Exploring Quantum Optimization for Software Engineering

Yuechen Li

liyuechen@buaa.edu.cn

Beihang University

1st Workshop on Quantum Optimization Algorithms and Applications (Q-OptAA 2025)

Co-located with IEEE Congress on Evolutionary Computation (IEEE CEC 2025)

June 10, 2025, Hangzhou, China

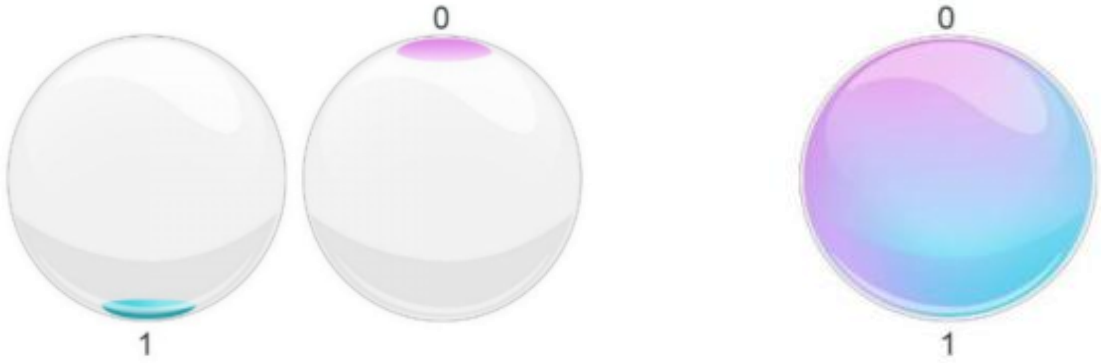
Content

1 Background: Opportunities for quantum computing

➢ Principle perspective:

- **Quantum computer**: a computer that exploits **quantum mechanical phenomena** (e.g., **both particles and waves**).
- **Computational unit** (more details can be referred to [1])
  - Classical bit: either 0 (low voltage) or 1 (high voltage)
  - Quantum bit (a.k.a. qubit): **other than** the two values (|0⟩ and |1⟩)

the North Pole



the South Pole

the entire sphere

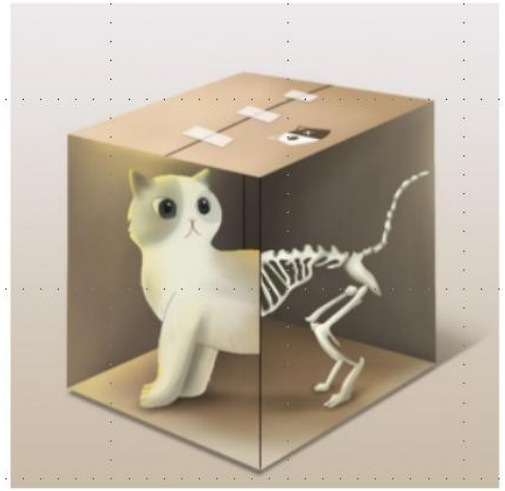
The Bloch sphere for qubit

Physical support:

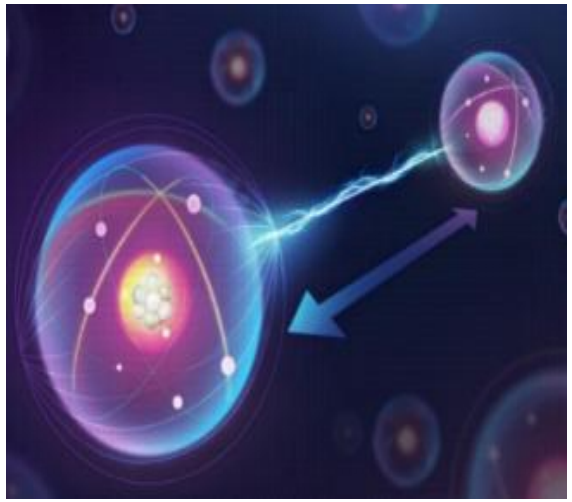
- ✓ Photon
- ✓ Coherent state of light
- ✓ Electrons
- ✓ Nucleus
- ✓ Josephson junction
- ✓ …

1 Background: Opportunities for quantum computing

➢ Principle perspective:



The Schrödinger's cat



Entangled qubits with far distance

Quantum superposition: enabling a system in the linear combination of all possible states.

Quantum entanglement: allowing two qubits sharing and correlating information to represent more complicated states.

Possible advantages of exploring quantum principles result in **quantum-inspired techniques**.

