Introduction to Quantum Annealing: A Quantum Software Engineering Perspective

Pauli Taipale

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What is Quantum Annealing?

Quantum annealing is a quantum computational method used to find the minimum of a given objective function over a set of candidate solutions. It leverages quantum mechanics to solve optimization problems, particularly those that are computationally hard for classical computers. The process involves encoding the problem into a Hamiltonian, a mathematical representation of energy states, where the ground state corresponds to the optimal solution. By starting with a quantum system in a known ground state and slowly evolving it, quantum annealing allows the system to settle into the ground state of the problem Hamiltonian, effectively solving the optimization problem.

How is Quantum Annealing Different from Classical Computing?

Quantum annealing differs from classical computing in several ways:

- **Superposition:** Quantum bits (qubits) can exist in multiple states simultaneously, enabling parallel exploration of the solution space.
- **Tunneling:** Quantum systems can tunnel through energy barriers, potentially avoiding local minima that would trap classical algorithms.
- **Entanglement:** Correlations between qubits can encode complex interactions, enhancing the representation of certain problems.
- **Energy Landscape Navigation:** Unlike classical systems that move stepwise through the energy landscape, quantum annealing evolves the system globally.

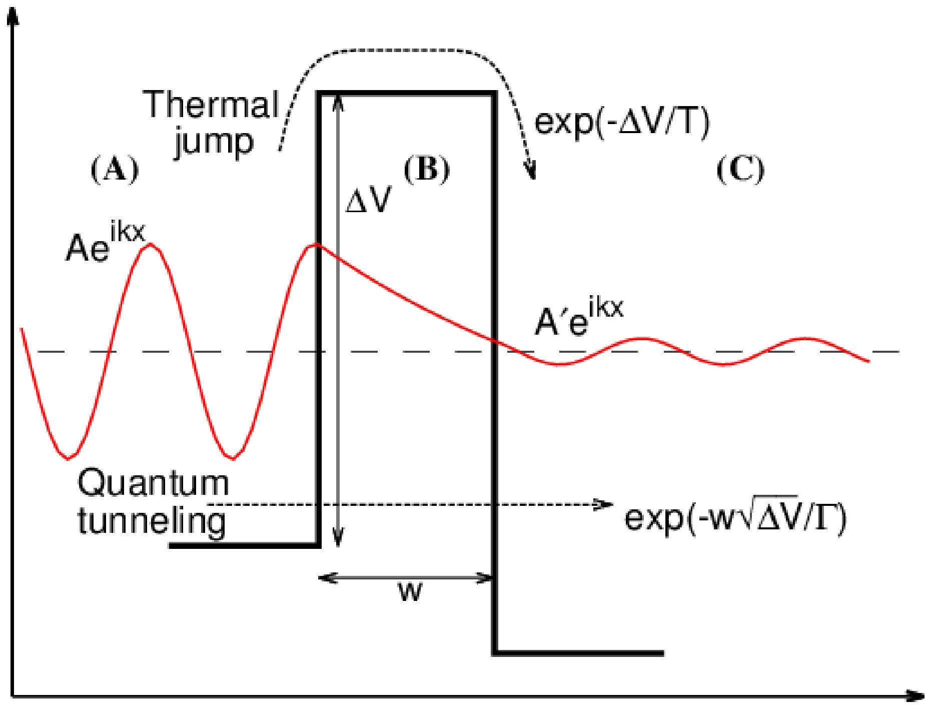

Figure 1: Schematic diagram indicating the advantage of quantum tunneling over thermal hopping across a potential barrier.

Key Quantum Phenomena in Quantum Computation

Quantum annealing exploits several quantum mechanical principles:

- **Quantum Superposition:** Enables simultaneous exploration of multiple configurations.
- **Quantum Tunneling:** Allows the system to pass through energy barriers, facilitating escape from local minima.
- **Adiabatic Evolution:** Ensures that the quantum system remains in the ground state if the evolution is slow enough.

D-Wave Quantum Annealing: Practical Considerations

D-Wave Systems is a pioneer in quantum annealing, providing hardware that implements quantum annealing for practical problem-solving. Key aspects of working with D-Wave systems include:

- **Problem Representation:** Problems are encoded into a Quadratic Unconstrained Binary Optimization (QUBO) form or Ising model, which maps directly to the hardware's architecture.
- **Minor Embedding:** Due to hardware connectivity constraints, logical qubits must often be mapped onto physical qubits through a process called minor embedding. This can lead to challenges such as longer chains of qubits.
- **Chains and Chain Breaks:** Physical qubits in a chain represent a single logical qubit. Chain breaks occur when these physical qubits fail to act as a single unit.
  - Use efficient embedding tools provided by D-Wave.
  - Optimize chain strength parameters to balance problem constraints and chain integrity.
  - Simplify problem formulation to reduce embedding complexity.
- **Debugging and Error Handling:**
  - **Detecting Errors:** Errors often manifest as high-energy solutions or inconsistent results across runs.
  - **Common Issues:**
    * Incorrect problem formulation.
    * Inefficient embedding leading to long or broken chains.
    * Suboptimal annealing schedules.
  - **Debugging Strategies:**
    * Validate QUBO or Ising model formulation.
    * Visualize embeddings to ensure logical coherence.
    * Experiment with annealing time and chain strength parameters.

Glossary

- **Quantum Annealing:** In quantum annealing, the quantum system starts from an initial state and then evolves over time, gradually moving toward a state that represents the optimal solution to a given problem. Quantum annealing does not enable universal quantum computing, i.e., programming in any desired way, but it is suitable for many optimization tasks. While classical annealing is inherently probabilistic and relies on randomness to explore the solution space, quantum annealing exploits quantum effects, such as tunneling and entanglement, to traverse the solution space more efficiently.

- **The Ising Model:** A mathematical model used in statistical mechanics to describe ferromagnetism in statistical physics. The model consists of discrete variables that represent magnetic dipole moments of atomic spins that can be in one of two states (+1 or 1). The Hamiltonian for an Ising model describes the energy of the system in terms of the spins and their interactions.

- **Quadratic Unconstrained Binary Optimization (QUBO):** An Ising model with two possible states for spin can be directly mapped onto a QUBO problem. A QUBO problem is characterized by a goal of minimizing (or maximizing) a quadratic polynomial function of binary variables (0 or 1). The conversion from an Ising model to a QUBO model involves representing the Ising spins (+1, −1) as binary variables (0, 1) and then encoding the interactions and fields of the Ising model into a matrix of coefficients that define the QUBO problem. The diagonal entries of this matrix represent linear terms, while the off-diagonal entries represent quadratic interactions between variables.