



Quantum Software Testing Tutorial

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Outline

- Introduction to software testing
- Introduction to quantum software testing
- Introduction to quantum software testing with Quito tool
- Hands on Quito and exercises

Introduction to software testing

Software is all around us

- **Airplanes:** Boeing 787 Dreamliner, approx. 6.5 million lines of code
- **Cars:** Chevy Volt, over 10 million lines of code
- **Android operating system:** 12–15 million lines
- **All Google services:** approx. 2 Billion lines of code
- ...

[1] <https://www.visualcapitalist.com/millions-lines-of-code/>

And so do their failures...

- June 1996: Ariane 5 disaster right after the take-off [1]
- April 2014: Around 11 million effected due 911 emergency services shut down [2]
- November 2021: Tesla recalled 12000 cars due to software error [3]
- ...

[1] <https://www.bugsnag.com/blog/bug-day-ariane-5-disaster>

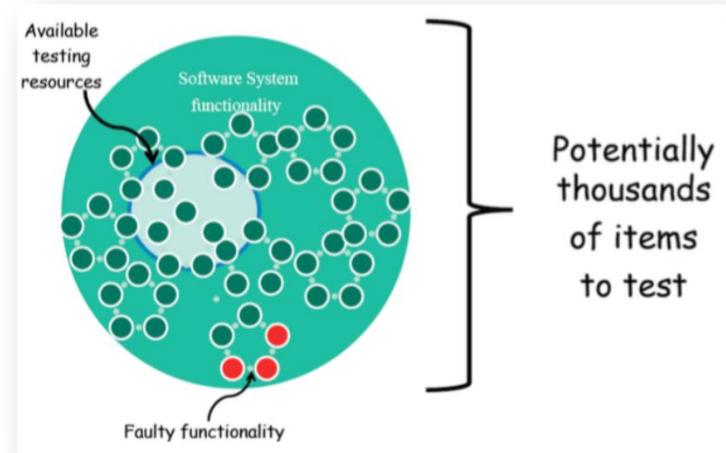
[2] <https://www.theverge.com/2014/10/20/7014705/coding-error-911-fcc-washington>

[3] <https://www.reuters.com/business/autos-transportation/tesla-recalling-nearly-12000-us-vehicles-over-software-communication-error-2021-11-02/>

What is Software Testing?

- “Testing is the process of executing a program with the intent of finding faults” [1]
- The challenge is to identify scenarios that trigger the faulty functionality of software

“To test a program is to try to make it fail” [2]



[1] Mayers G.J. 1977. The Art of Software Testing. John Wiley and Sons, New York, USA

[2] B. Meyer, “Seven principles of software testing,” *Computer*, vol. 41, no. 8, 2008.

Introduction to quantum software testing

Quantum Computing (QC)

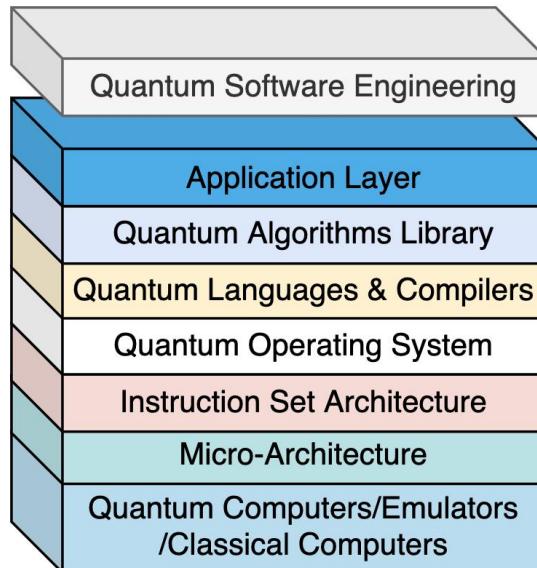


- QC promises to revolutionize the present form of computing
- QC Platforms
 - ✓ Quantum Inspire from QuTech
 - ✓ Microsoft Quantum computing platform
 - ✓ IBM Quantum Experience
 - ✓ D-Wave
- QC High level programming languages
 - ✓ OpenQL by TU Delft, Silq by ETH Zürich, Q# by Microsoft, Qiskit by IBM, Cirq by Google

It is time to build useful QC applications!