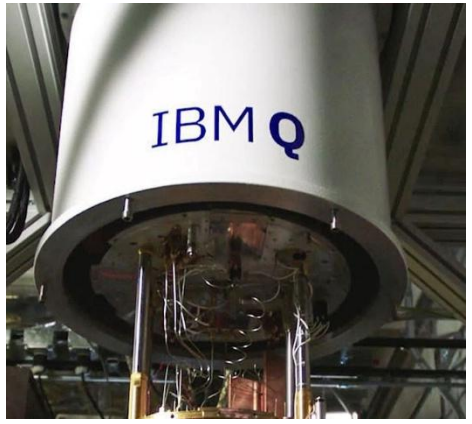
1 Background: Opportunities for quantum computing

➢ Hardware perspective:

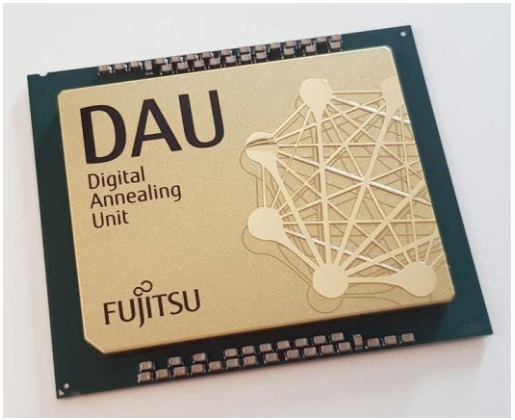
Current state: **Noisy Intermediate-Scale Quantum (NISQ)** era

- **Quantum annealers**: exploit **quantum tunneling and superposition** to find **low-energy of a quantum system**.
- **Gate-based quantum computers**: propose **universal** quantum gates to implement designed **quantum algorithms**.
- *__Quantum-inspired hardware__: **imitate** quantum mechanical phenomena on specific **classical hardware** (e.g., digital annealing, coherent Ising machines).

D-wave's quantum annealer



IBM's gate-based quantum computer



Fujitsu's digital annealing

1 Background: Opportunities for quantum computing

➢ Algorithm perspective:

- **NISQ-ready quantum algorithms**: find some practical useful examples **even if NISQ is used**, such as hybrid quantum-classical methods.

  ✓ Quantum approximate optimization algorithm (QAOA);
  ✓ Variational quantum eigensolver (VQE);
  ✓ Quantum machine learning (QML).

- **Post-NISQ quantum algorithms**: practically work only under the assumption that **a large number of qubits** are available and that **error correction** is possible.

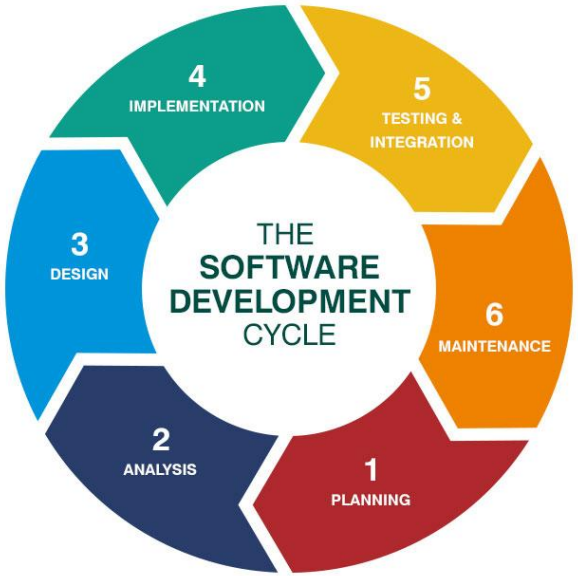
  ✓ Grover's search;
  ✓ Hadamard testing;
  ✓ Harrow-Hassidim-Lloyd algorithm (HHL).

Candidates for optimization tasks: QAOA, VQE, Grover's search.

1 Background: Quantum software engineering

➢ The scope of quantum software engineering (QSE) [2] :

- **SE4QC**: focusing on the principles, methodologies, standards and tools for **designing**, **developing**, **testing**, **maintaining**, and **managing** quantum software systems;
- **QC4SE**: applying **quantum-based** techniques, including quantum algorithms such as quantum annealing, to solve complex problems in **both classical and quantum** software systems.



