Team Qubitrix

Open track - Macroscopic Quantum tunnelling

Content:

1.) stage 1

- Introduction to MQT, modeled washboard potential and some key simulations of different quantities

2.) stage 2

- Extend MQT to arrays of coupled Josephson junctions to study collective tunneling dynamics for optimization problems.

3.) stage 3

- Classical ML model to predict escape probability. Best model achieved for PCA + MLP combination with R2 score of 0.21

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Introduction to Macroscopic quantum tunneling

Quantum Tunneling in a Josephson Junction

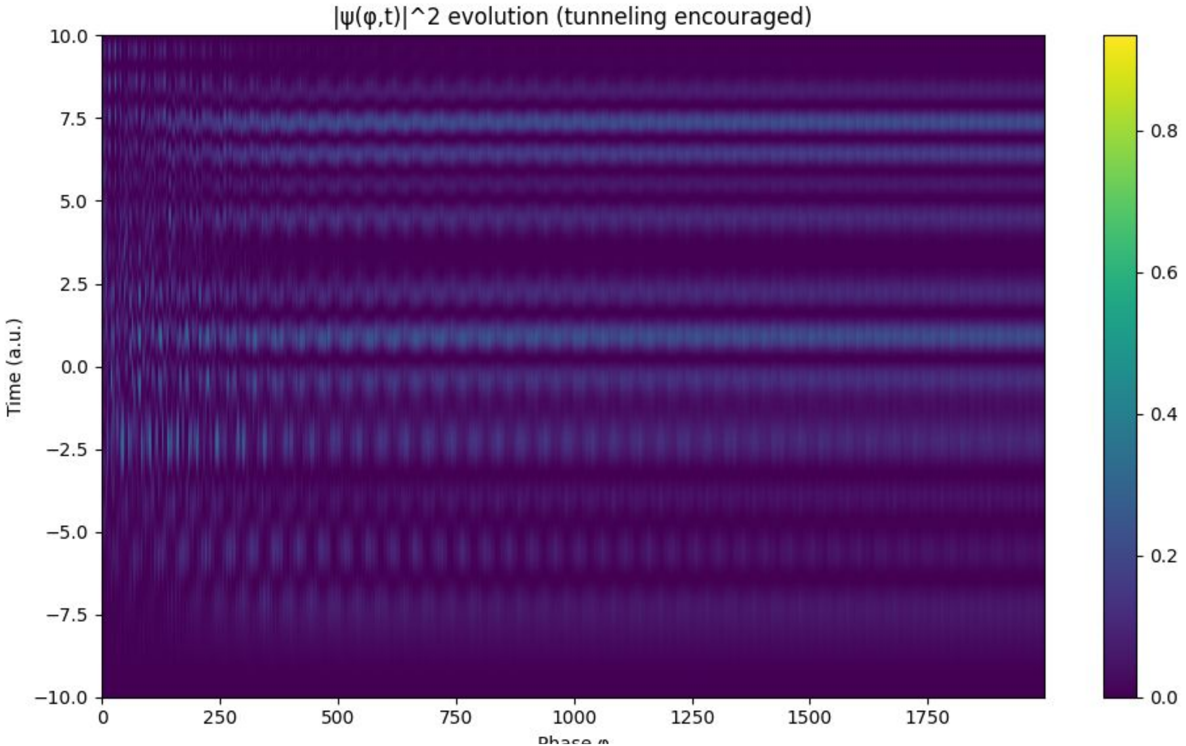
- What is Quantum Tunneling?

Quantum tunneling is one of the most fascinating consequences of quantum mechanics — it allows a particle to pass through an energy barrier even when it doesn't have enough classical energy to climb over it.