Quantum Software plays the key role in the Second quantum revolution.^[1]

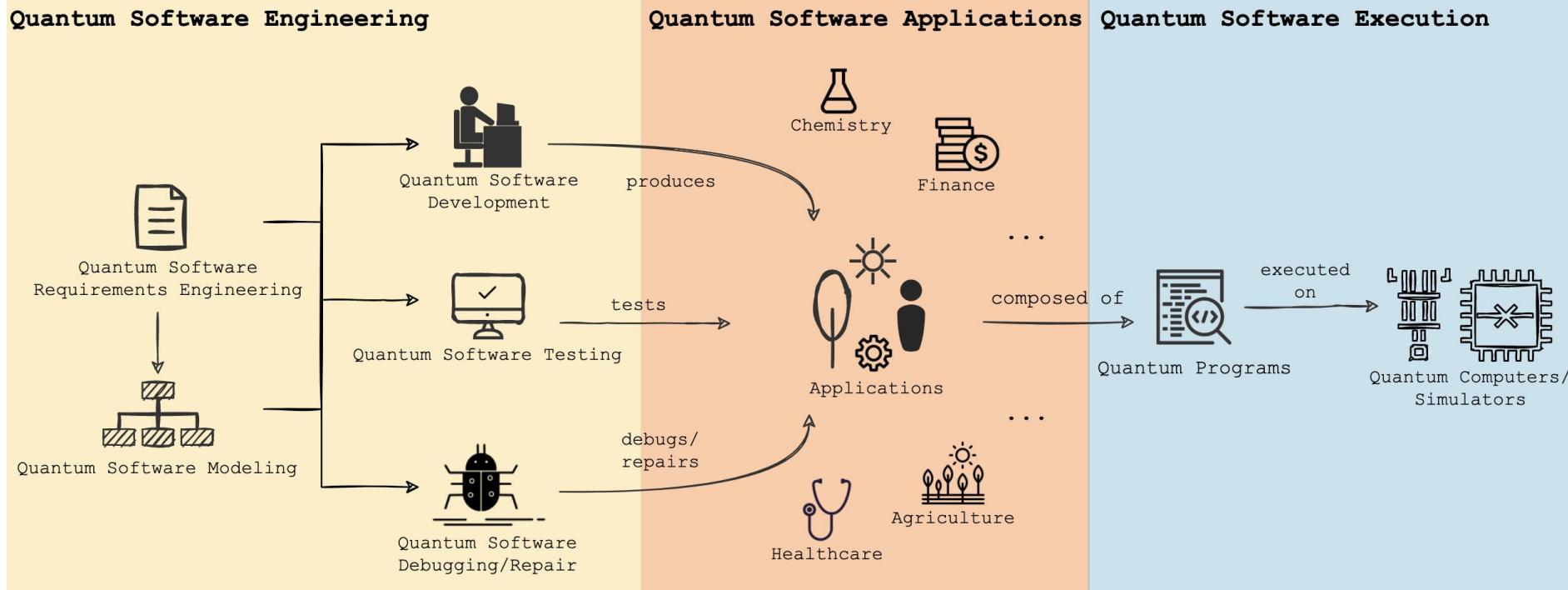


Quantum software is at the core of the promised revolutionary QC applications.

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

[1]. Dowling, Jonathan & Milburn, Gerard. (2003). Quantum Technology: The Second Quantum Revolution. Philosophical transactions. Series A, Mathematical, physical, and engineering sciences. 361. 1655–74. 10.1098/rsta.2003.1227.

Quantum software engineering



Thus, there is a need for novel quantum **software development methods** for developing complex quantum software-based QC applications that are dependable.

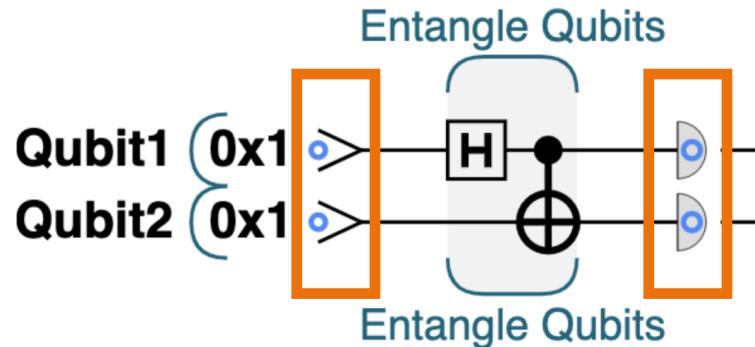
Challenges of testing quantum programs

- Probabilistic nature
- Difficulties in estimating a program's state in superposition
- Lack of precise test oracles or absence of oracles