Software development life cycle

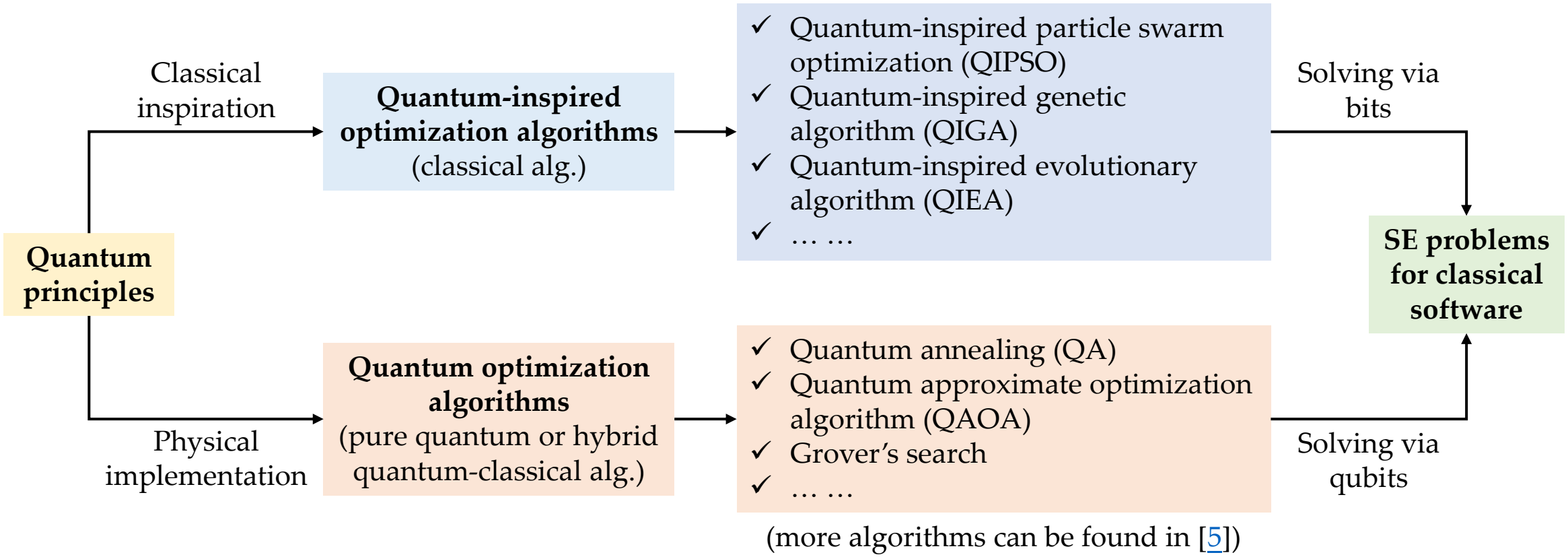
- ☐ Software requirements
- ☐ Software architecture
- ☐ Software design
- ☐ Software construction
- ☐ Software testing
- ☐ Software engineering operations
- ☐ Software maintenance
- ☐ Software security
- ☐ Software configuration management
- ☐ Software engineering management
- ☐ Software engineering process
- ☐ Software engineering models and methods
- ☐ Software quality
- ☐ Software security
- ☐ Software engineering professional practice
- ☐ Software engineering economics

Software engineering activities listed by *Software Engineering Body of Knowledge v4.0* (SWEBOK) [3]

1 Background: Quantum software engineering

➢ Preliminary attempt on QC4SE:

Quantum-based techniques (i.e., **quantum** and **quantum-inspired algorithms**) for the optimization of **classical SE problems**, particularly the ones investigated in **Search-based Software Engineering (SBSE)** [4].



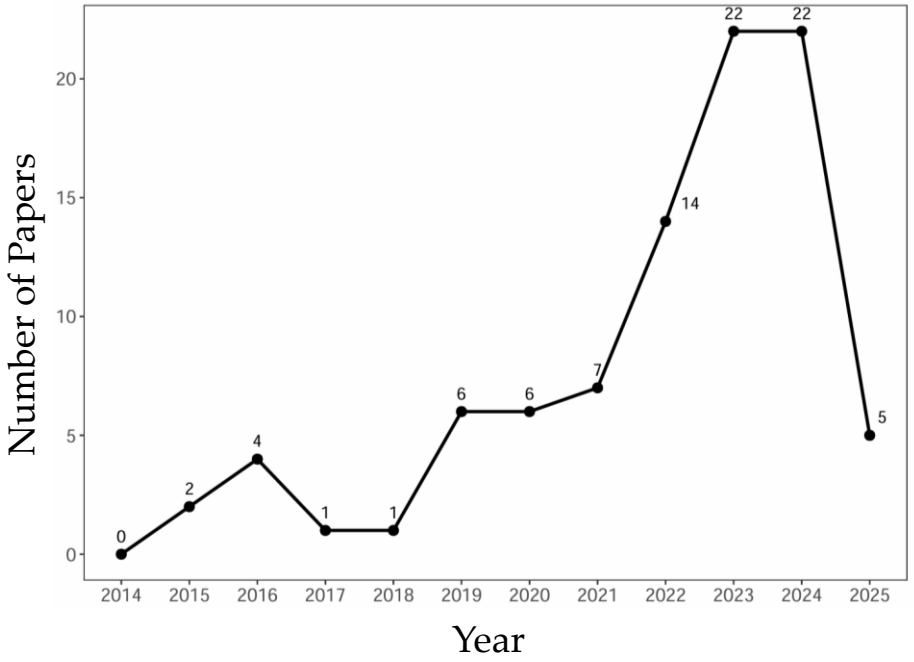
(more algorithms can be found in [5])

