Quantum Software Testing
A Brief Introduction

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May 17, 2023 ICSE 2023 Technical Briefing

Outline

- Quantum Computing: A Brief Introduction
- Quantum Software Engineering: Our Vision
- Quantum Software Testing: the State of the Art
- Quantum Software Testing Techniques

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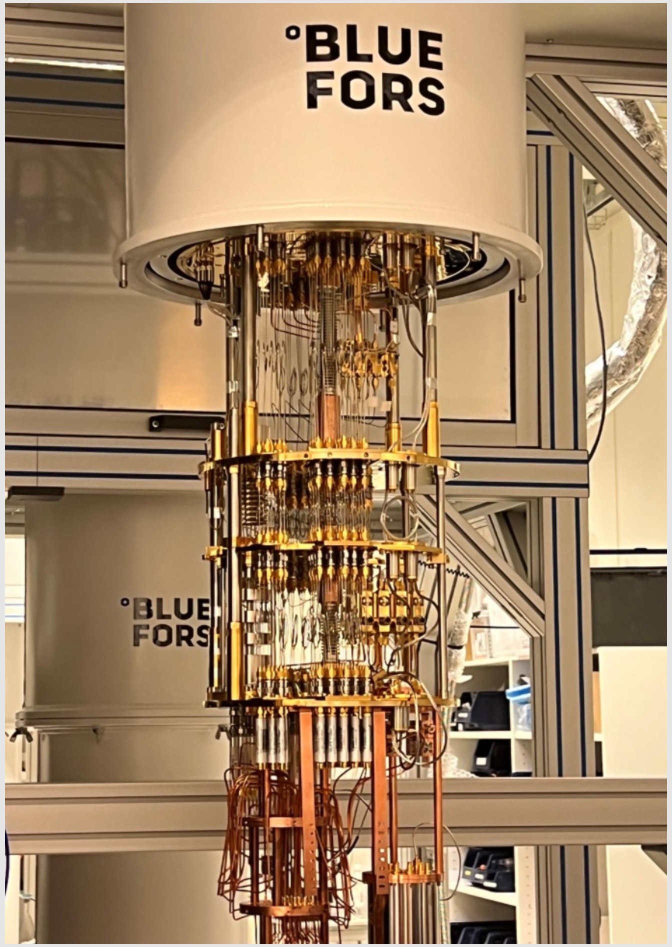
Quantum Computing (QC)

- QC promises to revolutionize classical computing.
- Quantum Computers
  - Gate-based quantum computers, e.g., IBM's Osprey, Google's Sycamore,
  - Annealing-based quantum computers, e.g., D-Wave
  - Photonic quantum computers: e.g., USIC's Jiuzhang, Xanadu's X24…
- Platforms
  - IBM Quantum Experience
  - D-Wave
  - Quantum Inspire from QuTech
  - Microsoft Quantum computing platform…
- High level programming languages
  - OpenQL by TU Delft, Q# by Microsoft, Qiskit by IBM, Cirq by Google



QAL 9000 quantum computer
Chalmers/Wallenberg Centre for Quantum Technologies, Sweden

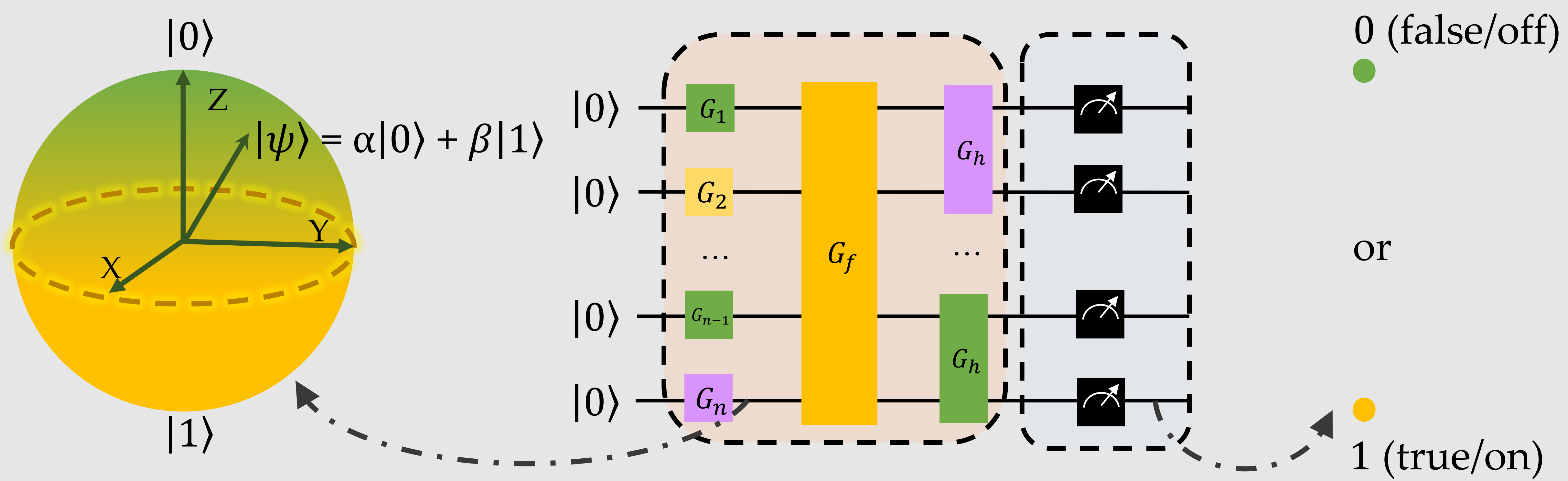
<u>QC is becoming a reality!</u>

Why quantum is different?

Qubit

Quantum Circuit

Bit



Bloch Sphere (1 qubit)

Quantum Gates

Measurements

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Quantum Software Engineering

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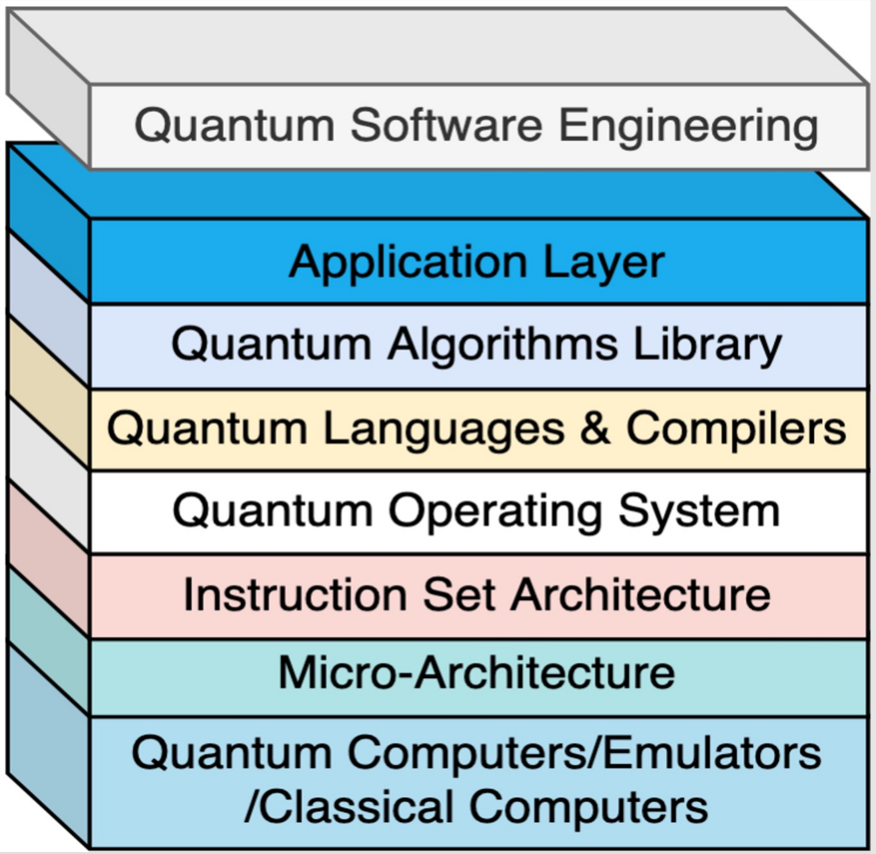
Quantum Software Engineering



Layered QC Architecture
(Prof. Koen Bertels's Vision)

Quantum software is at the core of the promised revolutionary QC applications.

Quantum software engineering enables cost-effective and scalable development of dependable quantum software.

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Shaukat Ali, Tao Yue, and Rui Abreu. 2022. When software engineering meets quantum computing. Commun. ACM 65, 4 (April 2022), 84–88. https://doi.org/10.1145/3512340

Why Quantum Software Engineering?

- **Application domains** are hard to comprehend.
- **Quantum software engineers** need to have *basic* knowledge about quantum mechanics, algorithms and their analysis, and more.
- Therefore, we need **tools**, **methodologies**, **standards**, **education**, etc. to help.

