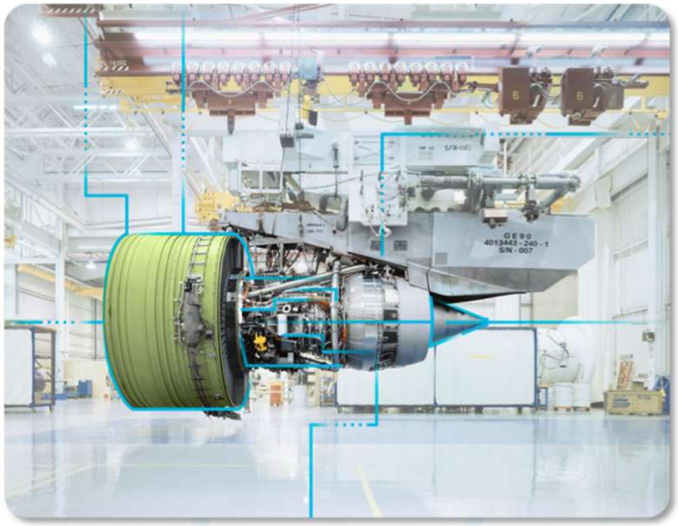
# Quantum Annealing for Asset Sustainment

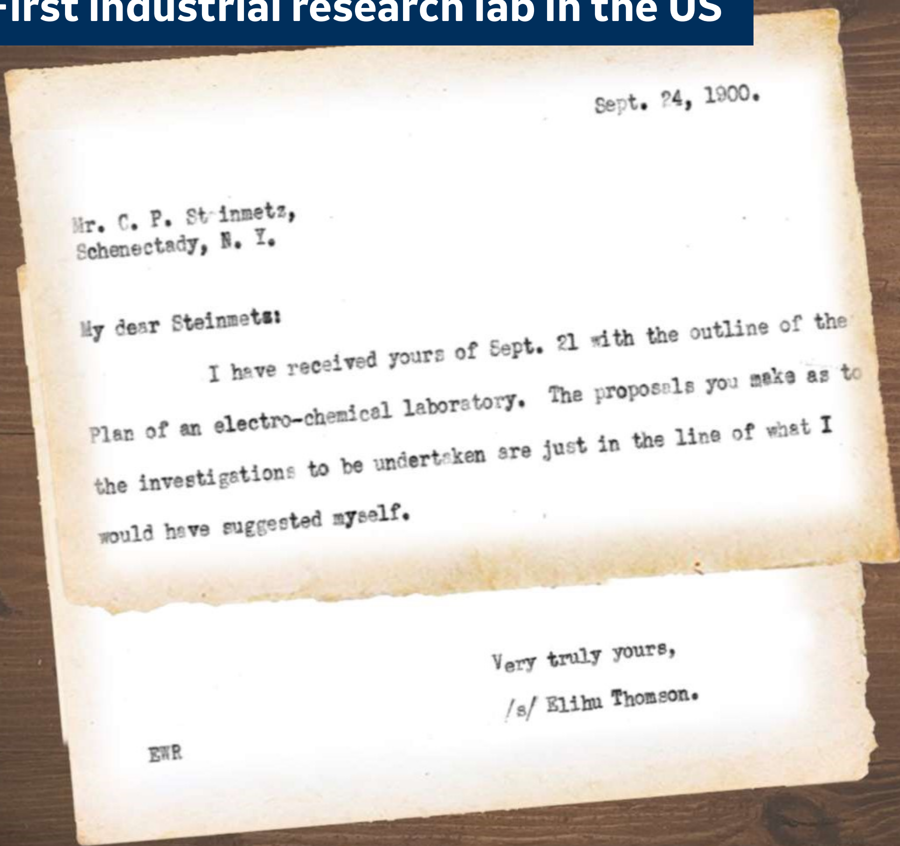
Annarita Giani
Aussie Schnore
GE Research



Qubits EUROPE 2019
Milan, Italy
26.03.2019

# GE's technical heritage

## First industrial research lab in the US


Sept. 24, 1900.

Mr. C. P. St-inmetz,
Schenectady, N. Y.

My dear Steinmetz:

I have received yours of Sept. 21 with the outline of the Plan of an electro-chemical laboratory. The proposals you make as to the investigations to be undertaken are just in the line of what I would have suggested myself.

Very truly yours,
/s/ Elihu Thomson.