Content

2 Literature review: Publication trends

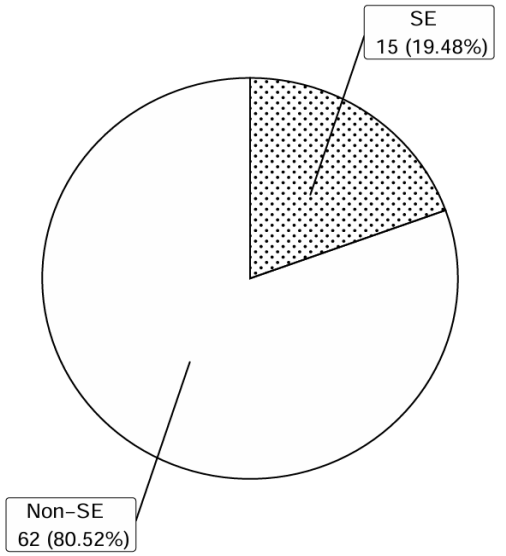
Note: *The results and findings of this section are selected from empirical studies in our recent systematic literature review.*

➢ Publication time & venues :



Trend over years

- ✓ Keyword searching: 2014-2024 (excluding arxiv);
- ✓ Snowballing: until April 2025 (including arxiv);
- ✓ In total, **77** primary papers are collected.

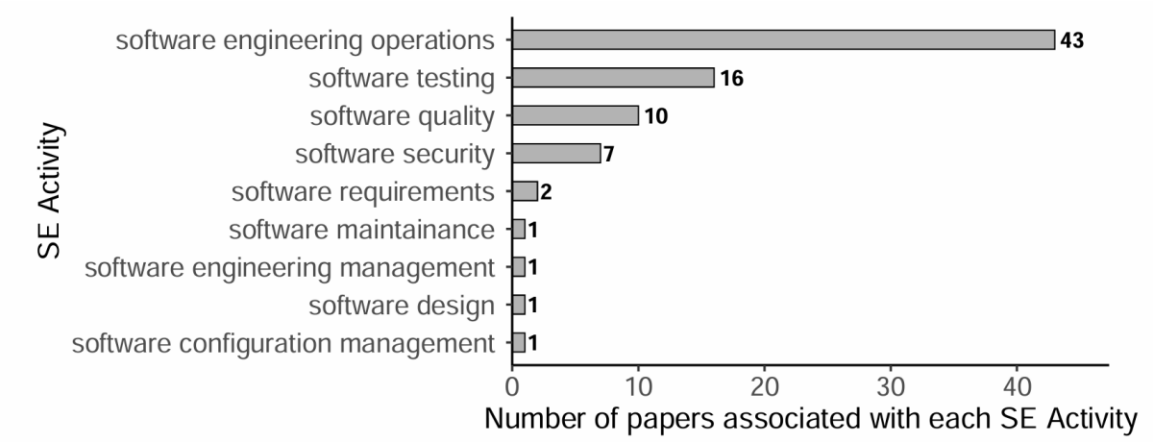


Number of primary studies whose venues belong to SE or Non-SE

- ✓ **Top SE journals**: including ACM Transactions on Software Engineering and Methodology (TOSEM) and IEEE Transactions on Software Engineering (TSE);
- ✓ **QC-related venues**: including IEEE International Conference on Quantum Computing and Engineering (QCE).