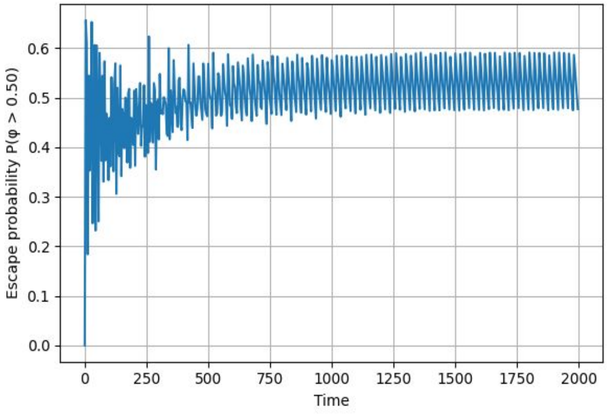
- What is MQT?

While MQT involves collective motion of macroscopic variables (e.g., magnetic flux or phase difference in a Josephson junction), representing the quantum behavior of an entire system.

Modeling and Simulation of Phase Escape in a Tilted Washboard Potential

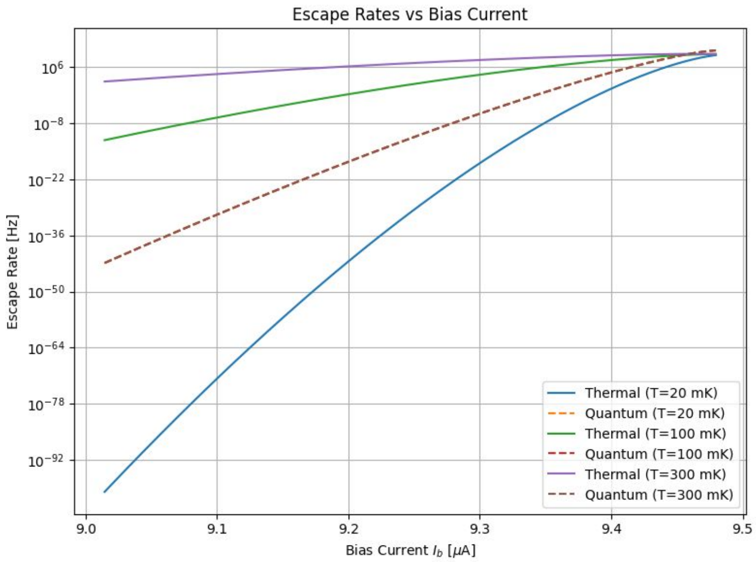


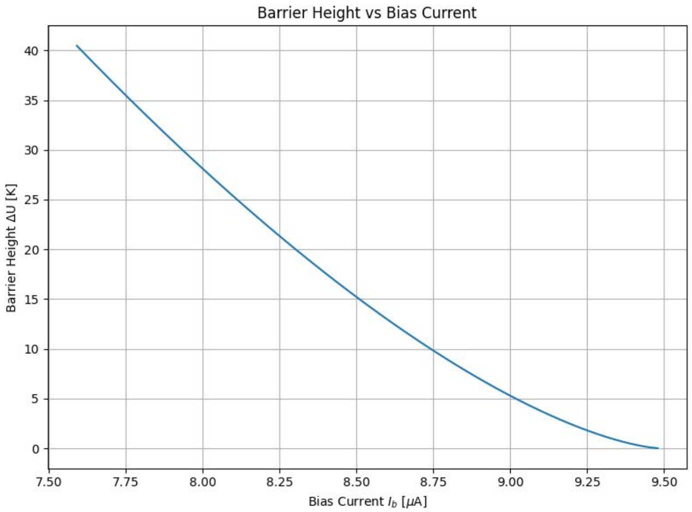
Description: quantum tunneling of the phase particle: the wavefunction, initially localized in a potential well, gradually leaks through the barrier, indicating escape due to tunneling. The periodic modulation reflects coherent oscillations and tunneling events encouraged by the reduced potential barrier and effective mass.



Description: Oscillations reflect coherent quantum dynamics; saturation indicates a steady-state tunneling rate.