EWR

## GE Research today

**1,000+** Scientists & Engineers

**~3,000 patents** /year across GE

**~60,000 visitors** globally/year

**"I find out what the world needs, then I proceed to invent it" – Thomas Edison**

# Contemporary Research ...

## Discovery... *world's firsts*


*Foreground IP*

## Portfolio ... *differentiated tech*

- ✓ **Top 10 global patents ...** 63,000+
- ✓ **Broad applicability ...** cross disciplinary
- ✓ **Market tested ...** product deployed

*Building background IP*

## Prosperity... *ecosystem impact*


*Generating*
**1/3 of world's electricity**

*Powering*
**Takeoff every 2 seconds**

*Curing*
**16,000+ scans every minute**

*GE Businesses "+"*

**GE's innovation legacy & scale**

# GE Research ... unique value proposition

## Capabilities

- Artificial Intelligence
- Biology & Physics
- Controls & Optimization
- Edge Computing
- Electronics
- Electric Power
- Functional Materials
- Mechanics & Design
- Software & Analytics
- Structural Materials
- Thermosciences

**600+ PhDs**

*Unmatched interdisciplinary expertise*

*Research to Reality*

## Breakouts

### VERTICAL

- 2 Cent Wind
- 65% CC GT
- Additive
- Renewables Full Time
- Castings
- Plug & Play MR
- Renewable Reservoir
- Hybrid – Electric Flight

### HORIZONTAL

- Additive
- Artificial Intelligence
- CMC
- Robotics
- Controls/ Edge
- Digital Twin and Ghost
- Specialized Materials
- SiC

### EXPONENTIAL

- Autonomous Imaging
- Bioelectronics
- Blockchain
- Microsystems
- Mission Unbreakable
- Trusted Autonomy

**Scientific Depth & Breadth ... Delivering Real Economics**

# GE Research

## Two core research centers


**A Focused, Competitive Industrial R&D Organization**

# Choosing the problem


## The problem

*Supply Chain Optimization* ▸ *Logistics* ▸ *Asset Sustainment*

Many repairs are requested at the same time. Each needs a sequence of resources.

**Objective Function**: Minimize resource contention

**Challenge**: NP-hard problems, closed form solutions quickly scale in complexity beyond the ability of classical methods to provide a timely and optimal answer

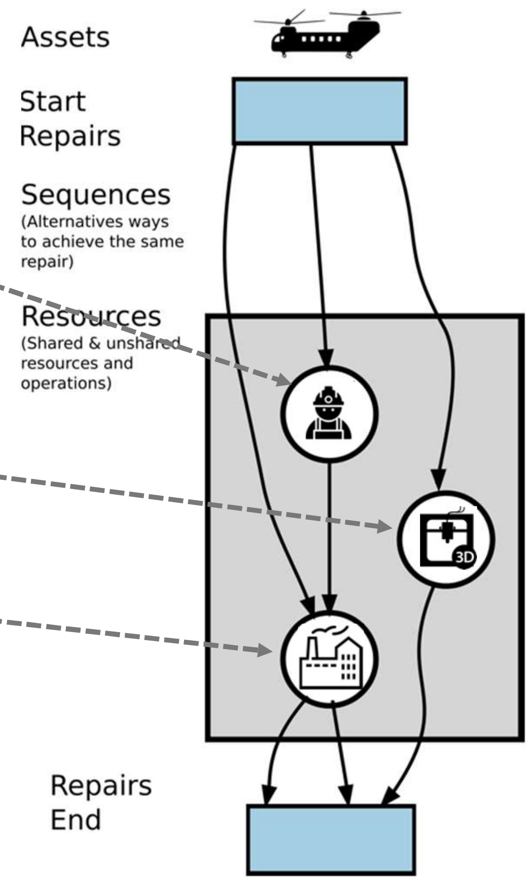
**Current Approach**: Sophisticated algorithms together with heuristics with less than optimal results

**Our Approach:** Quantum Annealing and QUBO formulation of the problem to be ingested in an annealing machine to get the *optimal* set of sequences

**Leveraging Previous Work on Supply Chain and Logistics**

# Resource Allocation Optimization

- Skilled operator
- Depot
- Warehouse
- Supplier
- Other plane
- 3D printer
- Spare parts
- Repair centers
- Bases
- Teardown centers
- Manufacturing centers