Chemistry

AI and ML

Drug Design & Development

Weather Forecasting

Financial Modeling

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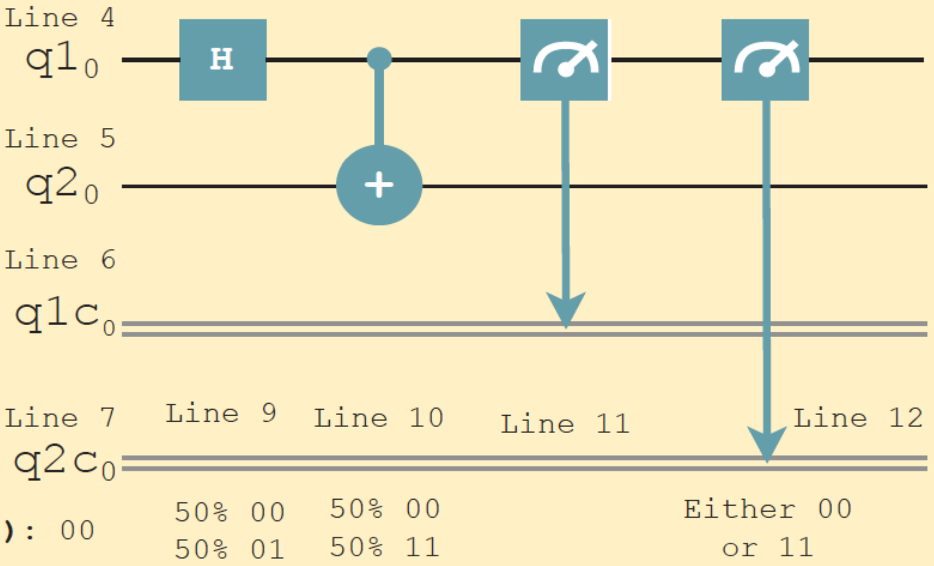
Quantum program, circuit and its execution

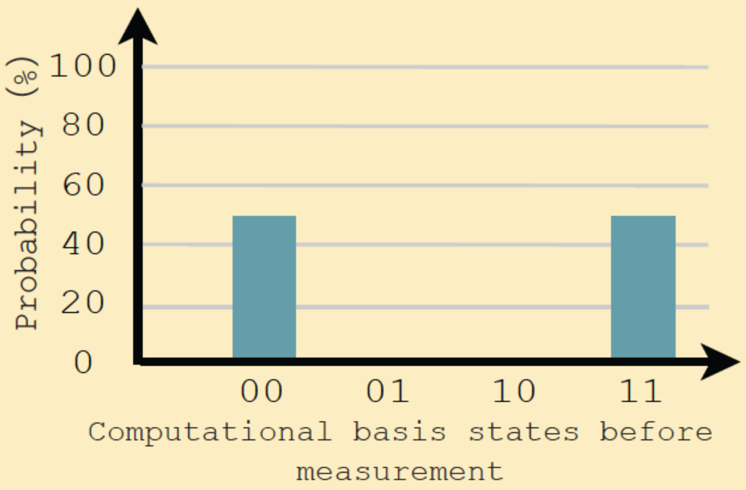
Code

```
1  OPENQASM 2.0;
2  include "qelib1.inc";
3
4  qreg q1[1];
5  qreg q2[1];
6  creg q1c[1];
7  creg q2c[1];
8
9  h q1[0];
10 cx q1[0],q2[0];
11 measure q1[0] -> q1c[0];
12 measure q2[0] -> q2c[0];
```

Quantum Circuit

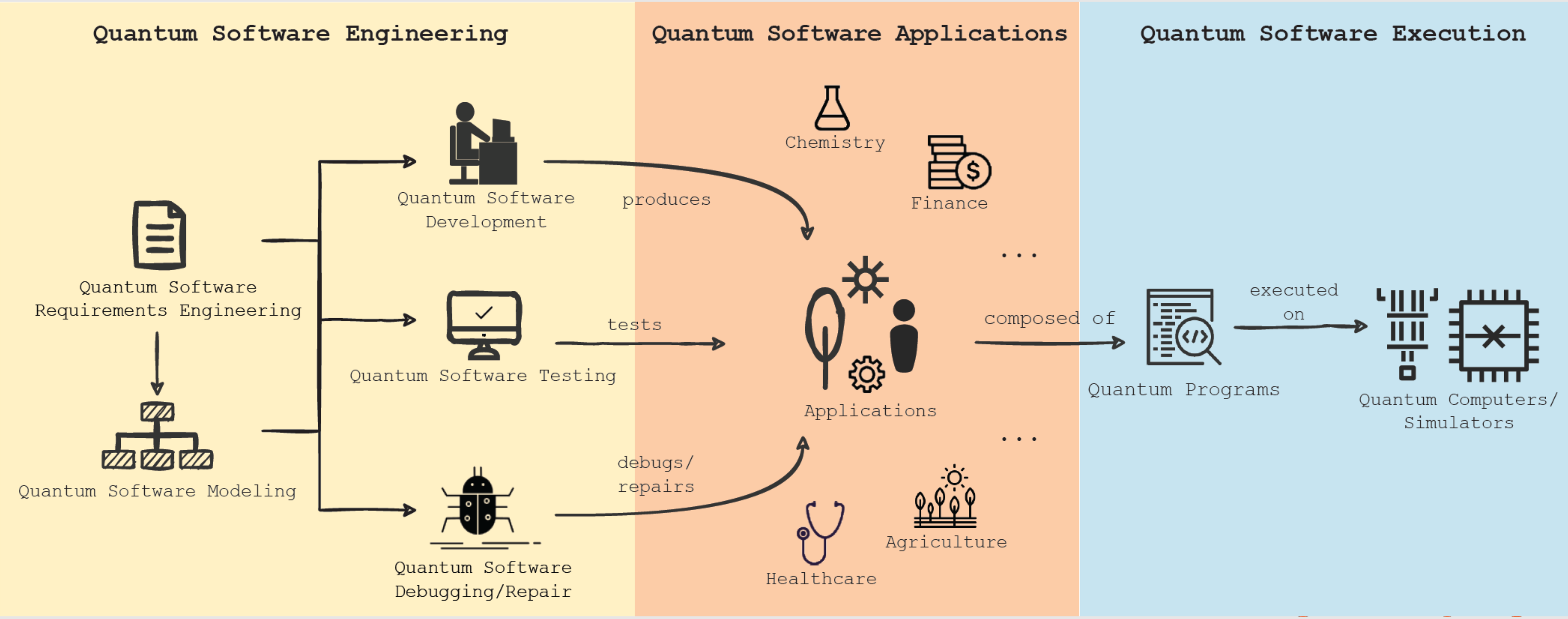


Execution Result



Description:
Lines 4-5 initialize two quantum registers (q1 and q2) in 0 states. Each register holds one qubit. **Lines 6-7** initialize two classical registers that will store the qubit values after the measurement (**Lines 11-12**). **Line 9** puts q1 in superposition with the Hadamard gate (h), whereas **Line 10** entangles q1 and q2 with the Conditional NOT gate (cx). As a result, whenever q1 and q2 are measured (e.g., in **Lines 11-12**), they will have the same values, i.e., either 00 or 11. Each value, i.e., 00 or 11 has an equal probability to be observed. Note that for simplicity, we show the states for the quantum circuit in terms of only probabilities and not as state vectors.

Developing dependable (quantum) software entails following a software development life cycle.



Shaukat Ali, Tao Yue, and Rui Abreu. 2022. When software engineering meets quantum computing. Commun. ACM 65, 4 (April 2022), 84–88. https://doi.org/10.1145/3512340

Requirements Engineering

- Quantum application **domains** are often **complex**.
- Need to ease **communication** among **stakeholders**, raise the level of **abstraction** in understanding domains and linking them to downstream activities.

Requirements engineering for quantum software is an uncharted area of research!

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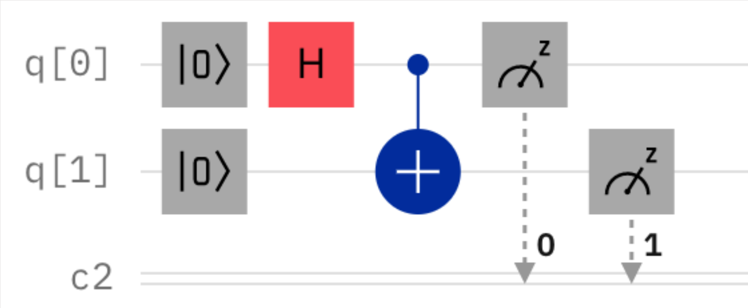
Abstraction and Modeling



mapping

```
OPENQASM 2.0;
include "qelib1.inc";

qreg q[2];
creg c[2];

reset q[0];
h q[0];
reset q[1];
cx q[0],q[1];
measure q[0] -> c[0];
measure q[1] -> c[1];
```

From: IBM Quantum Composer

mapping

```
from qiskit import QuantumRegister,
ClassicalRegister, QuantumCircuit
from numpy import pi

qreg_q = QuantumRegister(2, 'q')
creg_c = ClassicalRegister(2, 'c')
circuit = QuantumCircuit(qreg_q, creg_c)

circuit.reset(qreg_q[0])
circuit.h(qreg_q[0])
circuit.reset(qreg_q[1])
circuit.cx(qreg_q[0], qreg_q[1])
circuit.measure(qreg_q[0], creg_c[0])
circuit.measure(qreg_q[1], creg_c[1])
```

There is no abstraction!