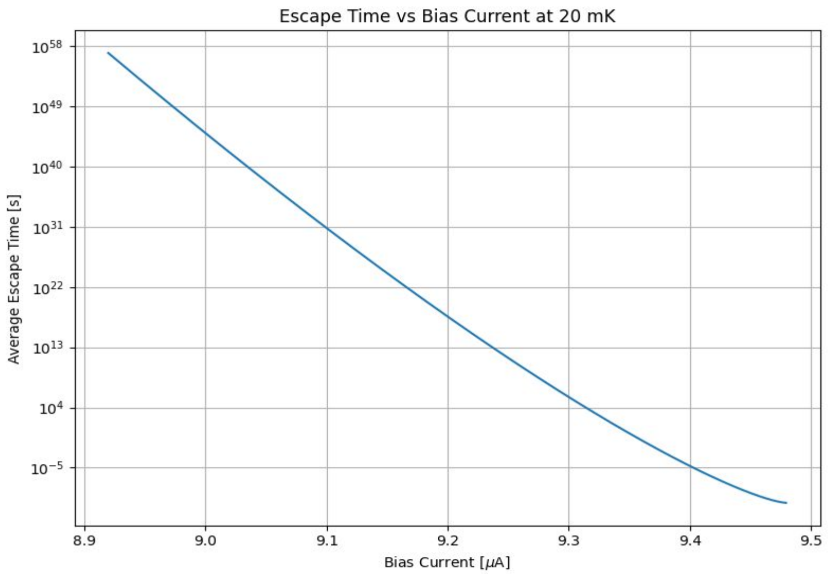
Key Quantities Simulated

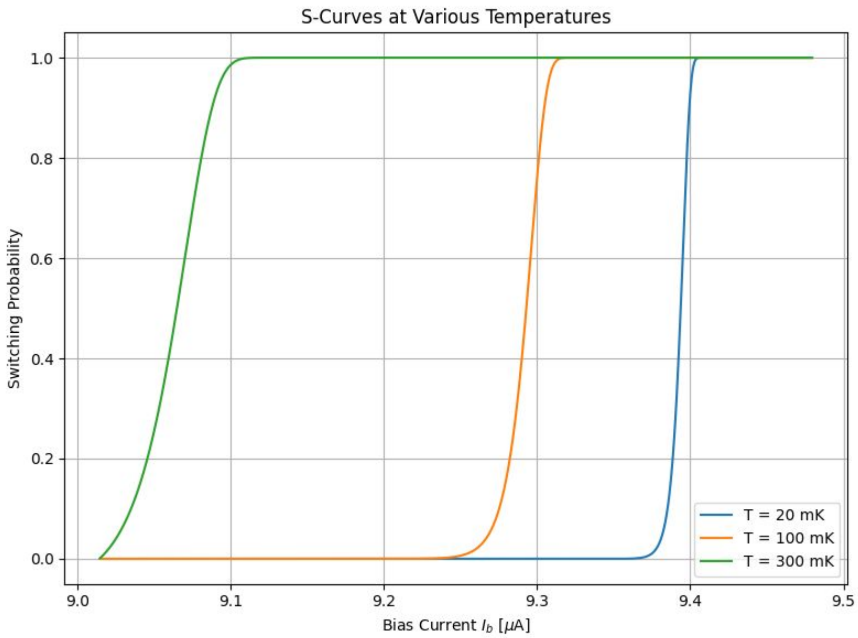




- As the bias current increases, the energy barrier decreases, leading to a **sharp rise** in escape rates.
- At **low temperatures (20 mK)**, the **quantum tunneling** rate dominates since the thermal rate is exponentially suppressed.
- At **higher temperatures (100 mK and 300 mK)**, **thermal activation** becomes dominant as thermal energy helps overcome the barrier.
- The **crossover point**, where thermal and quantum escape rates are comparable, marks the **quantum-to-classical transition** regime.

- As I_b **increases**, the barrier becomes **shallower**, reflecting the increased tilt of the potential.