**Engine needs a repair**

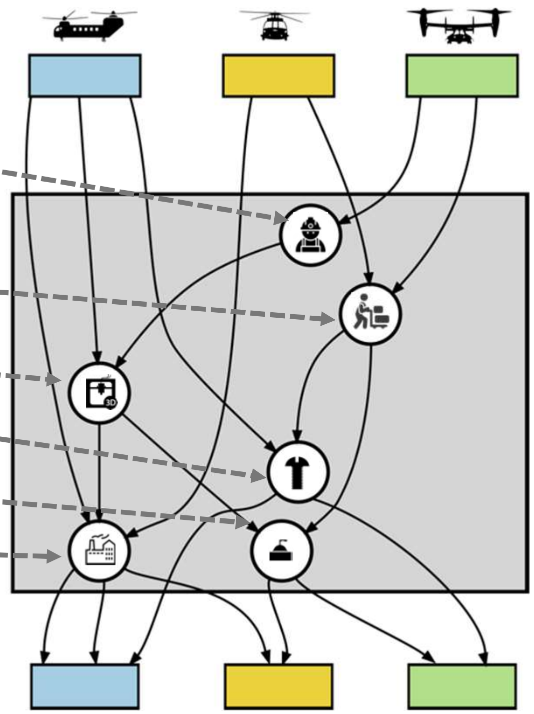
**Find all possible solutions (sequences of resources)**

**What is the optimal sequence of resources that address the repair?**

**A Single Repair has Multiple Paths**

# Resource Allocation Optimization

- Skilled operator
- Depot
- Warehouse
- Supplier
- Other plane
- 3D printer
- spare parts
- Repair centers
- Bases
- teardown centers
- manufacturing centers



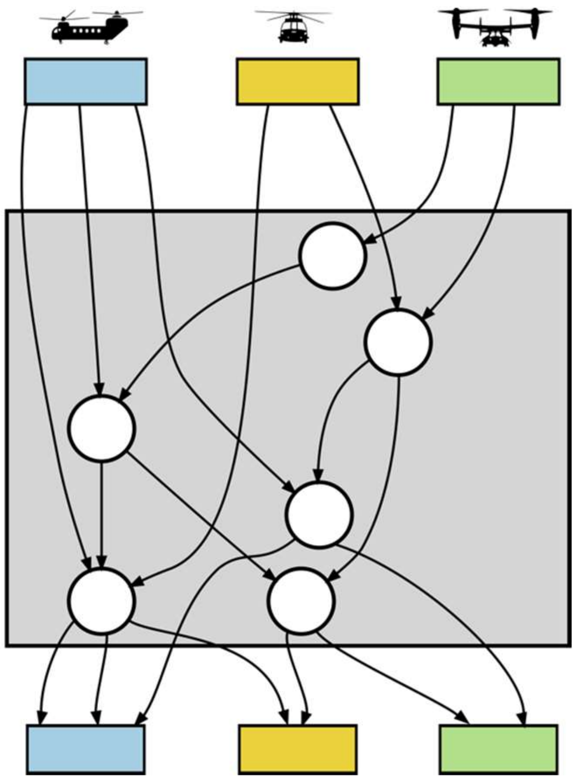
**Many parts/machines to be replace/repaired**

**Solutions are sequences of basic steps**

**What is the optimal sequence of resources that address all the repairs simultaneously?**

**Complexity Increases with Concurrent Repairs**

# Simple Problem



Reduce congestion at the network of repair resources

**Problem size:**

- **3** repairs
- **7** sequences
- **6** resources
- **128** possible choices
- **12** constrained answers

**Real World Problem of Interest to GE**

# From Real Problem to Results

**Problem Formulation**

COST

$$C_{n_0} = (q_{0,0} + q_{2,0})^2$$
$$C_{n_1} = (q_{1,1} + q_{2,1})^2$$
$$C_{n_2} = (q_{1,1} + q_{2,0})^2$$
$$C_{n_3} = (q_{0,1} + q_{0,2} + q_{1,0})^2$$
$$C_{n_4} = (q_{2,1})^2$$
$$C_{n_5} = (q_{0,1} + q_{2,1})^2$$
$$C_{total} = C_{n_0} + C_{n_1} + C_{n_2} + C_{n_3} + C_{n_4} + C_{n_5}$$
$$E_c = P_{all} + C_{total}$$

CONSTRAINTS

$$P_{r_0} = K * (q_{0,0} + q_{0,1} + q_{0,2} - 1)^2$$
$$P_{r_1} = K * (q_{1,0} + q_{1,1} - 1)^2$$
$$P_{r_2} = K * (q_{2,0} + q_{2,1} - 1)^2$$
$$P_{all} = P_{r_0} + P_{r_1} + P_{r_2}$$