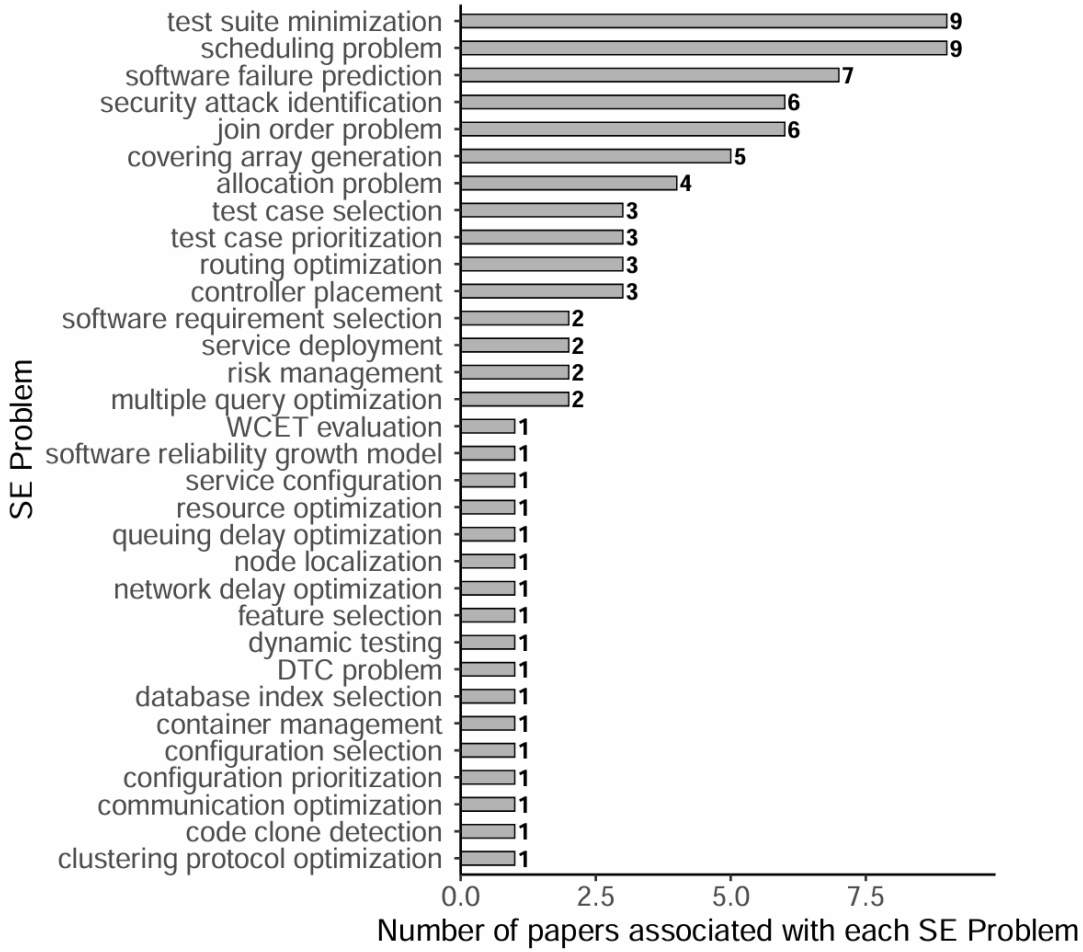
2 Literature review: SE activities and problems

➢ Addressed SE problems:



Distribution of papers across SE activities

- ✓ SE operations involve the interaction with other communities, such as databases, networking, and cybersecurity.
- ✓ Software testing gains great attention due to its high costs in software development life cycle.
- ✓ Some SE activities (e.g., software requirements) are widely investigated in SBSE, but seldomly explored by quantum-based optimization.



Distribution of papers across SE problems

2 Literature review: Used approaches

➢ Objectives of optimization problems:

- **Definitions in SBSE:**
  - ✓ **Single-objective**: a unique objective;
  - ✓ **Multi-objective**: 2 or 3 objectives;
  - ✓ **Many-objective**: 4 or more objectives.

- **Problem perspective**: objectives proposed according to requirements for SE problems to be solved

