Hyperspectral Image Segmentation Using Quantum Annealing

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Classical Computing vs Quantum Computing

Unit of information

Bits

- Binary
- Deterministic
- Relatively stable
- Boolean logic
  → Logic Gates

Qubits

- Superposition
- Entanglement
- Decoherence / Extreme sensitivity
- Quantum measurement
  → Quantum Gates

Advantages & Limits

Classical Computing

- **Advantages** :
  - Reliability
  - Accuracy
  - Cost-effectiveness
- **Limits** :
  - Transistor density in Integrated Circuits (IC)
    → Moore’s law
  - Exponential time complexity
    → NP-Hard problems
  - Simulation of large-scale quantum systems
    → Richard Feynman : "Nature isn't classical"

Quantum Computing

- **Advantages** :
  - Exponential speedup for certain problems
    → Shor's algorithm, Grover's algorithm
  - Large-scale memory capacity
    → Superposition of states represents large number of values simultaneously
  - Efficient simulation of real-world systems
    → Based on Quantum Mechanics
- **Limits** :
  - Decoherence
  - Error correction
  - Scalability

Quantum Annealers

Quantum

- Qubits
- Superposition
- Entanglement
- Interference

Annealing

- Probabilistic
- Randomness
- Exploration vs Exploitation
- Temperature schedule

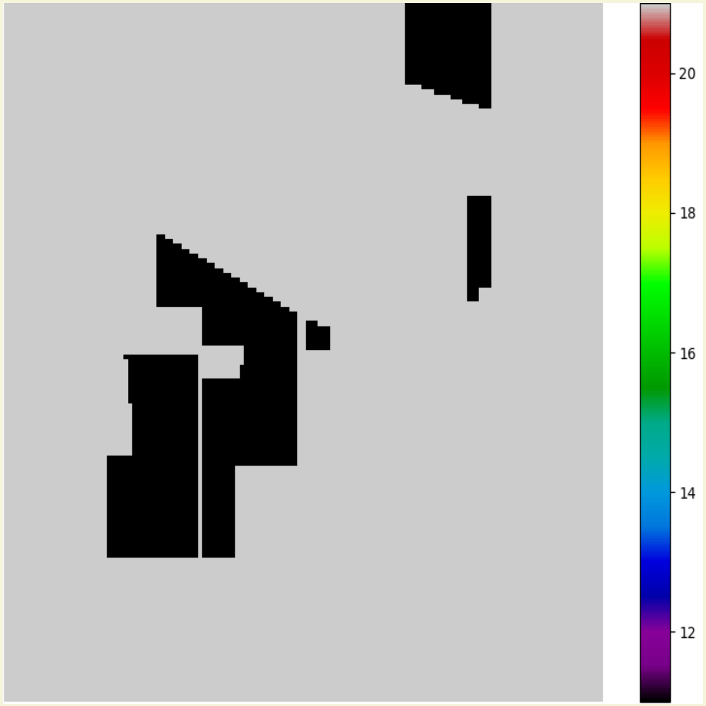
Hyperspectral Image Segmentation

Using Quantum Annealing

Indian Pines Dataset

- 145*145 pixels.
- 200 spectral reflectance bands (for the corrected version).
- Wavelength range : 400nm - 2500nm.
- One-vs-Rest Classification Algorithm.

Indian pines Dataset : Sample



Ground state : Target Class N°11

https://www.ehu.eus/ccwintco/index.php?title=Hyperspectral_Remote_Sensing_Scenes#Indian_Pines