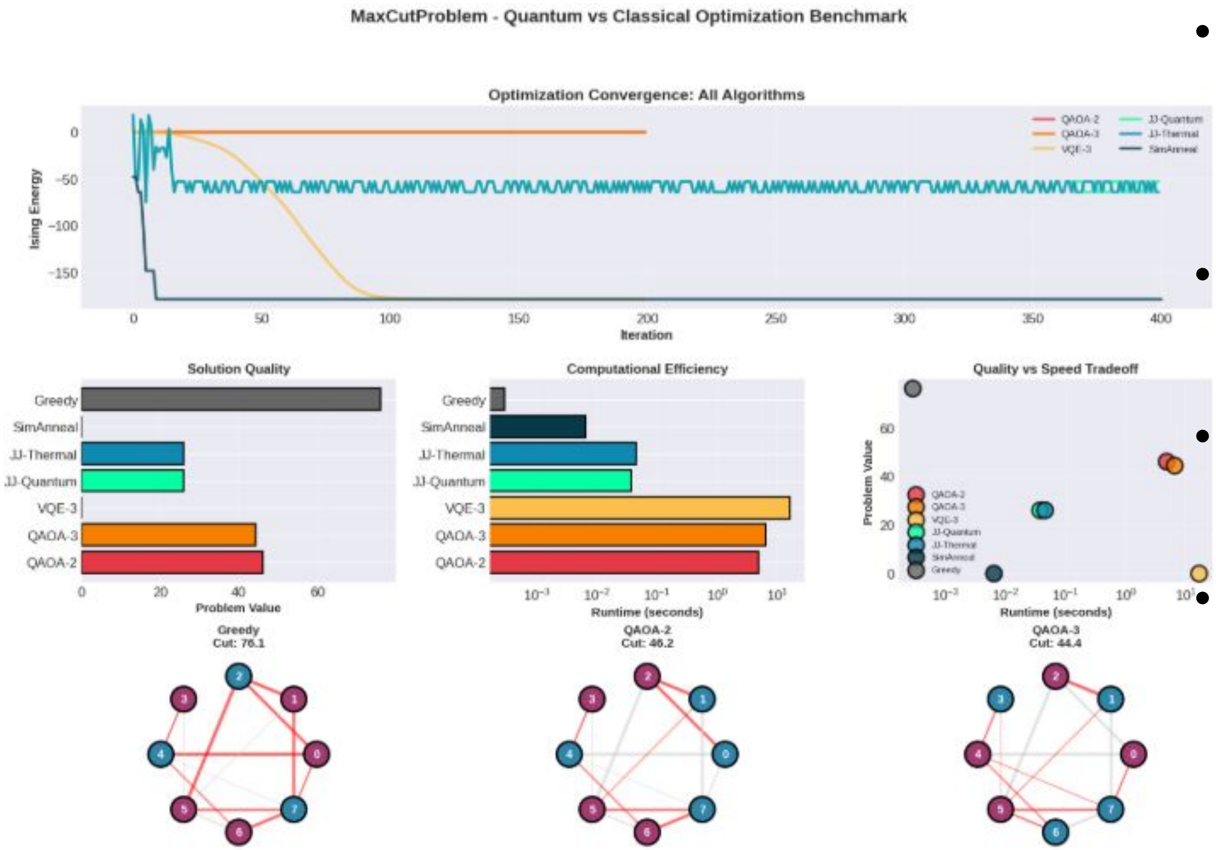




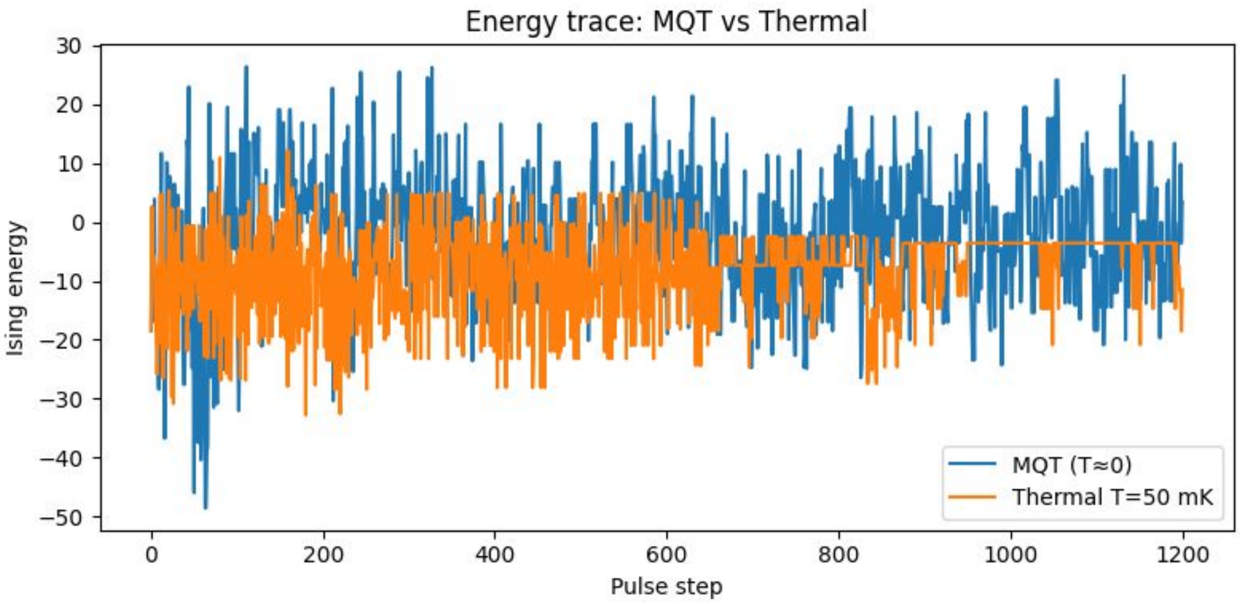
- As bias current increases, the barrier becomes **shallower**, leading to a **rapid drop** in escape time — sometimes below 1 s.