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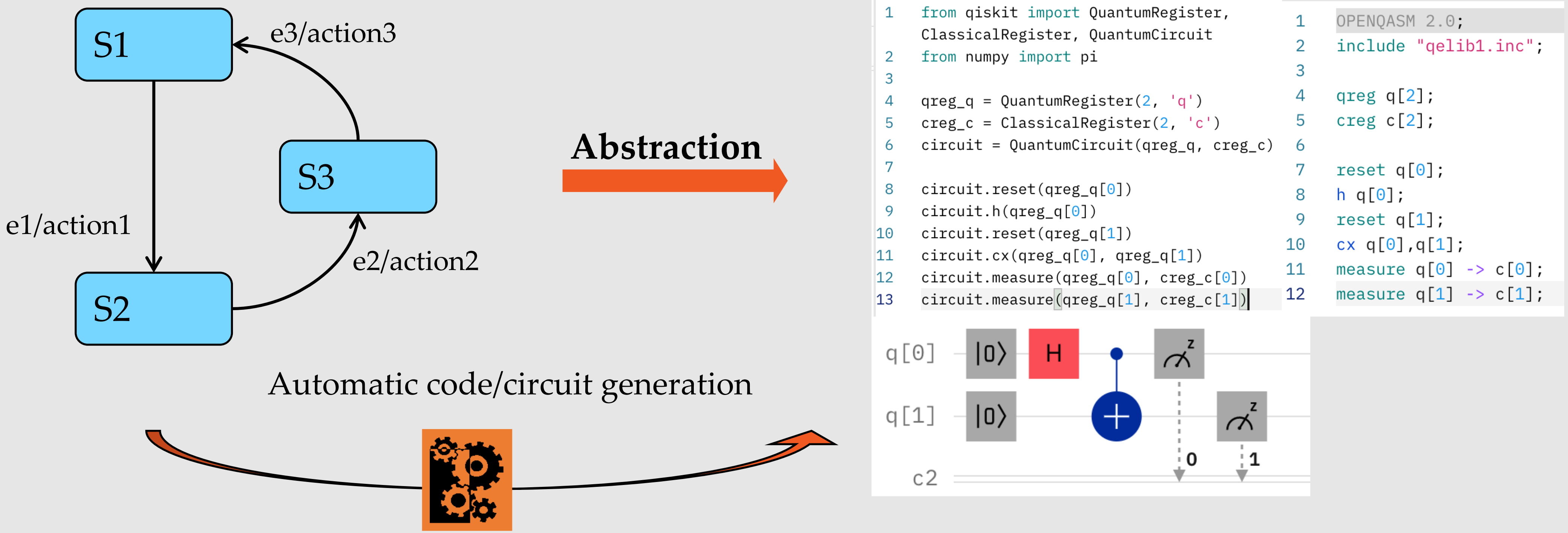
Abstraction and Modeling



Novel and intuitive **QSE methodologies**, with:

- **Quantum modeling notations**
- **V&V with quantum software models**
- **Code/circuit generation**

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Quantum Software Testing

- Software quality assurance
  - **Process** of ensuring that a software product meets and complies with established and standardized **quality specifications**.
- Testing
  - “Software testing is **a way to assess the quality of the software and to reduce the risk of software failure in operation**.” – from ISTQB

Quantum software testing is challenging, because:

- Computation in superpositions
- Use of advanced features (e.g., entanglement)
- Destructive measurements
- Lack of precise test oracles…

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Quantum Software Testing

- Research actions being taken or to be taken:
  - Define and check quantum test oracles without destroying superposition
  - Cost-effectively find test data to break a quantum program
  - Devise noise-aware testing techniques
  - Build theoretical foundations on coverage criteria, test models, and test strategies, etc.
  - Need practical applications, extensive empirical evaluations
  - Need benchmarks…

Quantum Software Testing
State of the Art

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Quantum Software Testing at ICSE

2019 IEEE/ACM 41st International Conference on Software Engineering: New Ideas and Emerging Results (ICSE-NIER)

On Testing Quantum Programs

Andriy Miranskyy and Lei Zhang
Department of Computer Science, Ryerson University, Toronto, Canada
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2020 IEEE/ACM 42nd International Conference on Software Engineering: New Ideas and Emerging Results (ICSE-NIER)

Is Your Quantum Program Bug-Free?

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Measurements and Assertions

- **Output Check:** Similar to classical, e.g., observed and expected outputs are compared [2-4]
- **Statistical Assertion:** Observed and expected distributions are compared [2-4, 8,11]
- **Dynamic Assertions:** With ancilla qubits collect information during program execution about qubits for asserting [12]
- **Projection-based:** Projective measurements to reduce the number of read operations [10]

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Coverage criteria

- **Quito:** Coverage of inputs and outputs of quantum programs [3-4]
  - ✓Input coverage
  - ✓Output coverage
  - ✓Input-output coverage
- **QSharpTester:** Equivalent class partition of quantum variables [5]

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Techniques (1/3)

- **Metamorphic testing**
  - ✓Metamorphic testing of oracle quantum programs [19]
  - ✓MorphQ: Testing quantum computing platforms (ICSE 2023, presentation later today) [6]
- **Property-based testing:** QSharpCheck framework for Q# [8]
- **Fuzz testing:** QuanFuzz framework for quantum programs [9]

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Techniques (2/3)

- **Search-based testing**
  - ✓**QuSBT:** Maximizing the number of failing test cases in a test suite with a genetic algorithm [13-14]
  - ✓**MutTG:** Finding a minimum number of test cases to kill the maximum number of mutants with NSGA-II [15]
- **Combinatorial testing** for quantum programs [21]

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Techniques (3/3)

- **Quantum mutation analysis**
  - ✓*Muskit:* Mutation generation framework for Qiskit [2]
  - ✓*QMutPy:* Generates realistic mutants by following real bug patterns [1]
- **Quantum platform testing**
  - ✓*QDiff:* Differential testing of quantum software stacks [7]
  - ✓*MorphQ:* Metamorphic testing of quantum computing platforms [6]

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Bug repositories and benchmarks

- Bug respository for quantum computing platforms [16]
- Bug repositories for quantum programs (Bugs4Q and Qbugs) [17]
- A multi-lingual benchmark for property-based testing of quantum programs [20]

Quantum Software Testing Techniques

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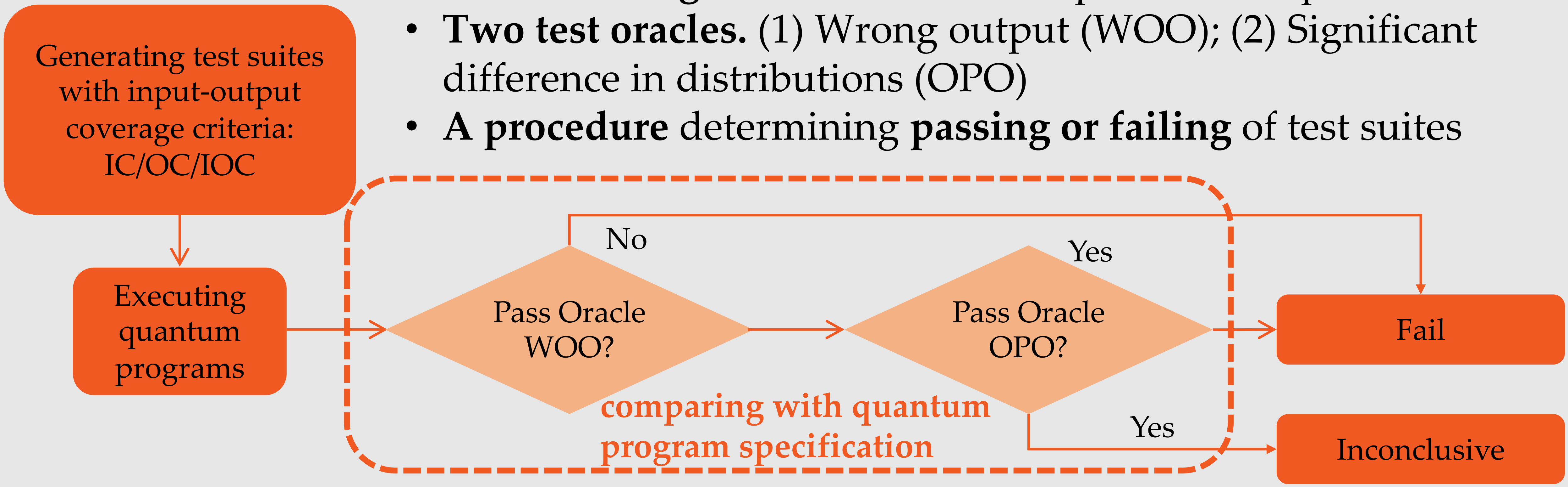
Work 1

Quito (QUantum InpuT Output coverage)

- **Three coverage criteria** based on inputs and outputs
- **Two test oracles.** (1) Wrong output (WOO); (2) Significant difference in distributions (OPO)
- **A procedure** determining **passing or failing** of test suites



Assessment: Mutation Analysis

Assessing the Effectiveness of Input and Output Coverage Criteria for Testing Quantum Programs
[ICST 2021] [3]

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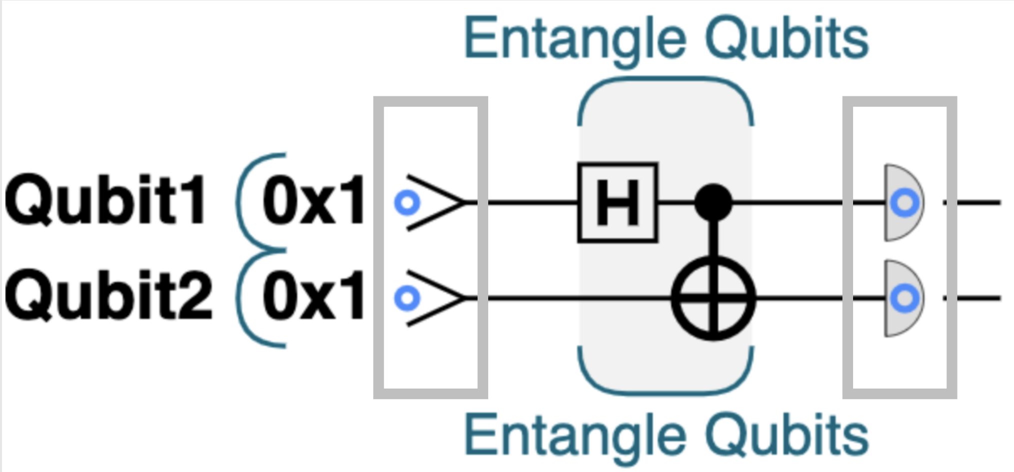
Inputs and Outputs of a Quantum Program (QP)