Step 1

Choose a Classifier

Support Vector Machine SVM

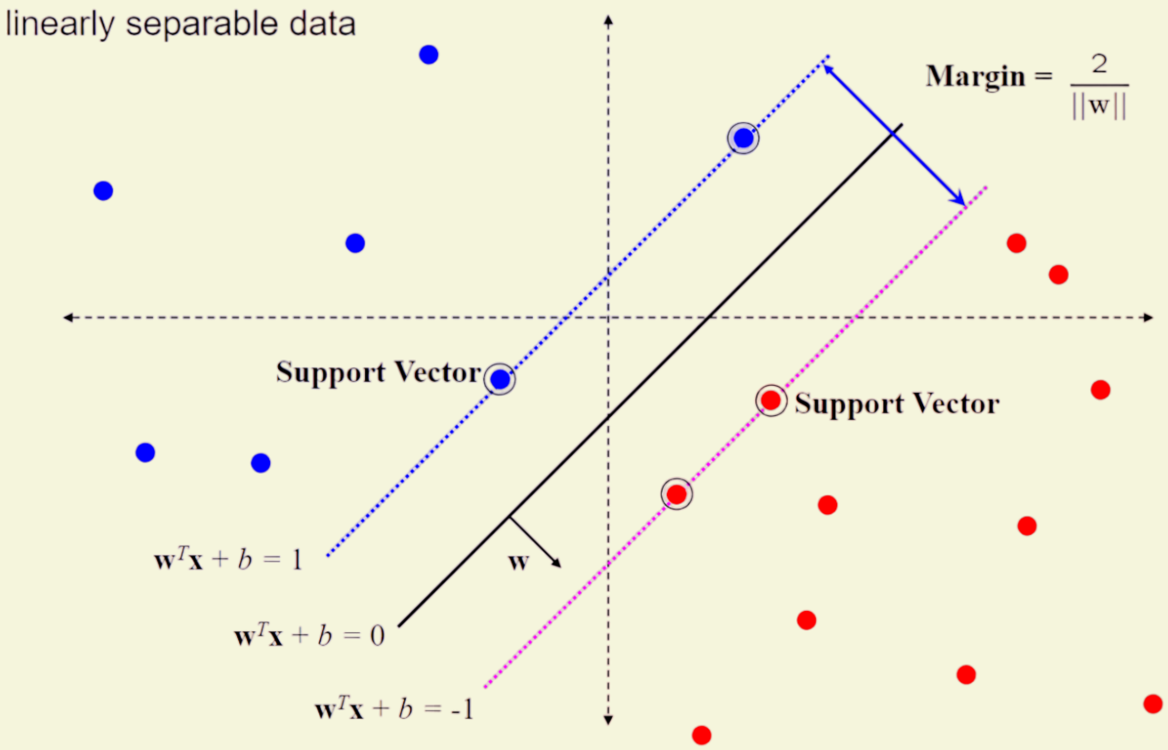
$$f(x) = w^T x + b$$

Given training data (x_i, y_i) for $i = 1 \ldots N$, with $x_i \in \mathbb{R}^d$ and $y_i \in \{-1, 1\}$, learn a classifier $f(x)$ such that :

$$f(x_i) = \begin{cases} \geq 0 \;\; if \;\; y_i = +1 \\ < 0 \;\; if \;\; y_i = -1 \end{cases}$$

i.e. $y_i f(x_i) > 0$ for a correct classification.

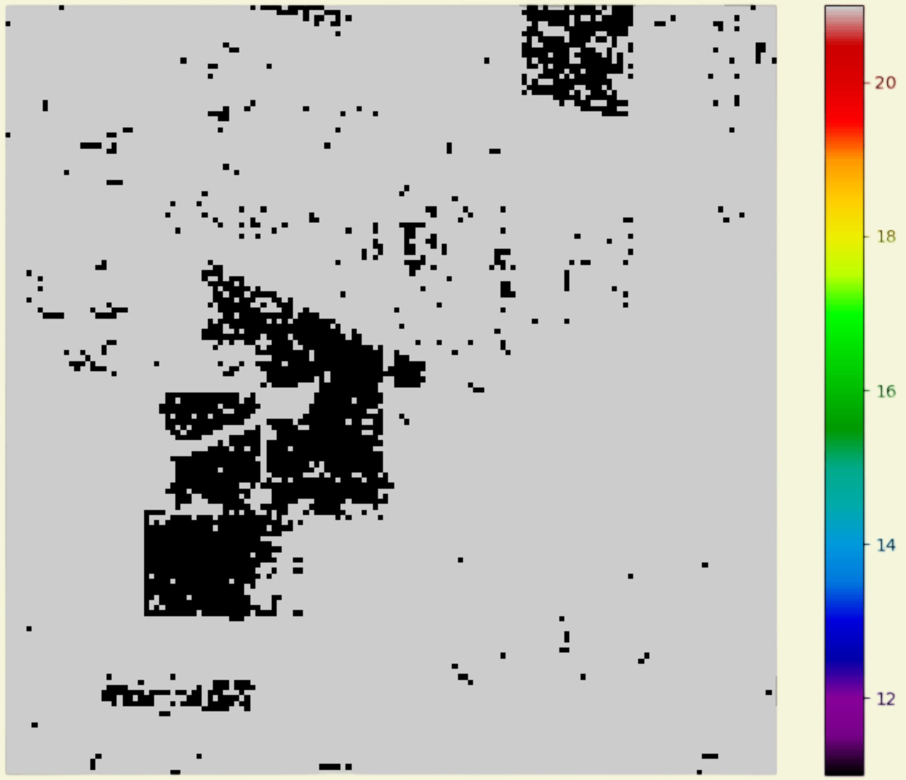
Trade off between the margin and the number of mistakes on the training data !