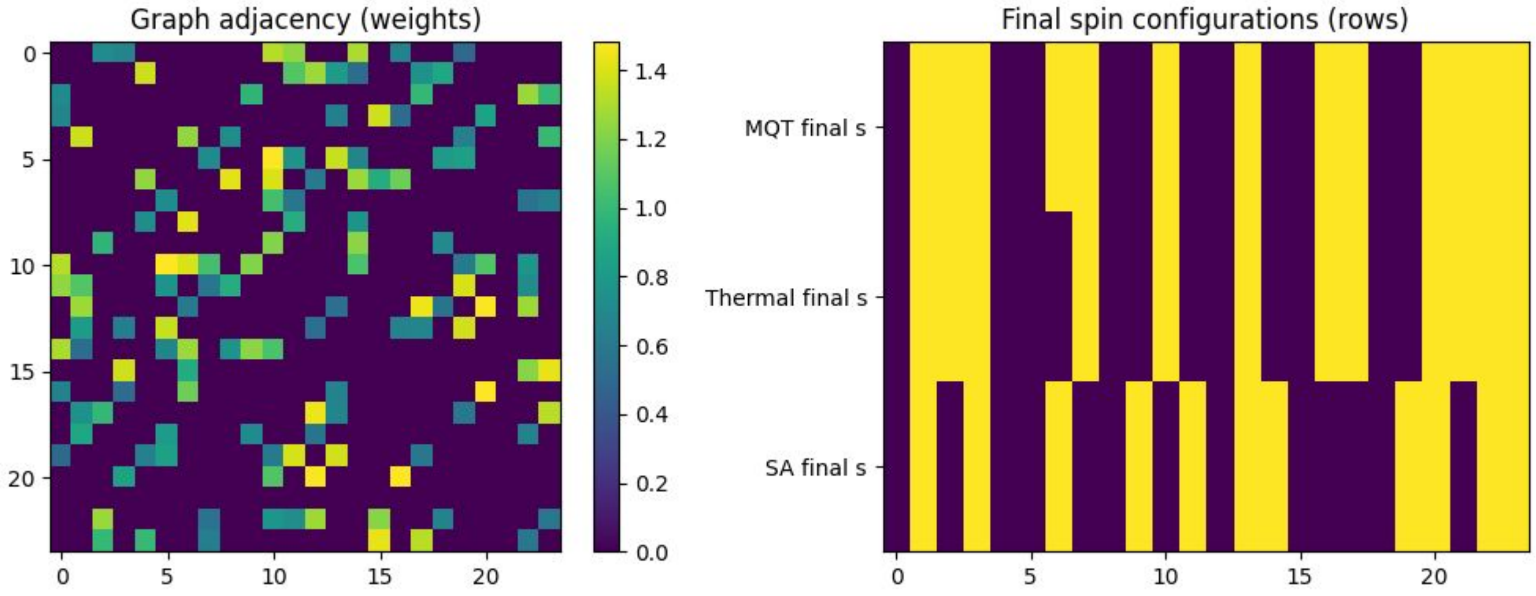
- Higher temperatures increase thermal fluctuations, enabling the phase particle to **escape earlier** and with more **statistical spread**, leading to a softer, more gradual S-curve.