- **Inputs**
  - Values of qubits after QP initialization
- **Outputs**
  - Values of qubits obtained after measurement



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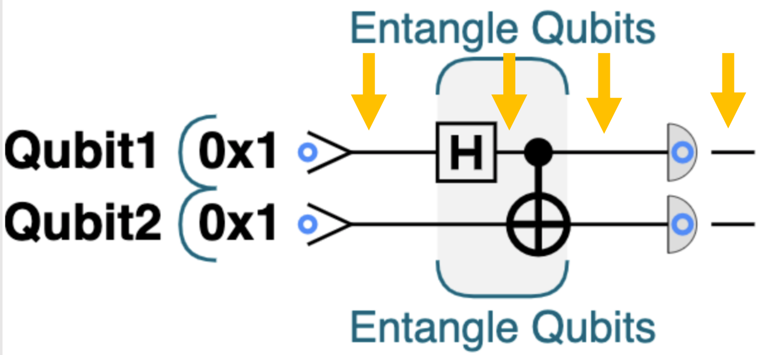
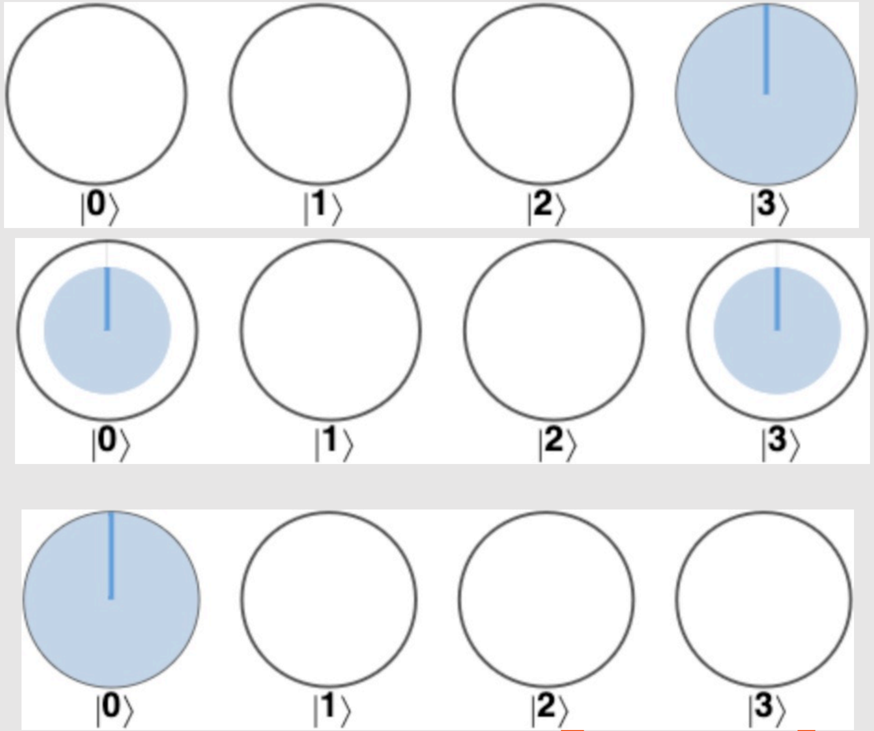
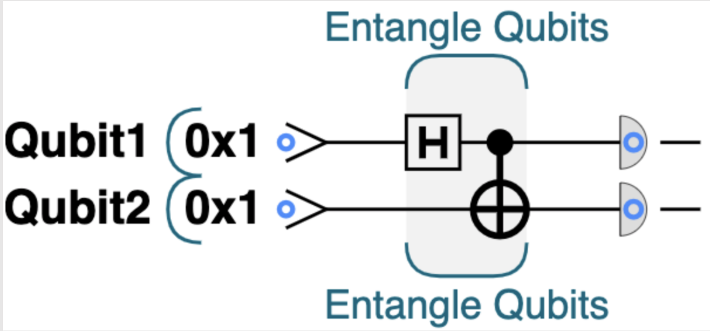
```
qc.reset(2);
var a = qint.new(1, 'a');
var b = qint.new(1, 'b');
qc.reset(2);
qc.write(0);          // Initialize with 0
qc.nop();
qc.label('entangle');
a.had();              // Hadamard Gate. Place into superposition
b.cnot(a);            // Control-NOT Gate. Entangle
qc.label();
qc.nop();
var a_result = a.read();   // The two bits will be random,
var b_result = b.read();   // but always the same.
qc.print(a_result);
qc.print(b_result);
```





[5] M. Gimeno-Segovia, N. Harrigan, and E. Johnston, Programming Quantum Computers: Essential Algorithms and Code Samples.O' Reilly Media, Incorporated, 2019. [Online].

Program Specification (PS) of a QP



- **Valid Inputs**
  - Input values that are valid according to PS
- **Valid Outputs Values**
  - Output values that can be produced with at least one valid input
- **Probabilities**
  - Given a valid input, expected probabilities of occurrence of all the valid output values

Valid Input	Valid Output 1	Probability 1	Valid Output 2	Probability 2
00	00	50%	11	50%
01	00	50%	11	50%

Quito: A Framework for Quantum Program Testing

3 Coverage Criteria

- Input Coverage
- Output Coverage
- Input-Output Coverage

2 Test Oracles

- Wrong Output Oracle
- Output Probability Oracle

Assessment

- Mutation Operators
- Mutation Analysis

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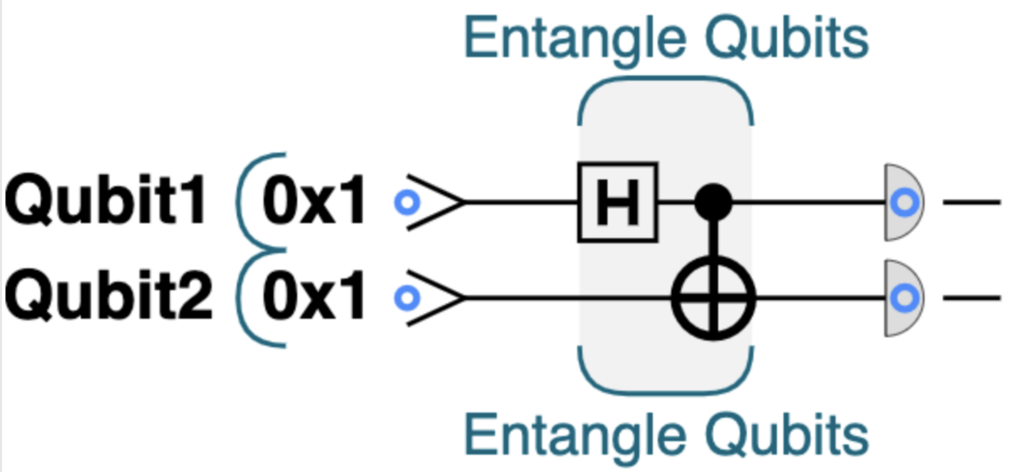
Input Coverage (IC)



- In one test suite, there exists a test for each valid input
- A statically generated test suite can achieve IC

One Possible Test Suite

Input	Output
00	0
01	0

Program Specification for Entanglement

Valid Input	Valid Output 1	Probability 1	Valid Output 2	Probability 2
00	0	50%	11	50%
01	0	50%	11	50%

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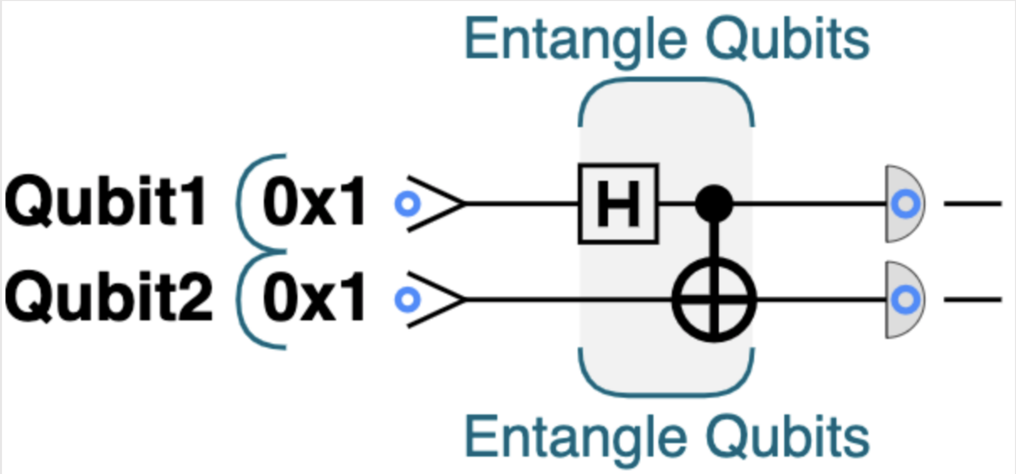
Output Coverage (OC)



- In one test suite, there exists a test for each valid output.
- The criterion cannot be achieved statically.