Result

- SVM.
- Parameters (GridSearchCV):

```
SVC(C=100, cache_size=1024, kernel="poly", probability=True)
```

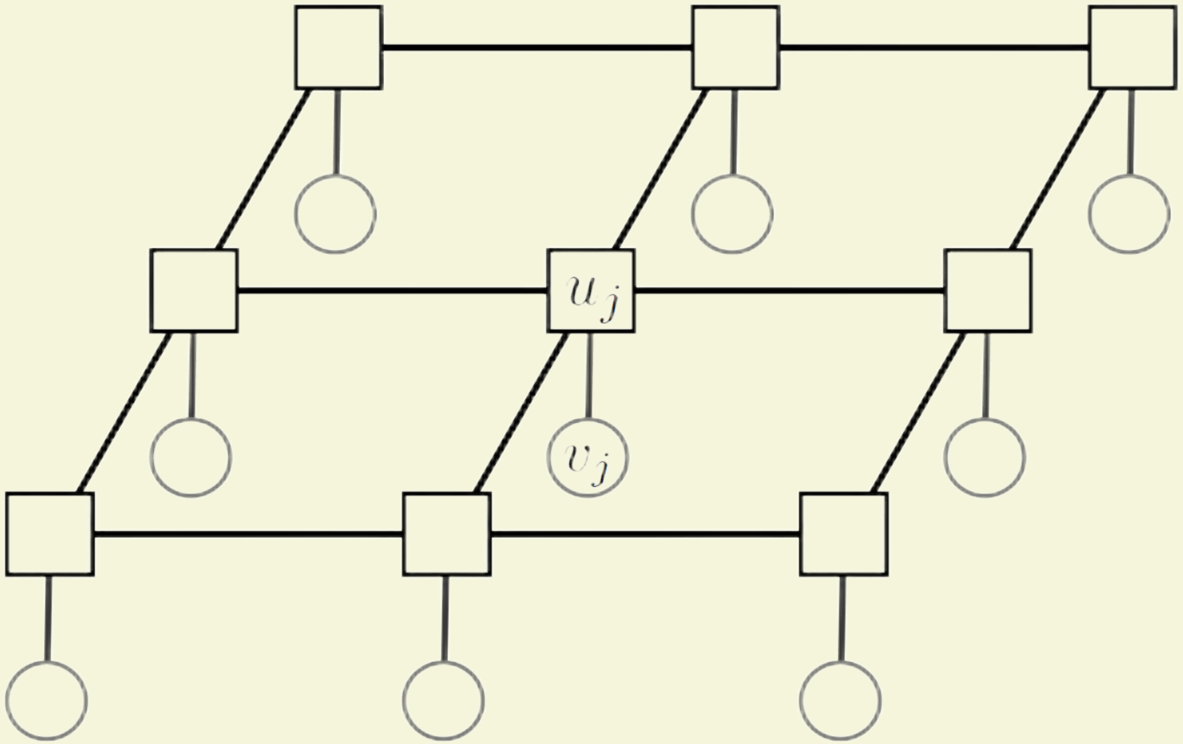


Step 2

Construct the adapted model for the problem formulation

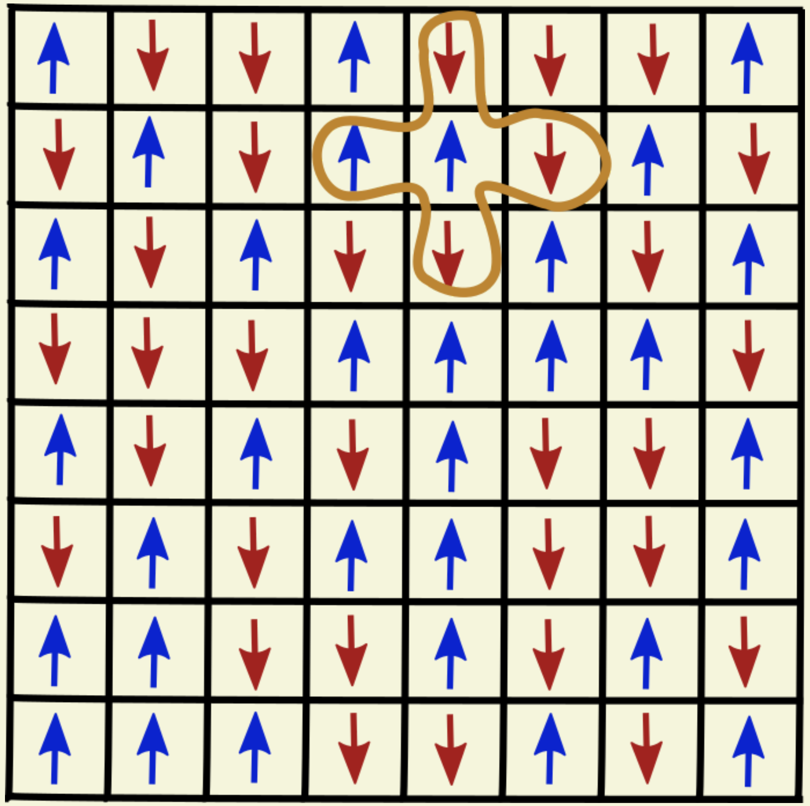
Markov Random Fields

- Undirected graph $G = (V, E)$.
- Nodes V :
  $\rightarrow$ Discrete or Gaussian Probability distribution of Random Variables RV : $\{u_j\}_{j \in V}$.
- Edges E :
  $\rightarrow$ Binary edges.
  $\rightarrow$ Strength of the dependence between both variables.
- Given N_i Markov blanket of Node i (Neighborhood) : $\forall i \in 1, 2, \ldots, N$:
  $p(u_i | \{u_j\}_{j \in V - i}) = p(u_i | \{u_j\}_{j \in N_i})$
- Energy expression :
  $$E(u) = E_{data}(u) + E_{smoothness}(u)$$



Ising model

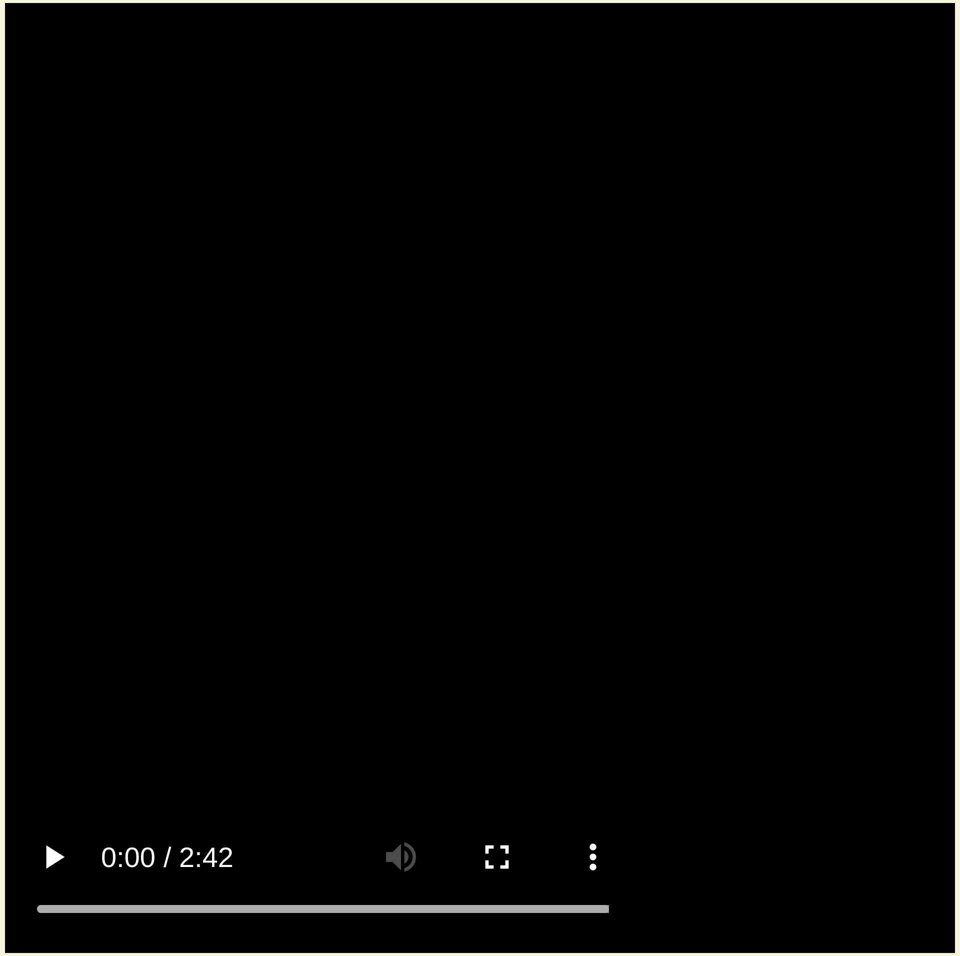
- Originated from Statistical Physics (Ferromagnetism).
- Hamiltonian :
  $\rightarrow H(s) = -\sum_i h_i * s_i - \beta \sum_{i\sim j} s_i * s_j$
- Parameters :
  - s : Spin configuration.
  - s_i : Pixel index i of the image (as a 1D vector).
  - h_i : Likelihood / Energy of being in a particular class.
    $\rightarrow h_i = -1/4log(1/Pi(c) - 1)$
  - β : How strongly its neighbors wants it to be in their class (magnetic moment).
    $\rightarrow \beta = 1$