MaxCut Solver Benchmark

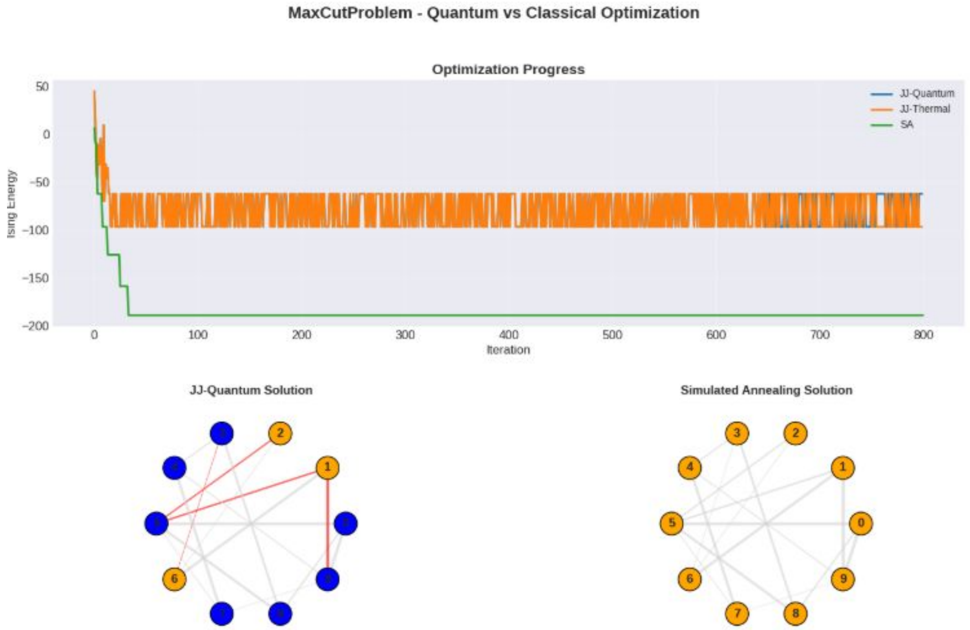


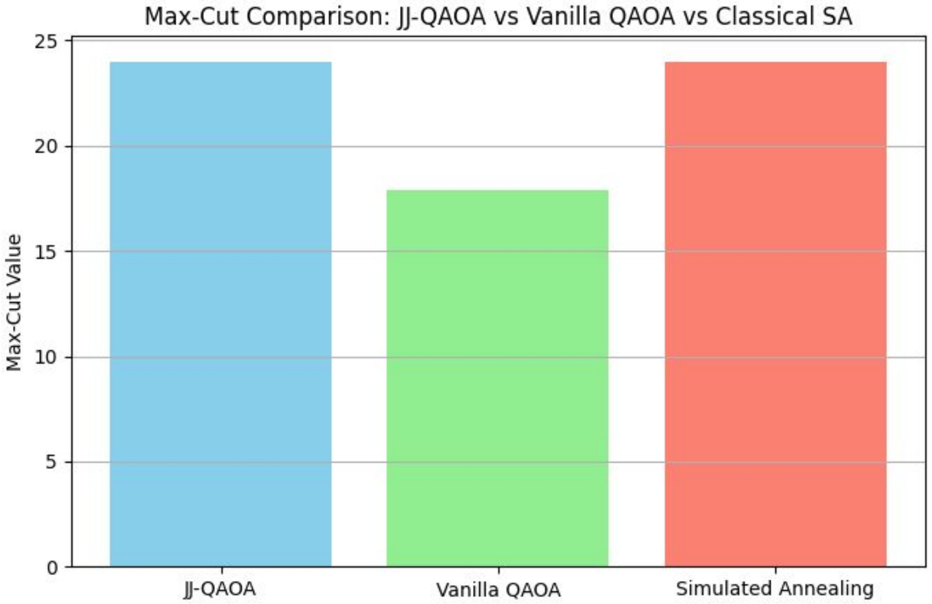
- **Josephson Junction (JJ) Solver:** Hardware-inspired stochastic simulation; spin flips via Macroscopic Quantum Tunneling (MQT) governed by tunneling rate (Γ□).
- **QAOA:** Hybrid VQA using parameterized Cost & Mixer unitaries optimized for maximum cut.