One Possible Test Suite

Input	Output
00	00
01	00
00	11

Program Specification for Entanglement

Valid Input	Valid Output 1	Probability 1	Valid Output 2	Probability 2
00	00	50%	11	50%
01	00	50%	11	50%

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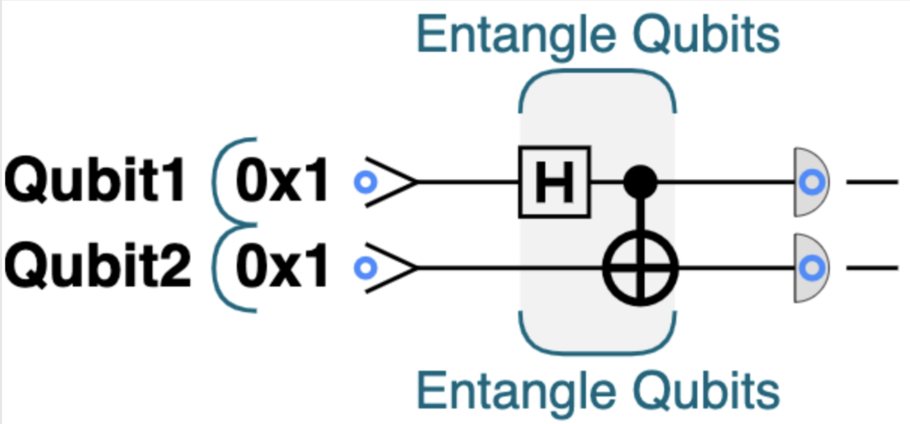
Input-Output Coverage (IOC)

- In one test suite, there exists a test for each input-output pair.
- The criterion cannot be achieved statically.



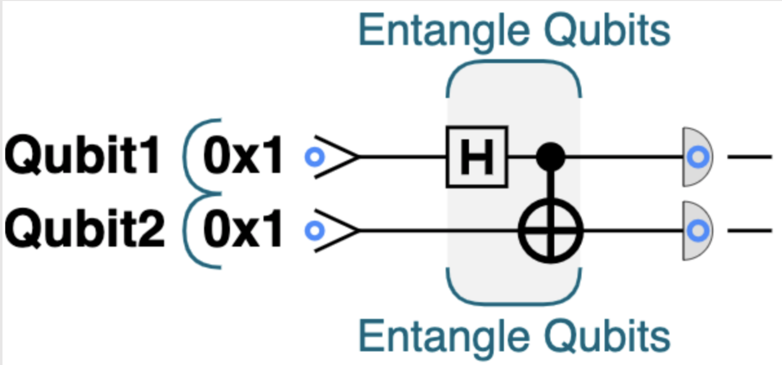
One Possible Test Suite

Input	Output
00	00
00	00
00	11
01	00
01	11

Program Specification for Entanglement

Valid Input	Valid Output 1	Probability 1	Valid Output 2	Probability 2
00	00	50%	11	50%
01	00	50%	11	50%

Test Oracle – Wrong Output Oracle (WOO)



WOO checks if the test outcome returned for a test input is invalid, which reveals a *definitely fail:* wrong outputs.

Valid Input	Valid Output 1	Probability 1	Valid Output 2	Probability 2
00	00	50%	11	50%
01	00	50%	11	50%

Input	Output
00	01

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Test Oracle – Output Probability Oracle (OPO)

- OPO checks if a QP returns an expected output with the expected probability.
  - **Likely Fail:** With a given confidence, multiple executions of a test show that the outputs do not occur with the expected probabilities.
  - **Inconclusive:** Multiple executions of the test do not allow to reject the null hypothesis of a statistical test.

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Key findings

- A **less expensive** coverage criterion (e.g., IC) may achieve higher mutation scores.
- An **expensive** coverage criterion (i.e., IOC) may increase mutation scores.
- If the fault in a program results in a **wrong output (WOO)**, it can possibly be caught with **a lower number** of test cases.
- If certain faults cannot be found with WOO, the cost of finding faults with **OPO** could be **quite higher**. However, it may be reduced with a proper budget upper limit.

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Limitations

- Quito suffer from scalability issue with an increased number of qubits.
  - 2023: Deployed Quito on an HPC platform
- Quito does not deal with phases of qubits.
  - Work in progress
- Quito's mutation analysis can be further improved.
  - 2023: Several tools are available such as Muskit, QMutPy, etc

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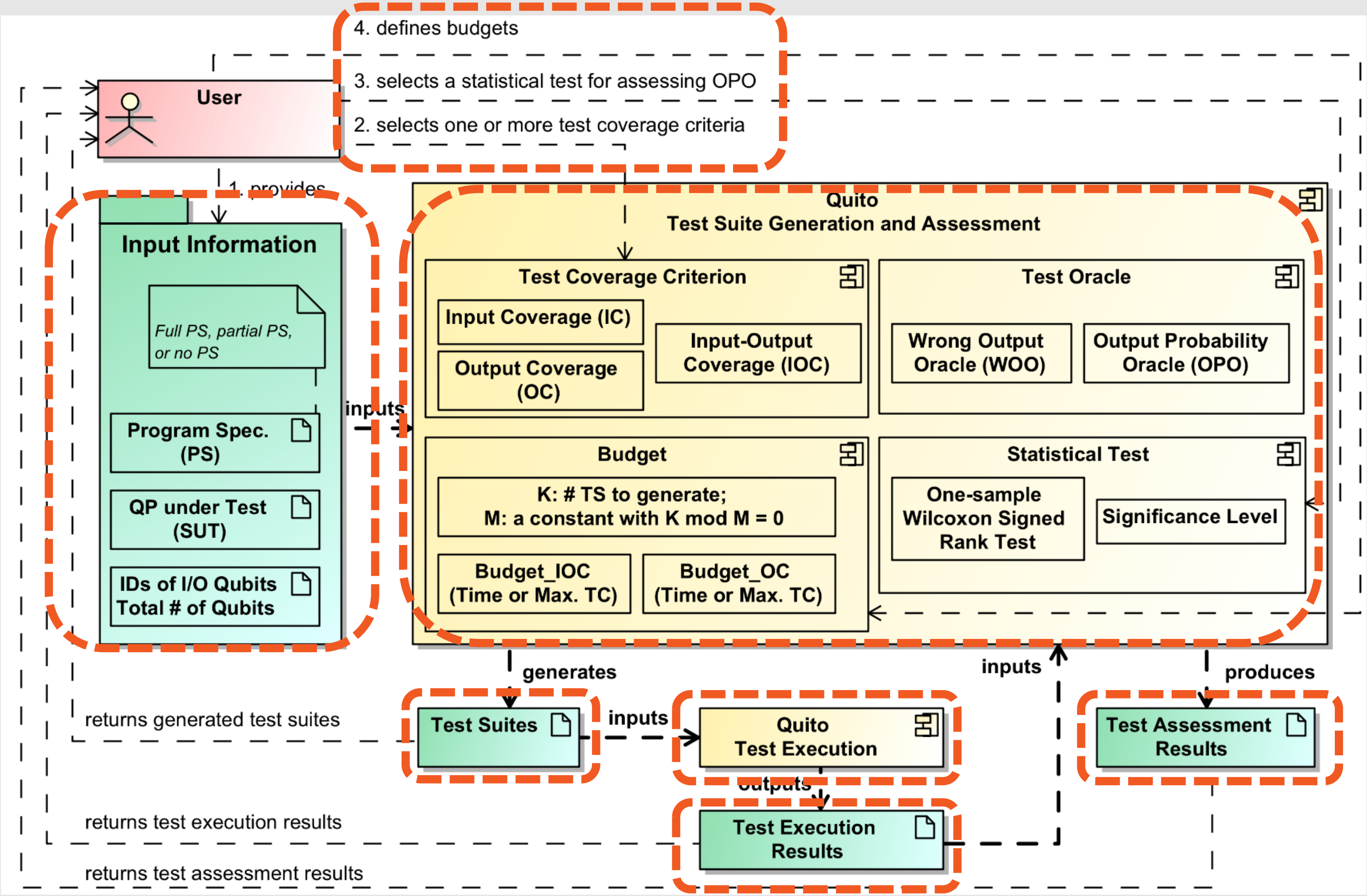
Work 1

Quito (QUantum InpuT Output coverage)



Quito: a Coverage-Guided Test Generator for Quantum Programs
[ASE Demo 2021] [4]

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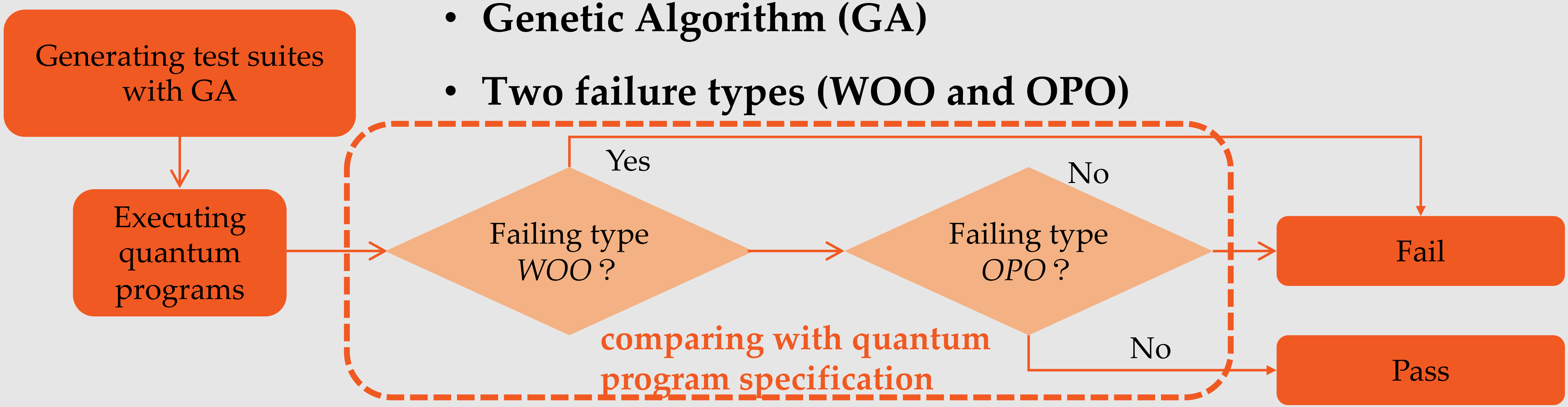
Work 2