https://astro.pas.rochester.edu/~aquillen/phy256/problems/ps8.html

Result

- Classical Simulated Annealing.
- Metropolis-Hastings algorithm:
  - State transition probability : $e^{-\delta E/T}$
- Parameters:
  - temperature: $4 \rightarrow 0.5$
  - beta: 0.5

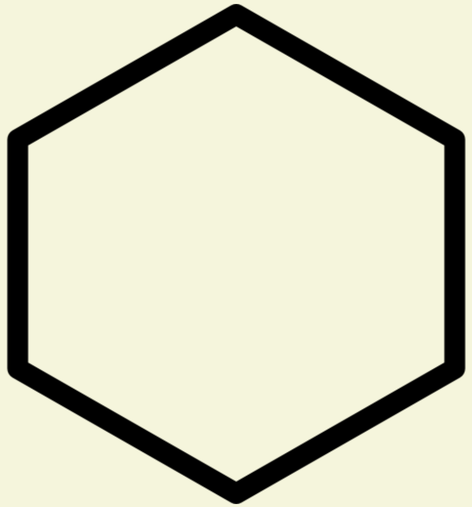


Step 3

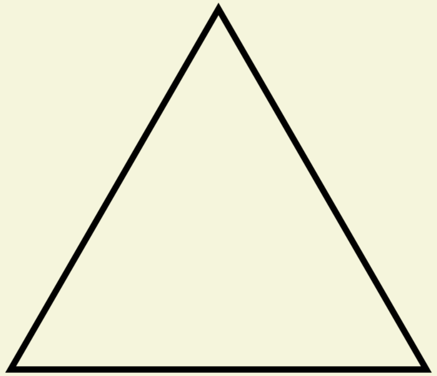
Embed the model into the Quantum Annealer