**QUBO/ Ising Model**

$$E(s) = \sum_i h_i q_i + \sum_{i,j} J_{i,j} q_i q_j + C$$

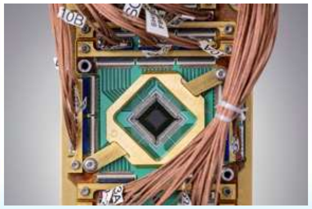
**Upper Triangular Matrix**

$$J_{i,j} = \begin{bmatrix} -9 & 18 & 18 & 0 & 0 & 0 & 0 \\ 0 & -7 & 20 & 2 & 0 & 0 & 2 \\ 0 & 0 & -7 & 2 & 0 & 2 & 0 \\ 0 & 0 & 0 & -8 & 18 & 0 & 0 \\ 0 & 0 & 0 & 0 & -7 & 2 & 2 \\ 0 & 0 & 0 & 0 & 0 & -7 & 18 \\ 0 & 0 & 0 & 0 & 0 & 0 & -6 \end{bmatrix}$$

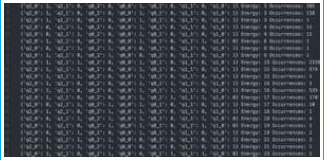
**Python**

```
from dimod import BinaryQuadraticModel
from dimod import BINARY
from dwave.system.samplers import DWaveSampler
from dwave.system.composites import EmbeddingComposite

h = {"q0_0": -9, "q0_1": -7, "q0_2": -7, "q1_0": -8, "q1_1": -7,
     "q2_0": -7, "q2_1": -6}
J = {("q0_0","q0_1"): 18, ("q0_0","q0_2"): 18,
     ("q0_1","q0_2"): 20, ("q0_1","q1_0"): 2, ("q0_1","q2_1"): 2,
     ("q0_2","q1_0"): 2, ("q0_2","q2_0"): 2,
     ("q1_0","q1_1"): 18,
     ("q1_1","q2_0"): 2, ("q1_1","q2_1"): 2,
     ("q2_0","q2_1"): 18}
C = 27

bqm = BinaryQuadraticModel(h,J,C,BINARY)

sampler = EmbeddingComposite(DWaveSampler())

response = sampler.sample(bqm,num_reads = 1000)

for datum in response.data(["sample", "energy", "num_occurrences"]):
    print datum.sample,
    print "Energy:", datum.energy,
    print "Occurrences:", datum.num_occurrences
```