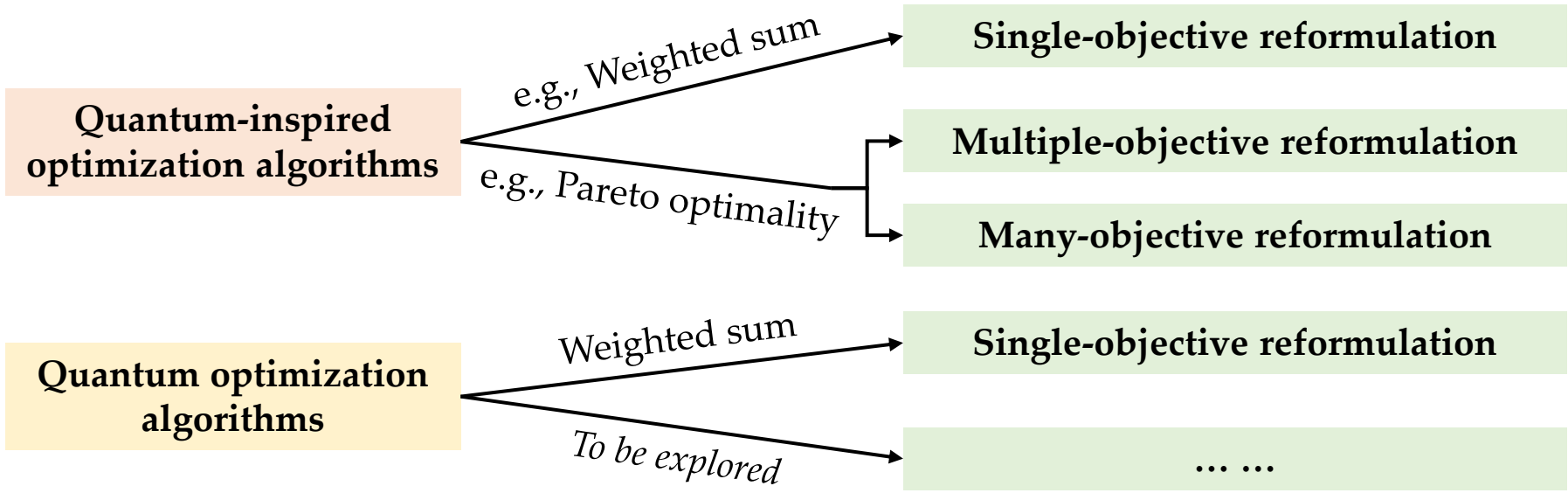
> *Example*: Test case minimization for regression testing with multiple objectives.
>
> **a)** **Maximize** the fault-detection capability;
> **b)** **Minimize** the execution time;
> **c)** **Minimize** the size of the reduced test suite.

High-level objectives for SE: **cost** and **effectiveness** that usually conflict with each other.

2 Literature review: Used approaches

➢ Objectives of optimization problems:

- **Reformulation perspective**: simplification or adaption to the approach



Example: Weighted sum for cost $\mathcal{O}_{\text{cost}}(\mathbf{x})$ and effectiveness $\mathcal{O}_{\text{effect}}(\mathbf{x})$,

$$\mathcal{O}_{\text{total}}(\mathbf{x}) = w\mathcal{O}_{\text{cost}}(\mathbf{x}) + (1-w)\mathcal{O}_{\text{effect}}(\mathbf{x})$$

w : user-defined weight, $\mathbf{x}$: the encoded solution.

2 Literature review: Used approaches

➢ Objectives of optimization problems:

- **Mathematical models for quantum optimization**

  Quadratic form:

$$\min \mathcal{O}(\mathbf{x}) = \sum_i Q_{i,i} x_i + \sum_{i<j} Q_{i,j} x_i x_j$$

  - ✓ **Quadratic unconstrained binary optimization (QUBO):** $x_i \in \{0,1\}$**;**
  - ✓ **Quadratic unconstrained discrete optimization (QUDO):** $x_i \in \mathbb{Z}$**;**
  - ✓ **Ising model:** $x_i \in \{+1,-1\}$ refers to the spin, which can be physically interpreted.

  Higher-order form: **Higher-order unconstrained binary optimization (HUBO)**

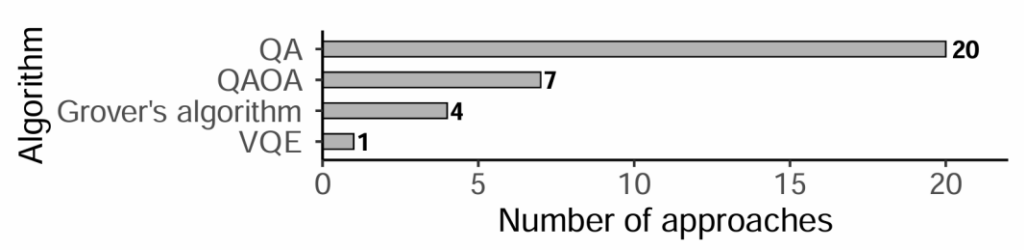
  Example: The clause formula $x_1 \vee x_2 \vee \neg x_3$ serving as the constraint can be converted into a HUBO model,

$$(1-x_1)(1-x_2)x_3 = (1+x_1x_2-x_1-x_2)x_3 = x_1x_2x_3 - x_1x_3 - x_2x_3 + x_3$$