Embedding

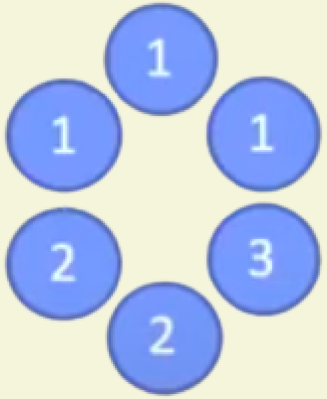
Host graph



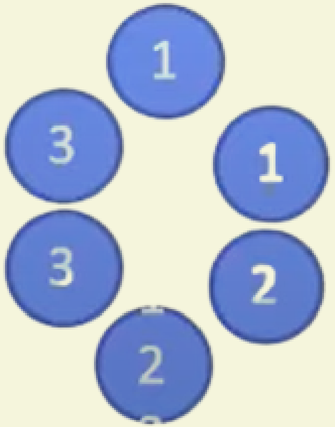
Problem graph



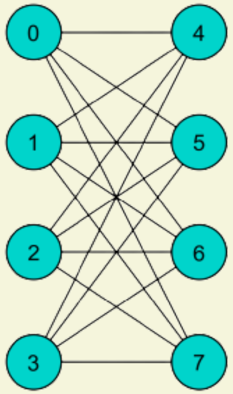
Embedding N°1

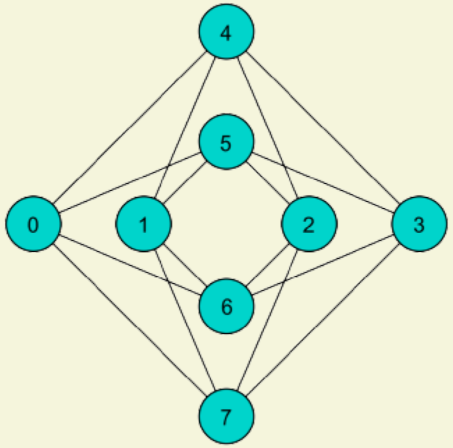


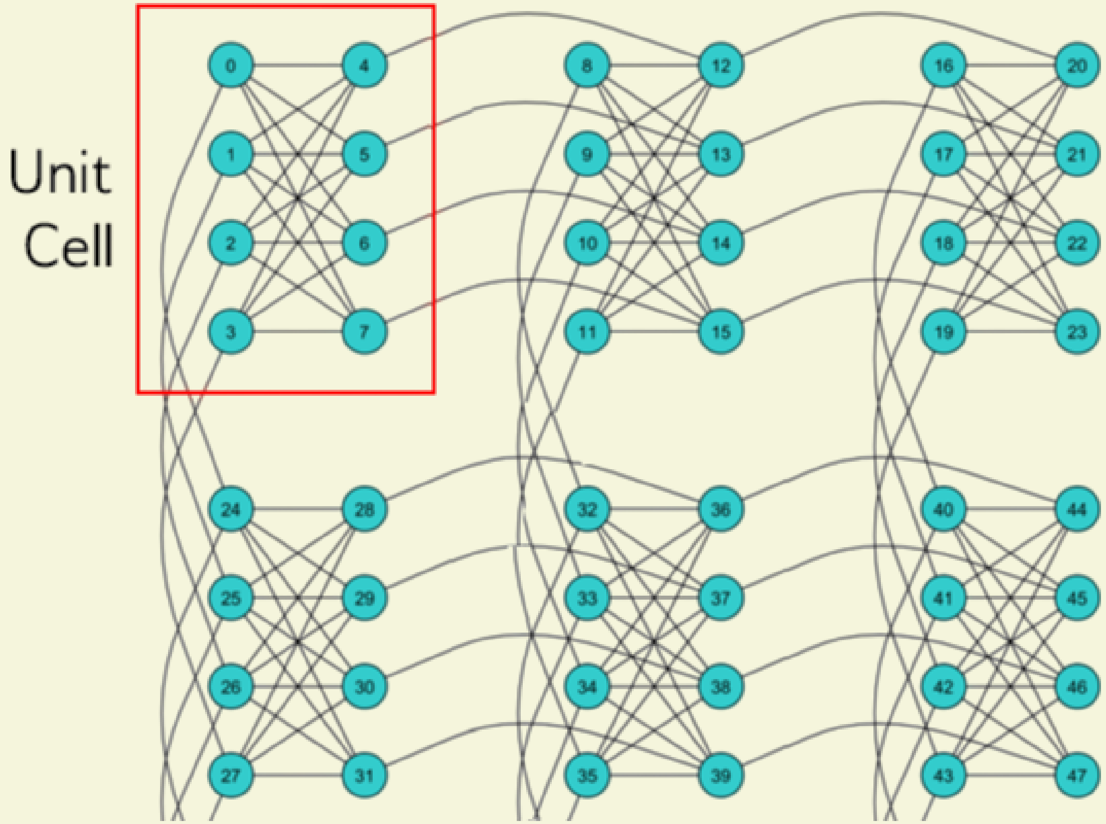
Embedding N°2



Chimera Graph

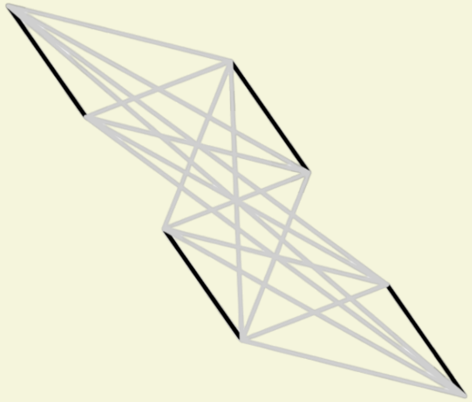


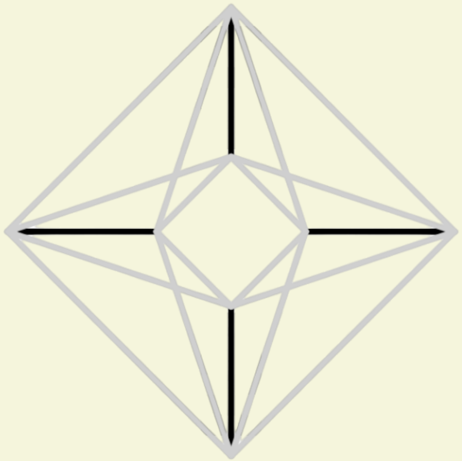


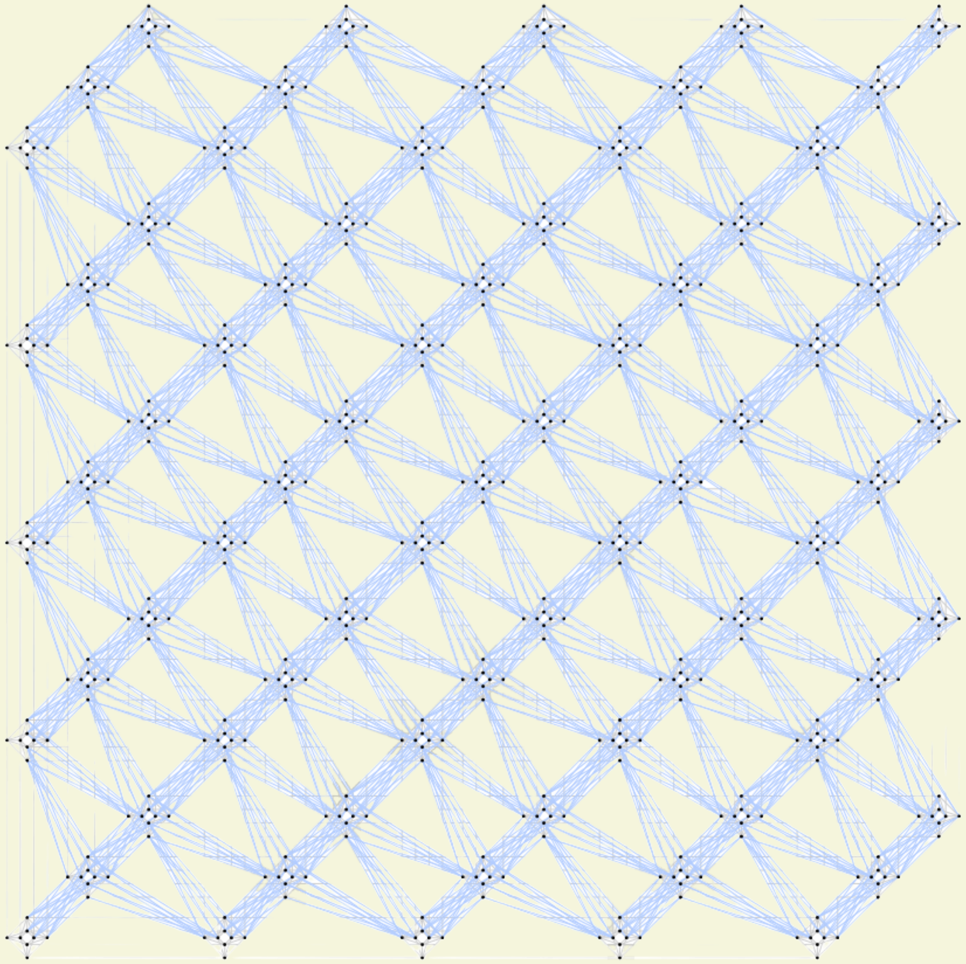


https://docs.ocean.dwavesys.com/en/stable/concepts/topology.html

Pegasus Graph



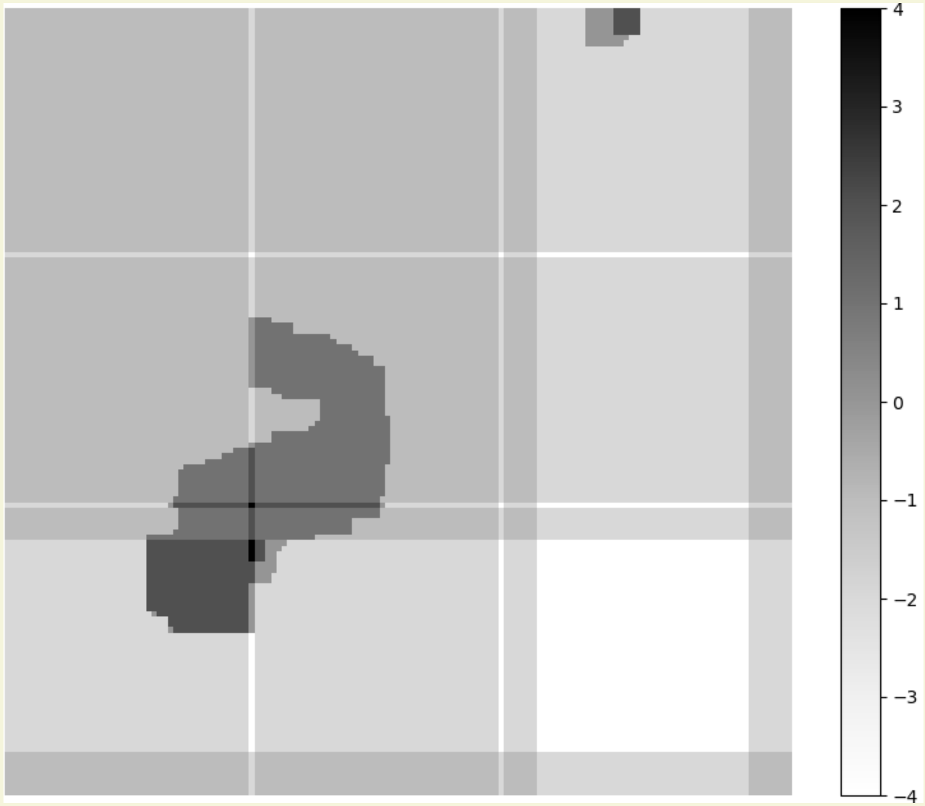




https://www.semanticscholar.org/paper/Pegasus%3A-The-second-connectivity-graph-for-quantum-Dattani-Szalay/16d0b6f7b4822a5093b1c204fe258d9ac2fd7820