- **Trotterized QA:** Digital Adiabatic Quantum Annealing using discrete (Trotter) time steps.
- **Simulated Annealing (SA):** Classical baseline using Metropolis updates with a cooling schedule to escape local minima.

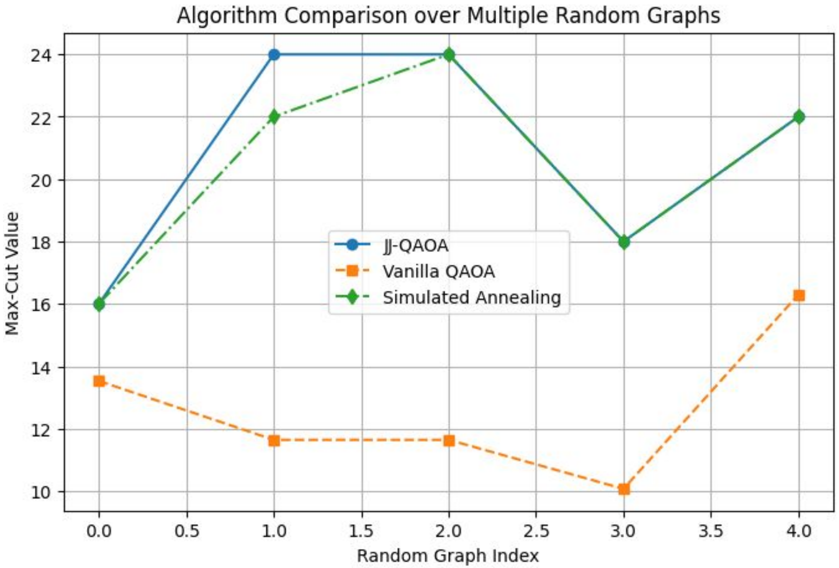

Energy trace: MQT vs Thermal
Ising energy
Pulse step
MQT (T≈0)
Thermal T=50 mK
30
20
10
0
−10
−20
−30
−40
−50
0
200
400
600
800
1000
1200