QuSBT (Quantum Search-Based Testing)

Goal: Generating a test suite with the maximum possible number of failing test cases

- **Genetic Algorithm (GA)**
- **Two failure types (WOO and OPO)**



Baseline: Random Search

Generating Failing Test Suites for Quantum Programs with Search
[SSBSE 2021] [13]

QuSBT: Quantum Search-based Testing

- **Test case generation** with a Genetic Algorithm (GA)
- **2 types of failures**
  - ✓Unexpected Output Failure
  - ✓Wrong Output Distribution Failure

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Test Case Generation

- Generating M search variables $x_1, \dots, x_M$, each representing one input
- Let D_I be the domain of possible valid inputs,

$$M = \lceil \beta \times |D_I| \rceil$$

- Let $ta = [\text{fail}_1, \dots, \text{fail}_M]$ be the assessments of M tests,
- Fitness function:

$$\max:\ f = \left|\left\{\text{fail}_j \in ta \middle| \text{fail}_i = true\right\}\right|$$

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Experiment Design

- **Frameworks:** Qiskit 0.23.2, jMetalPy 1.5.5
- **Baseline:** Random Search (RS)
- Six **benchmark** programs (e.g., quantum cryptography)
- **Faulty versions:** 30
- **Parameters:** β as 5%; 30 repetitions
- **GA:** Population size 10; termination criterion is max generation 50

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Experiment Design

- **Research Questions:**
  - RQ1: Does QuSBT perform better than RS?
  - RQ2: How does QuSBT perform on the benchmark programs?
- **Evaluation Metric: Number of failed tests (NFT)**
  - The best final solution
  - The best solution of each generation
- **Statistical tests**
  - The Mann-Whitney U test as the statistical test
  - The Vargha and Delaney's *A*12 statistics

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RQ1: Does QuSBT perform better than RS?

Comparison between GA and RS

Program	✓	≡
AS	4	1
BV	5	0
CE	5	0
IQ	4	1
QR	5	0
SM	3	2

No significant difference between GA and RS

GA is significantly better than RS

GA outperforms RS for 87% of the faulty quantum programs.

For BV, CE and QR, GA consistently performs better than RS.

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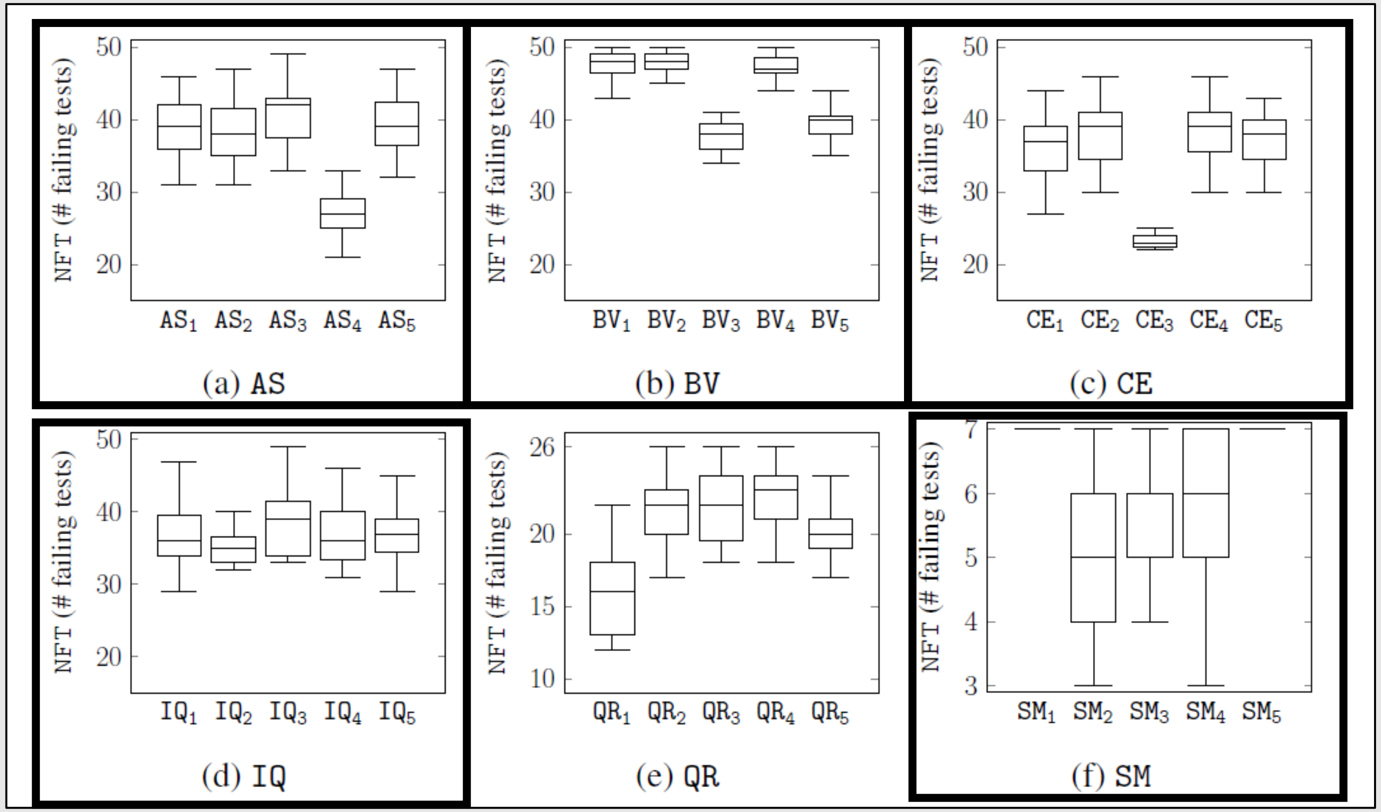
RQ2: How does QuSBT perform on the benchmark programs?

NFT of GA across 30 runs



In four groups of the most complex benchmarks, the variability is usually high, but it can still find the maximum number of failing inputs in some cases.

For the small program SM, the search can always find the maximum failing inputs of the test suite for two mutants.

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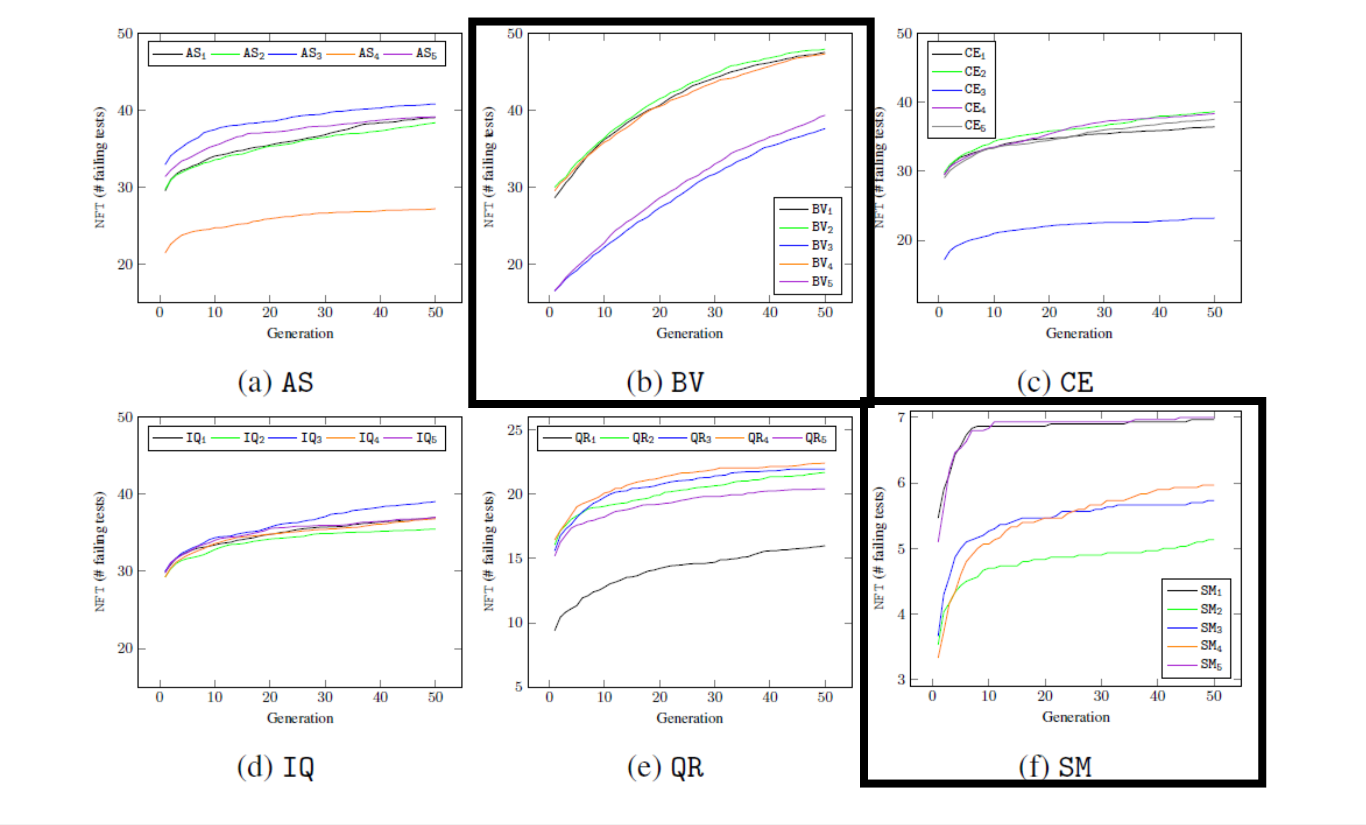
RQ2: How does QuSBT perform on the benchmark programs?