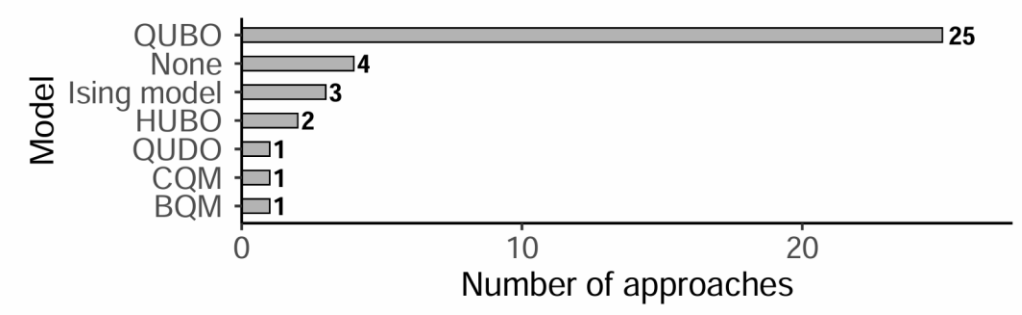
2 Literature review: Used approaches

➢ Approaches to solve optimization problems:

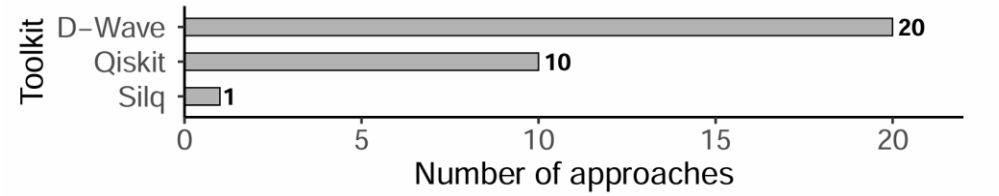
- **Results for quantum approaches and their implementations**



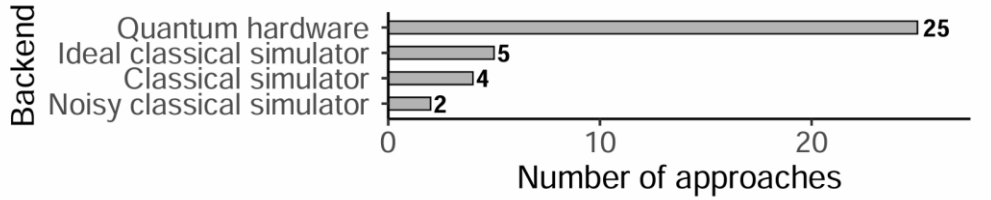
Frequencies of used quantum algorithms



Frequencies of used mathematical models



Frequencies of applied toolkits (quantum computing platforms)



Frequencies of selected backends

- ✓ Quantum annealing via D-Wave is currently the most widely used quantum algorithm.
- ✓ QUBO model is the most frequently utilized for objective formulation
- ✓ Quantum hardware has been the most extensively tested.

2 Literature review: Used approaches

➢ Approaches to solve optimization problems:

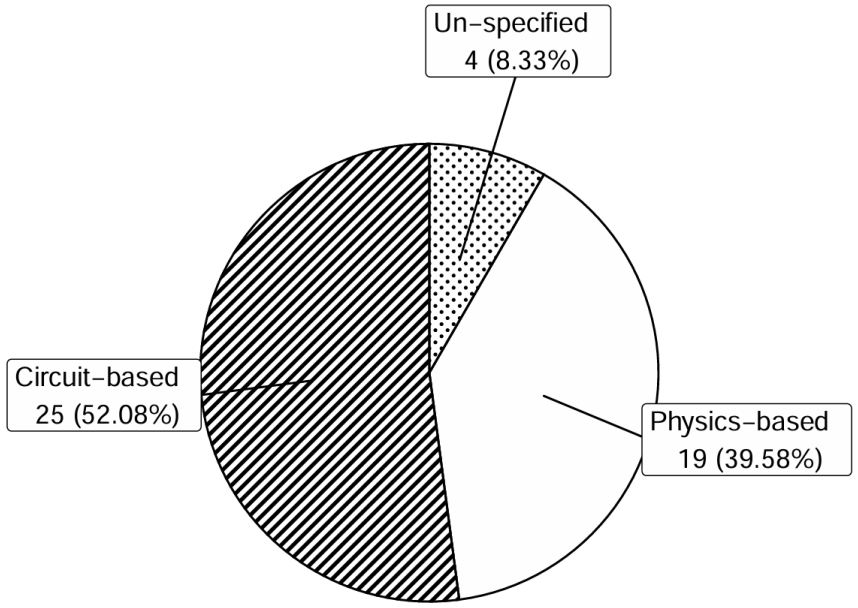
- **Results for quantum-inspired optimization**