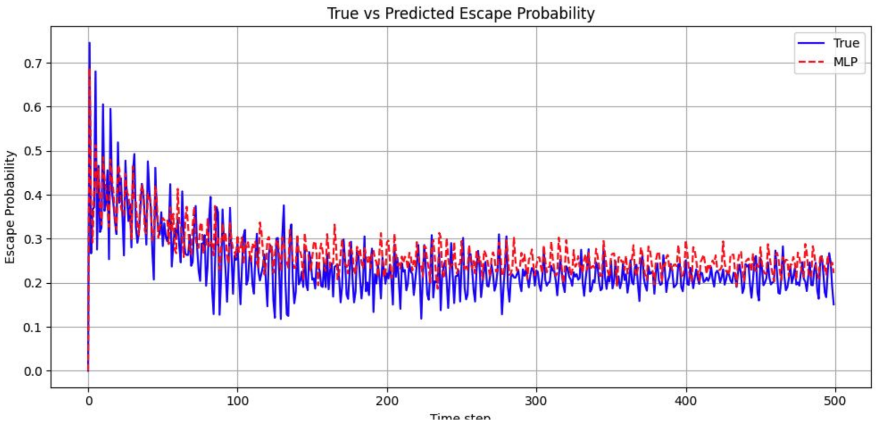
Graph adjacency (weights)
0
5
10
15
20
0
5
10
15
20
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Final spin configurations (rows)
MQT final s
Thermal final s
SA final s
0
5
10
15
20


MaxCutProblem - Quantum vs Classical Optimization
Optimization Progress
JJ-Quantum
JJ-Thermal
SA
Ising Energy
Iteration
50
0
−50
−100
−150
−200
0
100
200
300
400
500
600
700
800
JJ-Quantum Solution
Simulated Annealing Solution
2
1
6
3
4
5
0
9
8
7

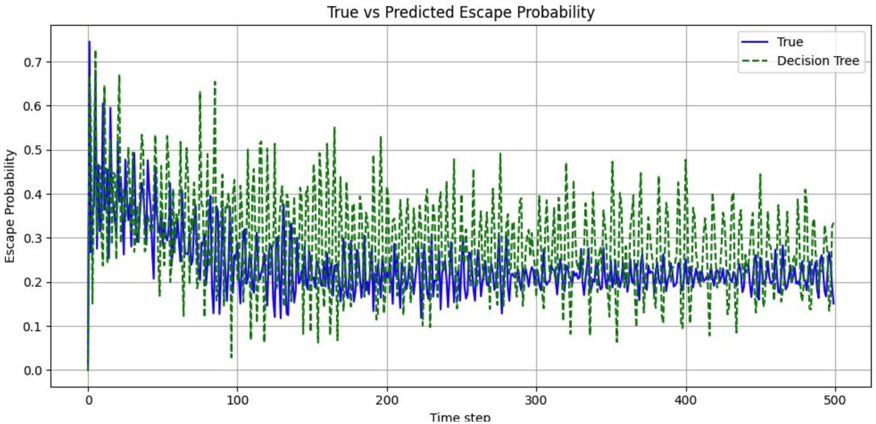

Max-Cut Comparison: JJ-QAOA vs Vanilla QAOA vs Classical SA
Max-Cut Value
0
5
10
15
20
25
JJ-QAOA
Vanilla QAOA
Simulated Annealing


Algorithm Comparison over Multiple Random Graphs
Max-Cut Value
10
12
14
16
18
20
22
24
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Random Graph Index
JJ-QAOA
Vanilla QAOA
Simulated Annealing

Surrogate Modelling for Potential Landscape & Dynamics (ML Task)



PCA + MLP prediction; R2 score = 0.21



PCA + Decision Tree prediction; R2 score = -0.4536

Escape Probability Prediction

References:

- Leggett, A. J. (1987). *Macroscopic quantum tunneling and related topics*. Journal of Superconductivity, **1**, 275–295
- The Royal Swedish Academy of Sciences - Nobel prize 2025 on MQT pdf
- Machine Learning Catalysis of Quantum Tunneling

Thank you