**Cloud Access**

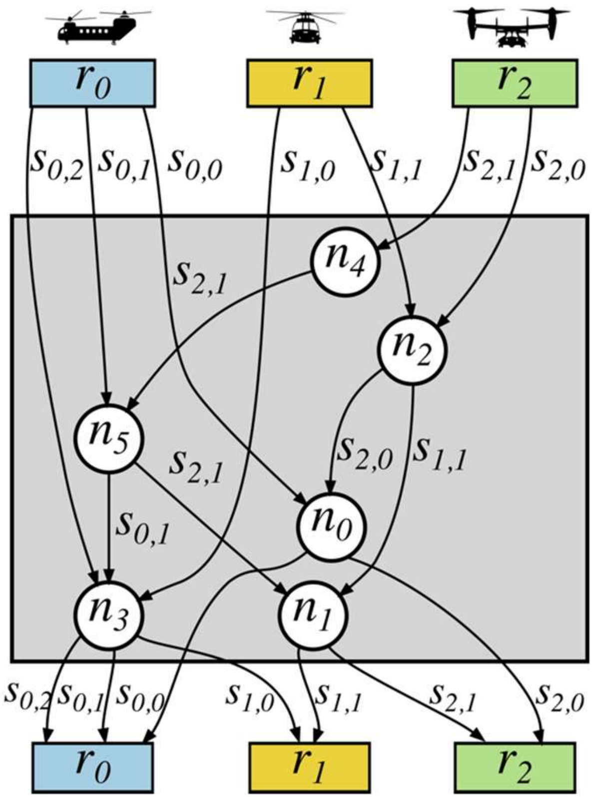


**Results**



**Creation of a Process for Problem Translation**

# Problem Formulation/QUBO/Ising Model




Qubit $q_{0,1}$ represents repair $i$ selecting sequence of resources $j$

**COST**: Measure of Congestions at each node

**CONSTRAINTS**: All repairs needs to be addressed once

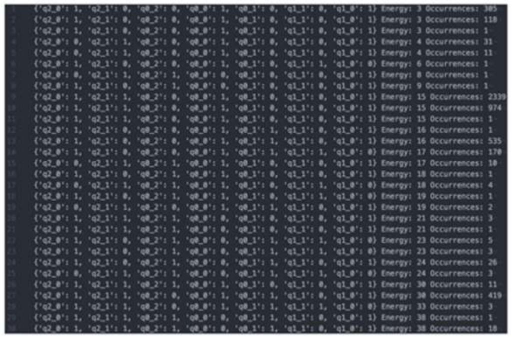
$$E(s) = \sum_i h_i q_i + \sum_{i,j} J_{i,j} q_i q_j + C$$

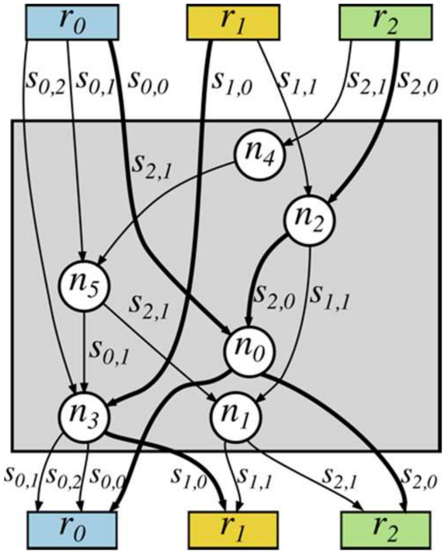
**Energy = Cost + Constraints**

**Previous Developed Applications Helped translate this problem into QUBO**

# Accessing the machine and getting Results

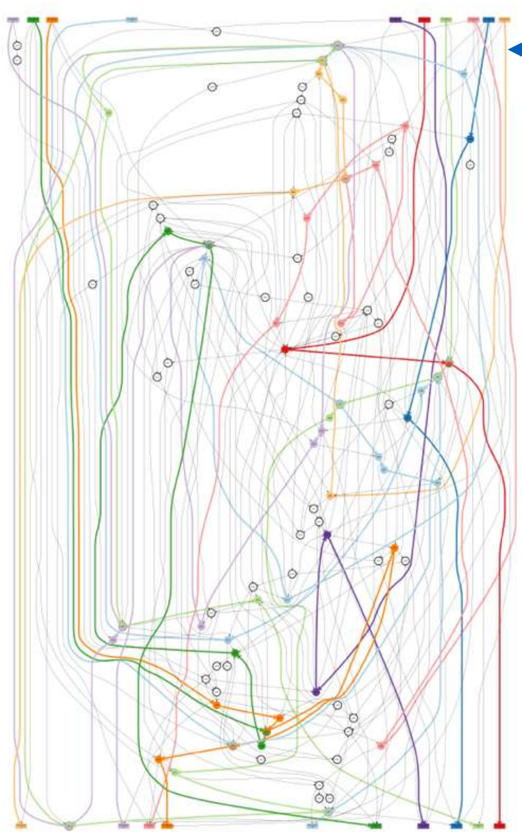
```python
from dimod import BinaryQuadraticModel
from dimod import BINARY
from dwave.system.samplers import DWaveSampler
from dwave.system.composites import EmbeddingComposite

h = {"q0_0": -9, "q0_1": -7, "q0_2": -7, "q1_0": -8, "q1_1": -7,
     "q2_0": -7, "q2_1": -6}
J = {("q0_0","q0_1"): 18, ("q0_0","q0_2"): 18,
     ("q0_1","q0_2"): 20, ("q0_1","q1_0"):  2, ("q0_1","q2_1"):  2,
     ("q0_2","q1_0"):  2, ("q0_2","q2_0"):  2,
     ("q1_0","q1_1"): 18,
     ("q1_1","q2_0"):  2, ("q1_1","q2_1"):  2,
     ("q2_0","q2_1"): 18}
C = 27

bqm = BinaryQuadraticModel(h,J,C,BINARY)

sampler = EmbeddingComposite(DWaveSampler())

response = sampler.sample(bqm,num_reads = 5000)

for datum in response.data(["sample", "energy", "num_occurrences"]):
    print datum.sample,
    print "Energy:", datum.energy,
    print "Occurrences:", datum.num_occurrences
```