Particle swarm optimization algorithm (16, 33.33%)
Genetic algorithm (8, 16.67%)
Salp swarm algorithm (4, 8.33%)
Evolutionary algorithm (3, 6.25%)
Gravitational search algorithm (3, 6.25%)

Top-5 base algorithms for quantum inspiration

Remark for inspiration mechanisms:

- ✓ **Circuit-based inspiration**: involve the quantum circuit model (e.g., qubit, quantum gate), and iterate via unitary matrices (i.e., quantum gates).
- ✓ **Physics-based inspiration**: include quantum physical concepts (e.g., wavefunction, potential well), and iterate by Monte Carlo sampling.



Number and proportion of quantum-inspired solutions by types of inspiration mechanisms

Content

3 Future directions

➢ SE topics not yet covered:

Chapter	Title	Covered?	Chapter	Title	Covered?
1	Software Requirements	✓	9	Software Engineering Management	✓
2	Software Architecture	✗	10	Software Engineering Process	✗
3	Software Design	✓	11	Software Engineering Models and Methods	✗
4	Software Construction	✗	12	Software Quality	✓
5	Software Testing	✓	13	Software Security	✓
6	Software Engineering Operations	✓	14	Software Engineering Professional Practice	✗
7	Software Maintenance	✓	15	Software Engineering Economics	✗
8	Software Configuration Management	✓			

Coverage of SE activities listed in SWEBOK

Suggested directions:

- **Software architecture** (being never explored in quantum-based optimization):
  Perform architecture tradeoff analysis based on the quality attributes;
- **Software requirements** (being seldomly explored in quantum-based optimization):
  Investigate requirement prioritization;
- **Software testing** (being widely explored in quantum-based optimization but scarcely involving other problems):
  Study scenario-based testing with search, and mutation testing with search;
- … …

3 Future directions

➢ Mapping of solutions to problems:

- **Handling constraints for quantum optimization:**
  - **Encoding inequalities**: Introduce reasonable slack variables or reformulate the objective function.
  - **Mapping to benchmark problems**: Transform SE problems into benchmark problems in quantum computing, such as Maximum cut (Max-cut), Boolean satisfiability problem (SAT).

- **Enhancing hybrid quantum-classical methods:**
  - **Decomposition**: Decompose a large problem into many sub-problems for NISQ devices.
  - **Warm-start and cold-start methods**: Consider preprocessing or postprocessing when using quantum optimizers.

- **Extending quantum-inspired algorithms:**
  - **More sophisticated algorithms**: Inspired from other optimization algorithms or explore other inspiration mechanisms.
  - **Hybrid paradigms:** Explore potential integration with quantum optimization approaches [6].

References (selection)

[1] Nielsen M A, Chuang I L. Quantum computation and quantum information[M]. Cambridge university press, 2010.

[2] Pezzè M, Abrahão S, Penzenstadler B, et al. A 2030 roadmap for software engineering[J]. ACM Transactions on Software Engineering and Methodology, 2025, 34(5): 1-55.

[3] H. Washizaki, eds., Guide to the software engineering body of knowledge (SWEBOK Guide), Version 4.0, IEEE Computer Society, 2024; www.swebok.org.

[4] Harman M, Mansouri S A, Zhang Y. Search-based software engineering: Trends, techniques and applications[J]. ACM Computing Surveys (CSUR), 2012, 45(1): 1-61.

[5] Abbas A, Ambainis A, Augustino B, et al. Challenges and opportunities in quantum optimization[J]. Nature Reviews Physics, 2024: 1-18.

[6] Qiu Q, Zhang L, Wu M, et al. A practical applicable quantum-classical hybrid ant colony algorithm for the NISQ era[J]. arXiv preprint arXiv:2410.17277, 2024.

Acknowledgments

The talker appreciates Prof. Tao Yue and Prof. Man Zhang for their great contributions to the involved systematic literature review. Besides, the talker thanks for the public webs and repositories that offer pictures for the introduction of quantum computing

Thanks for listening !

Yuechen Li

liyuechen@buaa.edu.cn

Beihang University

1st Workshop on Quantum Optimization Algorithms and Applications (Q-OptAA 2025)

Co-located with IEEE Congress on Evolutionary Computation (IEEE CEC 2025)

June 10, 2025, Hangzhou, China