Evolution of the fitness values over generations



(Values are averages across 30 runs of the fitness of the best individual in the population)

The first generations already find some failing tests, the values keep increasing across generations.

3 benchmarks of BV and 2 benchmarks of SM almost find all failing tests.

The numbers failing tests vary across benchmark programs, depending on the types and locations of faults.

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Conclusions

- QuSBT is a **search-based approach** for testing quantum programs with **Genetic Algorithm**, aiming at finding **as many failing tests** as possible.

- QuSBT was assessed with **30 faulty quantum programs**. **QuSBT** outperformed **Random Search** in **87%** of the programs.

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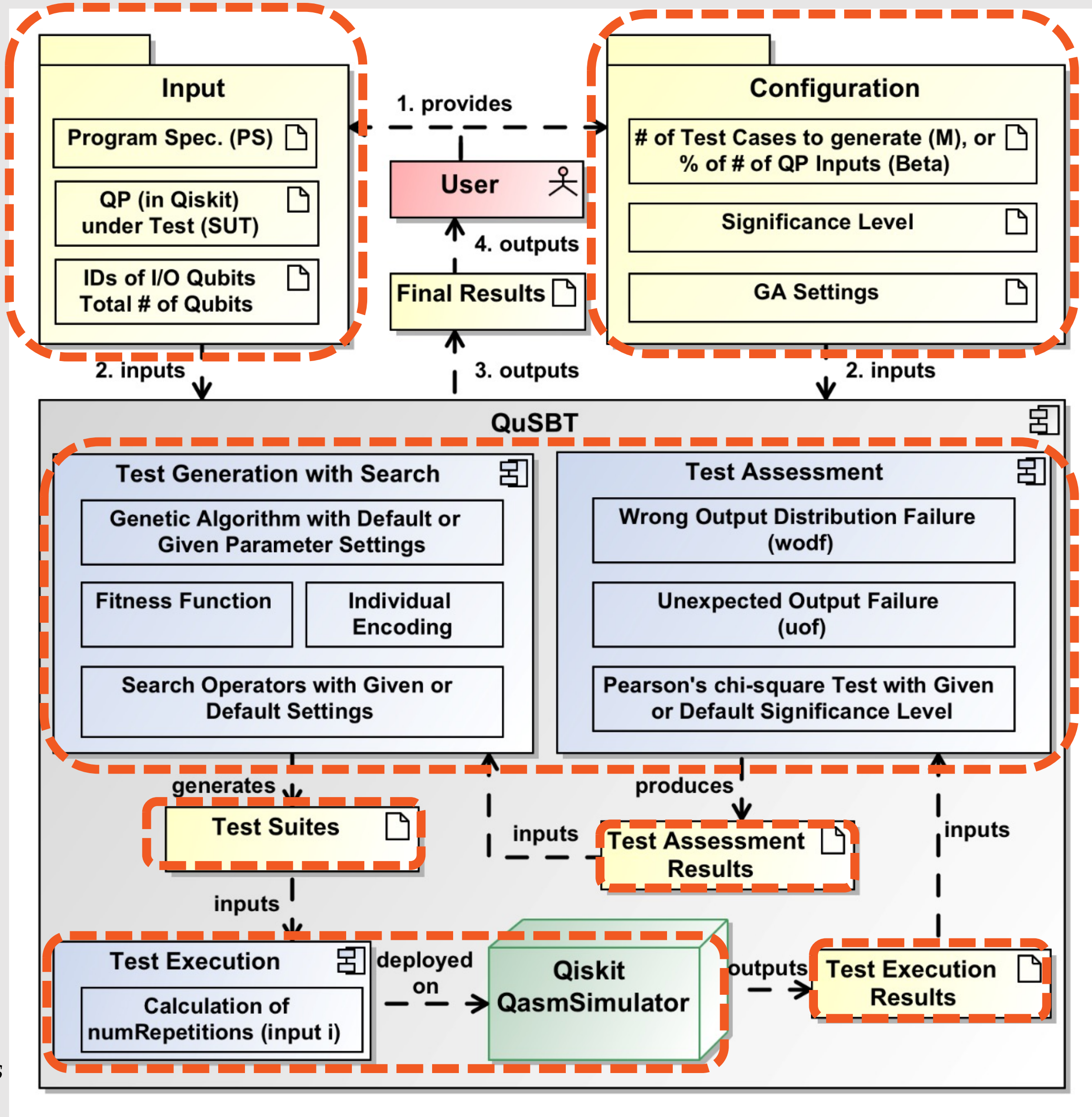
Work 2

QuSBT (Quantum Search-Based Testing)



QuSBT: Search-Based Testing of Quantum Programs
[ICSE Demo 2021] [14]

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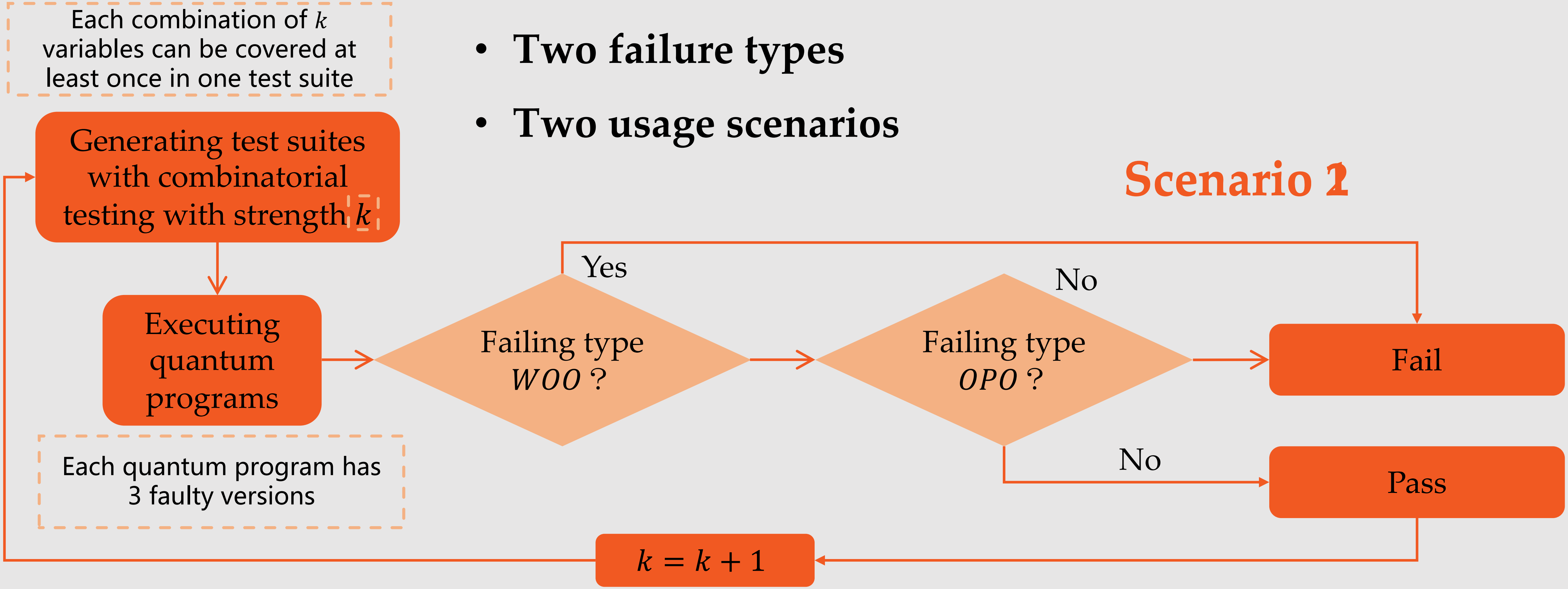
Work 3

QuCAT (QUantum CombinAtorial Testing)