Result

- Quantum Annealing
  - Patches: 16 * (47, 47, 2)
  - Default "minorminer" embedding algorithm.
- Parameters :
  - beta: 0.5
  - num_reads: 100



Thank you!

Appendix

One-vs-Rest Classification Algorithm

1. Normalize the data.
2. For each class $c \in C$:
   2.1 Split X_{train} into classes: c, ¬c (not c).
   2.2 Train a binary SVM using X_{train} and y_{train}.
   2.3 Calculate probabilities $P_i(c)$, $P_i(\neg c)$ of i-th pixel from X having/not having class c.
   2.4 Calculate **local energy**: $h_i = -1/4log(1/Pi(c) - 1)$.
   2.5 Build **Ising model**: $H(s) = -\sum_i h_i * s_i - \beta * \sum_{i\sim j} s_i * s_j$.
   2.6 Embed grid model into **chimera graph**.
   2.7 Sample K = 10 low energy states samples using DWave annealer.
   2.8 Unembed the model back to grid.
   2.9 For each pixel i: $P_i'(c) = \sum_{k=1}^{K} \frac{1}{\sum_{\xi=1}^{K} exp(-H(s^{[\xi]}) + H(s^{[k]}))} \times \delta(s_i^{[k]} = 1)$, where $s^{[k]}$ is a configuration and $H(s^{[k]})$ is energy of sample k.
3. For each pixel i assign class c_i^*: $c_i^* = argmax_{c\in C} P\prime_i(c)$.

https://www.researchgate.net/publication/367340565_Hyper-spectral_Image_Classification_using_Adiabatic_Quantum_Computation