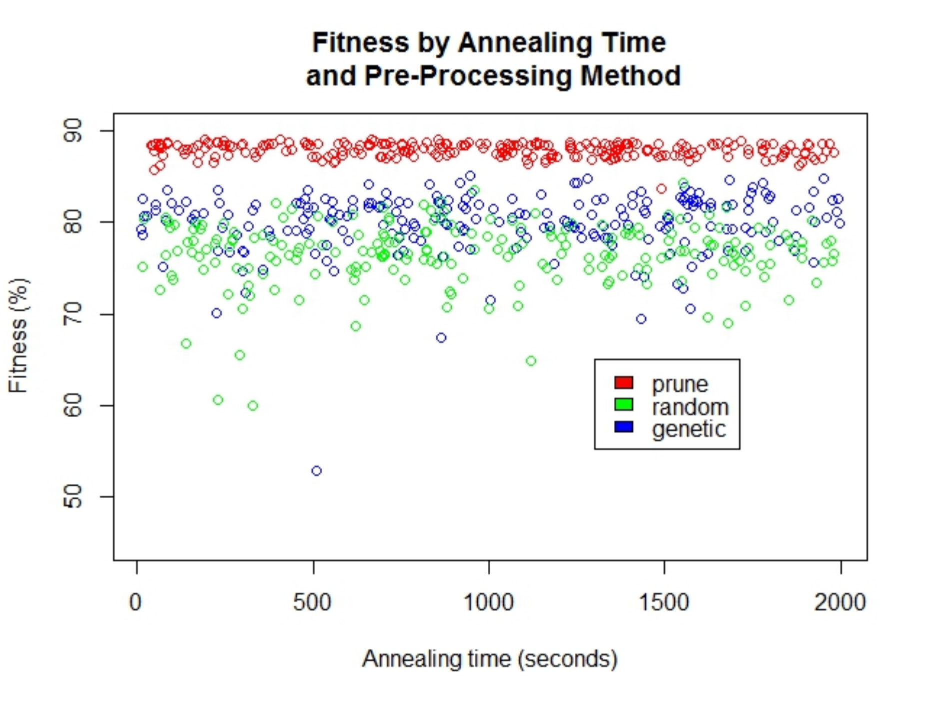


Purely **Classical** Genetic Algorithm



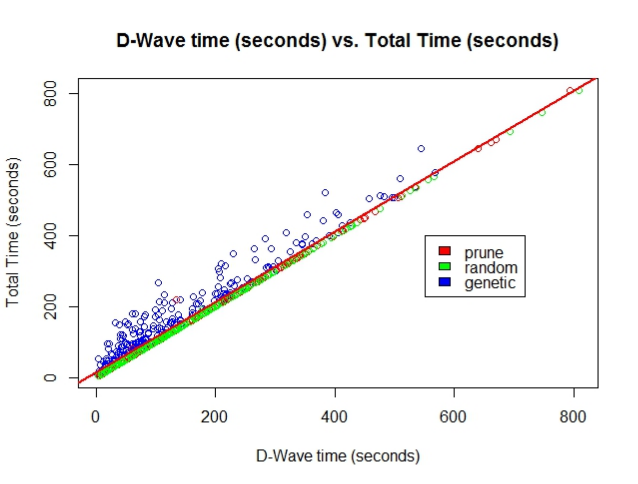
Simulated **Quantum** Prune and Anneal

RESULTS COMPARISON: D-WAVE



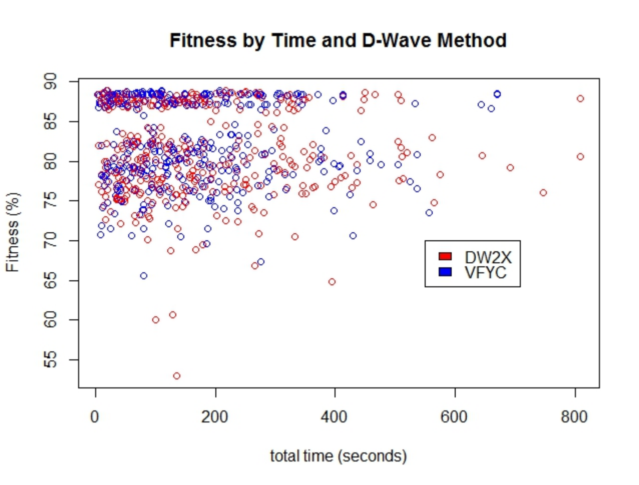
- Results are **nearly constant** with processing time
- Results are highly dependent on pre-processing method (color)
  - 80% is minimal acceptable
  - 90% is likely near the true maximum.

RESULTS COMPARISON: D-WAVE



- D-Wave time makes up most of the time, GA adds a little more

- Including D-Wave's "Virtual Full Yield" does not significantly change performance while improving portability



SUMMARY

Method	Uses Domain-Knowledge	Time Needed	Performance
Prune + Anneal	✓	Very Little	90%
GA + Anneal	X	Some	80-85%
Random + Anneal	X	Very Little	75-80%

- The D-Wave **functions best as a co-processor**
- Performance is highly dependent on problem formulation, classical processing step
- Quantum portion does appear to provide significant improvement.

CONCLUSIONS

- As problems and datasets grow, modern computing systems have had to scale with them. **Quantum computing offers a totally new and potentially disruptive computing paradigm.**
- For problems like this satellite optimization problem, **heterogeneous quantum techniques will be required to solve the problem at larger scales.**
- Preliminary results on this problem using heterogeneous classical/quantum solutions **are very promising.**
- Exploratory studies in this area **have the potential to break new ground** as one of the first applications of quantum computing to a real-world problem

Thank You

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