Introduction to quantum software testing with Quito tool

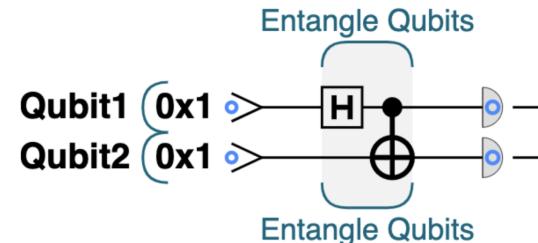
Inputs and Outputs of a Quantum Program (QP)

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



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

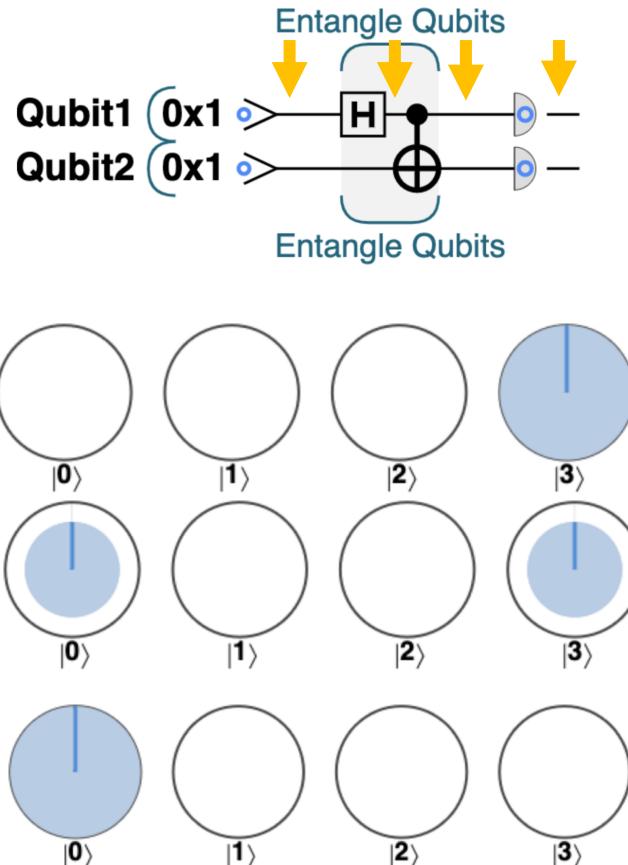


Valid Input	Valid Output 1	Probability 1	Valid Output 2	Probability 2
$0 \rightarrow (00)_2$	$0 \rightarrow (00)_2$	50%	$3 \rightarrow (11)_2$	50%
$1 \rightarrow (01)_2$	$0 \rightarrow (00)_2$	50%	$3 \rightarrow (11)_2$	50%

```

1   qc.reset(2);
2
3   var a = qint.new(1, 'a');
4
5   var b = qint.new(1, 'b');
6
7   qc.reset(2);
8
9   qc.write(0); // Initialize with 0
10
11  qc.nop();
12
13  qc.label('entangle');
14
15  a.had(); // Hadamard Gate. Place into superposition
16
17  b.cnot(a); // Control-NOT Gate. Entangle
18
19  qc.label();
20
21  qc.nop();
22
23  var a_result = a.read(); // The two bits will be random,
24
25  var b_result = b.read(); // but always the same.
26
27  qc.print(a_result);
28
29  qc.print(b_result);

```



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

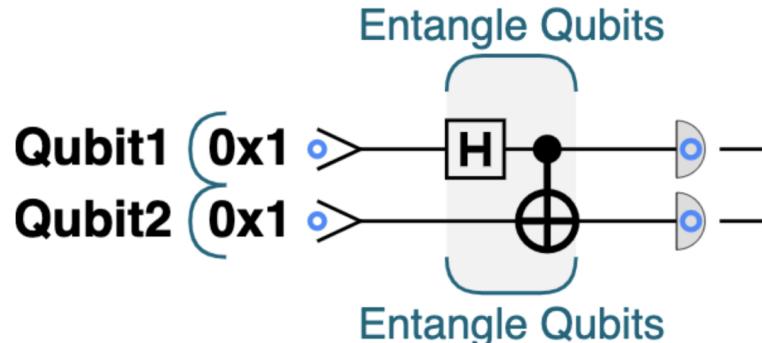
- Mutation Operators
- Mutation Analysis

Input Coverage (IC)

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

Program Specification for Entanglement

Valid Input	Valid Output 1	Probability 1	Valid Output 2	Probability 2
0	0	50%	3	50%
1	0	50%	3	50%