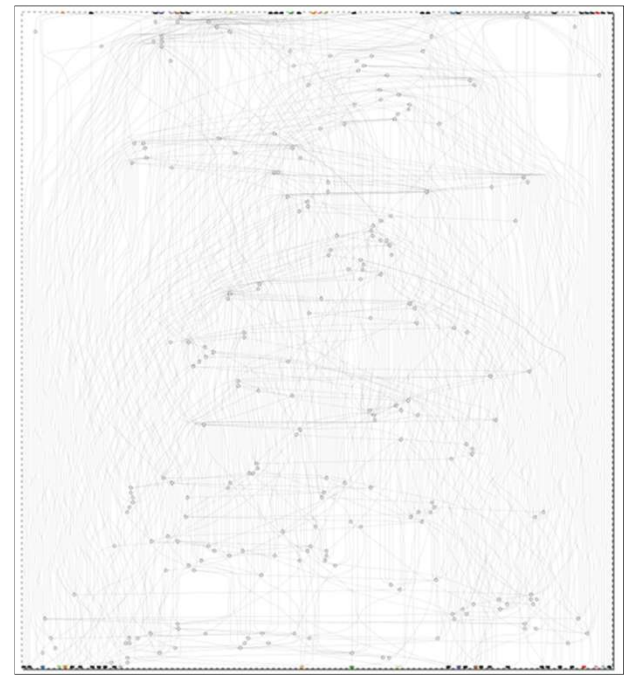



**Getting the Optimal Choice of Resources per Repair**

# Scaling: Complexity Rapidly Increases



**Problem size:**
- **10** repairs
- **28** sequences
- **94** resources
- **268,435,456** possible choices
- **12,288** constrained answers



**Problem size:**
- **30** repairs
- **92** sequences
- **230** resources
- **4,951,760,157,141,521,099,596,496,896** possible choices
- **160,489,808,068,608** constrained answers

**This is not even close to the size of a real sustainment problem**

**Classical Computing no Longer a Feasible Approach**

# Summary Results

| Repairs | Trajectories | Resources | Combinations | Constrained Choices | Scale |
|---|---|---|---|---|---|
| 3 | 7 | 6 | 128 | 12 | Small Farm |
| 10 | 28 | 94 | 268,435,456 | 12,288 | Corner Garage |
| 30 | 92 | 230 | 4.9x10^27 | 1.6x10^4 | Dealer Service Shop |

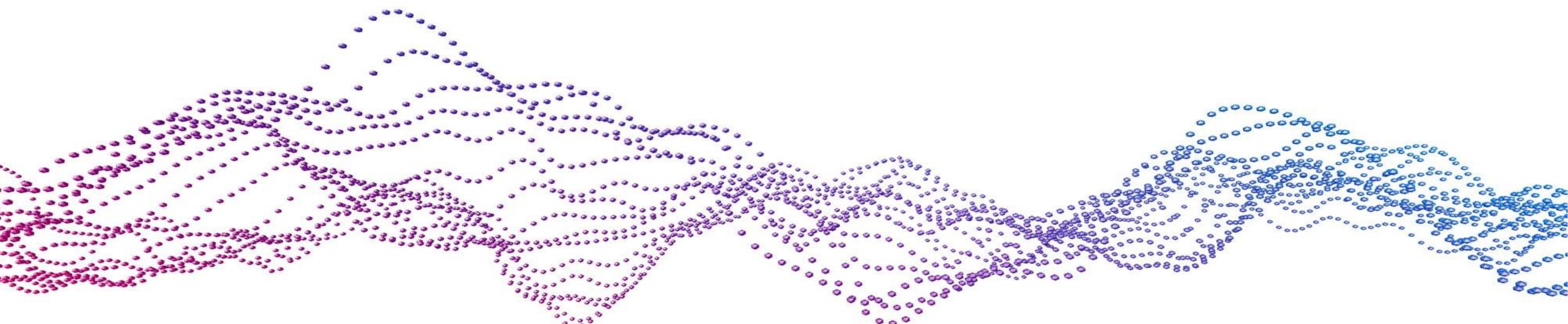
**Challenges**

- Deciding the problem
- Formulating the problem
- Once the problem was formulated in QUBO model
  - Value of K
  - Big Problem does not embed well into the Chimera topology
  - Chain strength

**Waiting for new Topology and more Qubits**

# Current effort

- Making this problem more **realistic**
- New real world **applications** of interest to GE
- Real world problems on **gate model** (NISQ)




# Thank you for your time

Questions?

ge.com/research/

ge.com/research/forge

Twitter: @GEResearch