- **Combinatorial testing**
- **Two failure types**
- **Two usage scenarios**



Baseline: Random Testing

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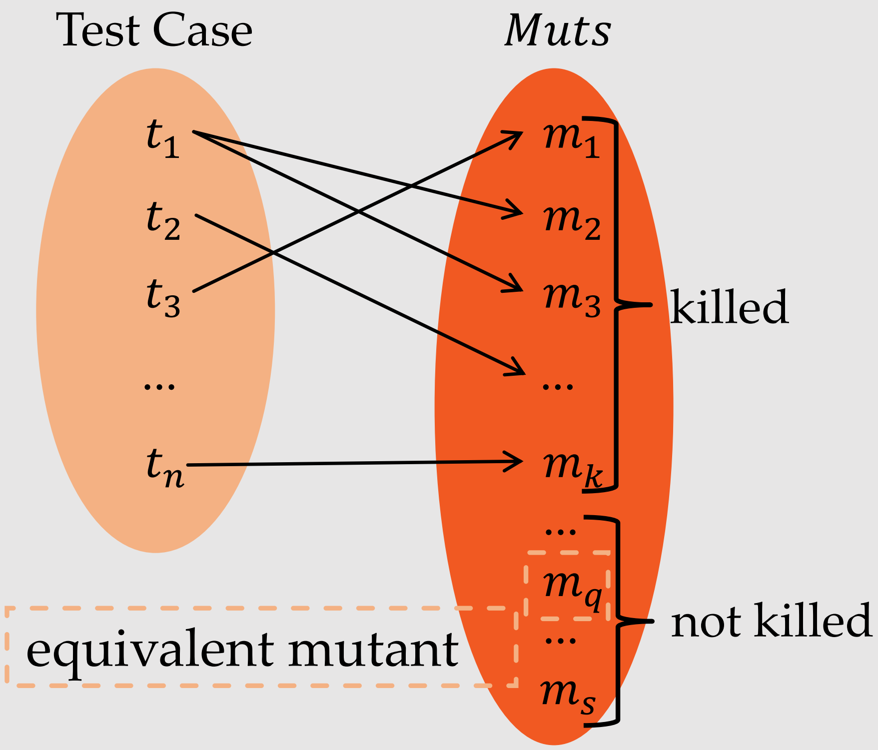
Application of Combinatorial Testing to Quantum Programs
[QRS 2021] [21]

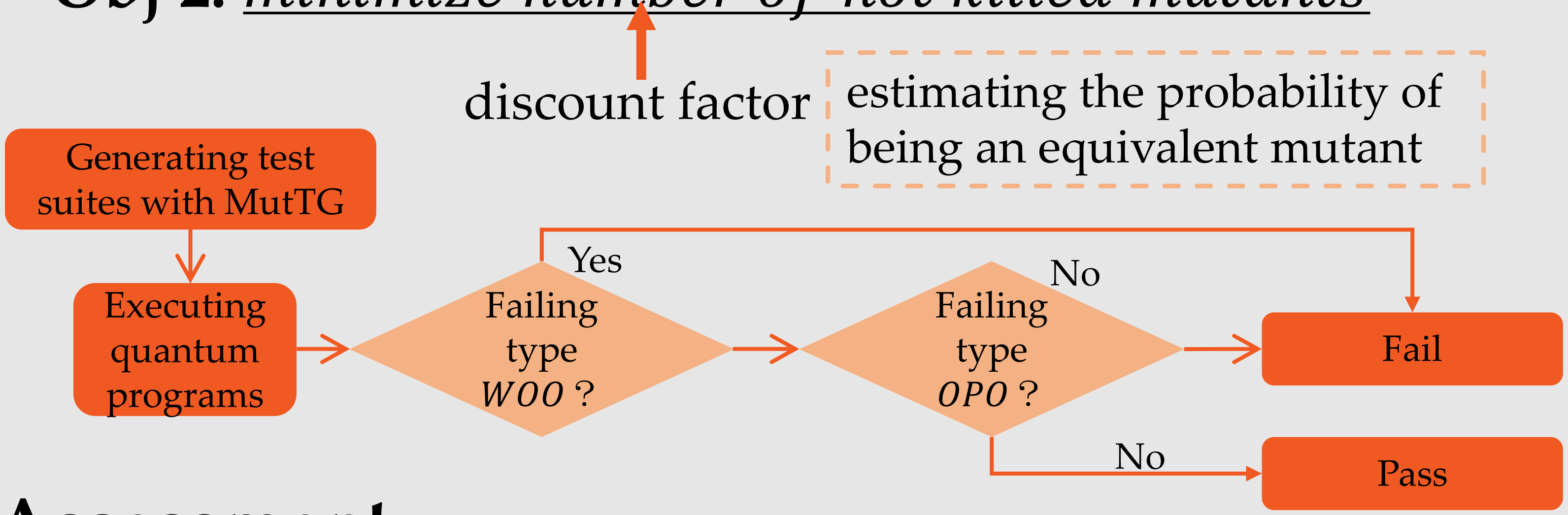
Work 4

MutTG (multi-objective search-based approach)



Obj 1: *minimize test suite size*

Obj 2: *minimize number of not killed mutants*



Assessment:

- **Baseline:** (1) random search, (2) approach without discount factor
- **Benchmarks:** *Mutants* with different difficulty levels

Mutation-based test generation for quantum programs with multi-objective search. [GECCO '22][15]

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Work 5

Noise-Aware Quantum Software Testing (Ongoing)

- **Problem:** Hardware Noise
  - ✓Environmental characteristics, e.g., magnetic fields, radiations, interactions of qubits with environments
  - ✓Unwanted interactions of qubits exist among themselves (crosstalk noise)
  - ✓Imprecise quantum gate calibrations

Challenges:

- Due to noise, a program can produce wrong output states or correct output states with wrong probabilities
- Does quantum program really failed or is it due to noise?

	Probability							
State	**000**	**001**	**010**	**011**	**100**	**101**	**110**	**111**
Ideal	0.495	-	-	-	-	-	-	0.505
Noisy	0.476	0.013	0.007	0.016	0.008	0.019	0.020	0.443

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Work 6

Muskit: A Mutation Analysis Tool for Quantum Software Testing

- **Problem:** Lack of bug repositories and benchmarks to assess quality of test cases generated for testing quantum programs
- **Solution:** Mutation analysis tool for quantum programs in IBM's Qiskit
- **Features**
  - ✓Mutation Operator Types: Add, Remove, Replace gates
  - ✓Mutation Selection Criteria: All, Gate selection (one qubit, two-qubit, etc), …

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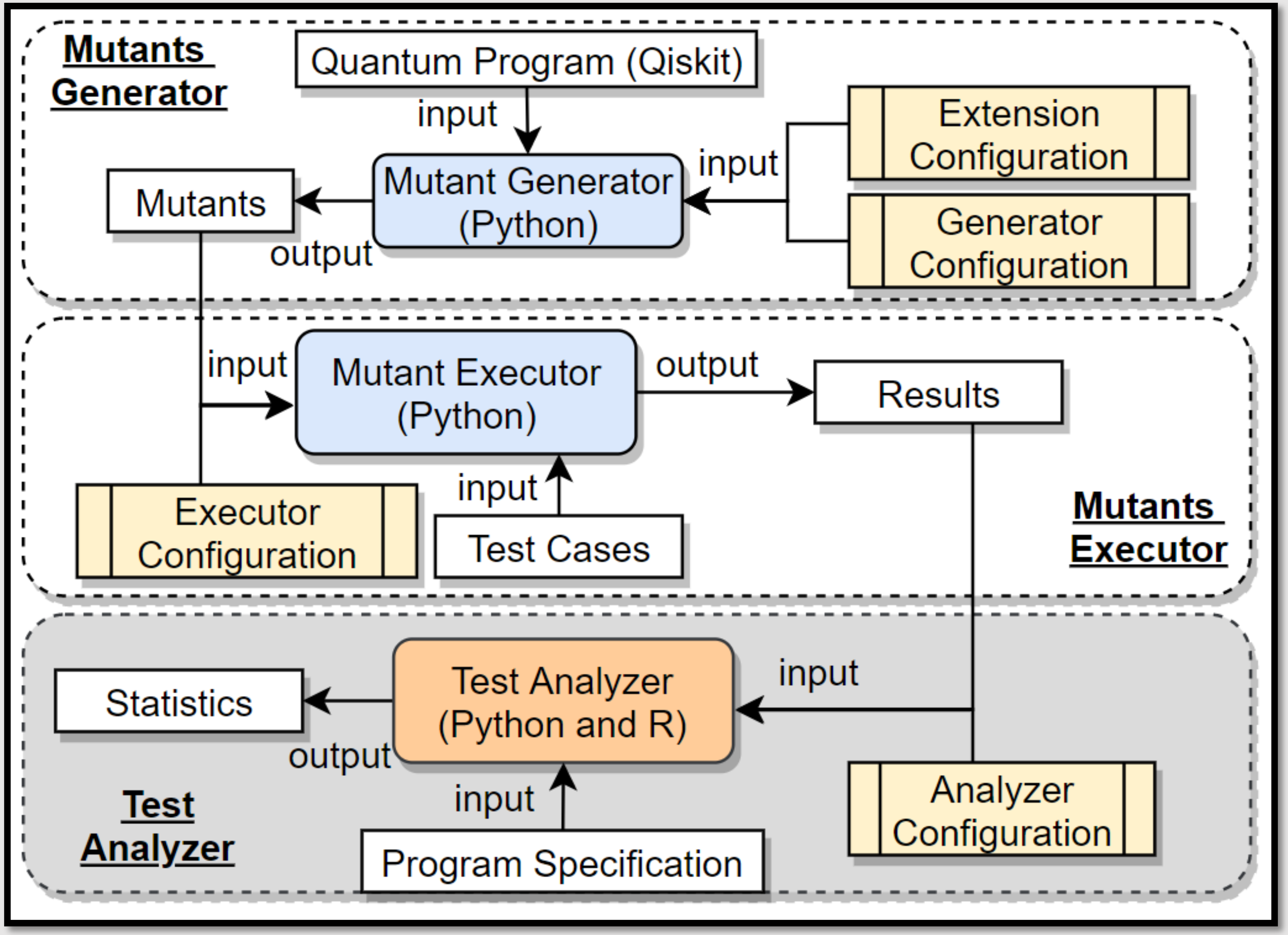
Work 6

Muskit: A Mutation Analysis Tool for Quantum Software Testing



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Tools, datasets, and publications

MutTG **Quito** **QuSBT** **QuCAT** **Muskit**

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Quantum Software Testing
A Brief Introduction

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