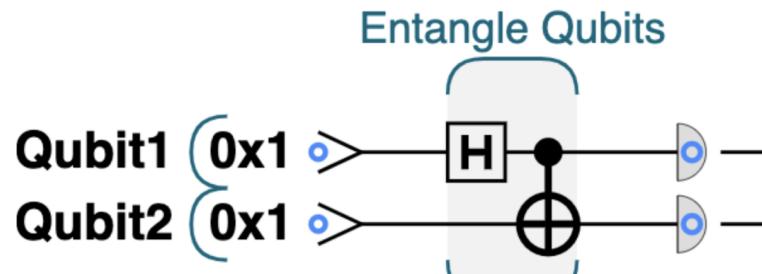


One Possible Test Suite

Input	Output
0	0
1	0

Output Coverage (OC)

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



Entangle Qubits

Qubit1
Qubit2

0x1
0x1

Entangle Qubits

One Possible Test Suite

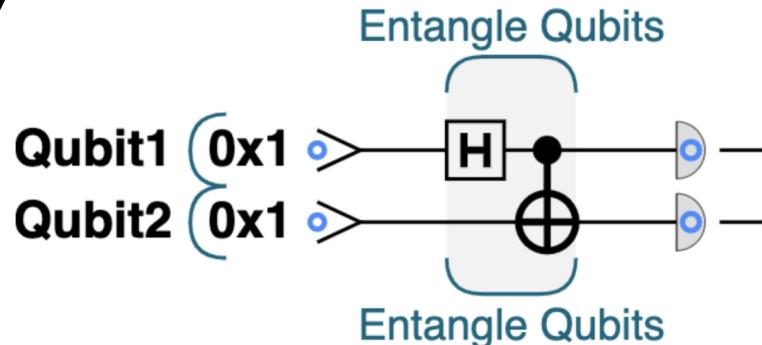
Input	Output
0	0
1	0
0	3

Program Specification for Entanglement

Valid Input	Valid Output 1	Probability 1	Valid Output 2	Probability 2
0	0	50%	3	50%
1	0	50%	3	50%

Input–Output Coverage (IOC)

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



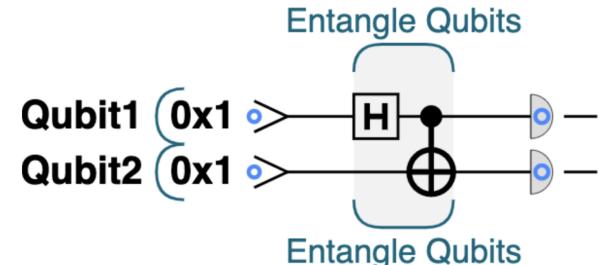
One Possible Test Suite

input	Output
0	0
0	0
0	3
1	0
1	3

Program Specification for Entanglement

Valid Input	Valid Output 1	Probability 1	Valid Output 2	Probability 2
0	0	50%	3	50%
1	0	50%	3	50%

Test Oracle – Wrong Output Oracle (WOO)



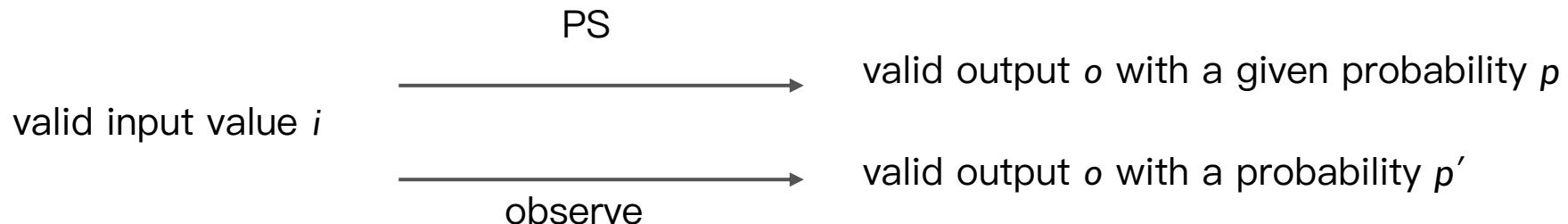
WOO checks if the test outcome returned for a test input is invalid, which reveals a *definitely fail*: wrong outputs.

Valid Input	Valid Output 1	Probability 1	Valid Output 2	Probability 2
0	0	50%	3	50%
1	0	50%	3	50%

Input	Output
0	1

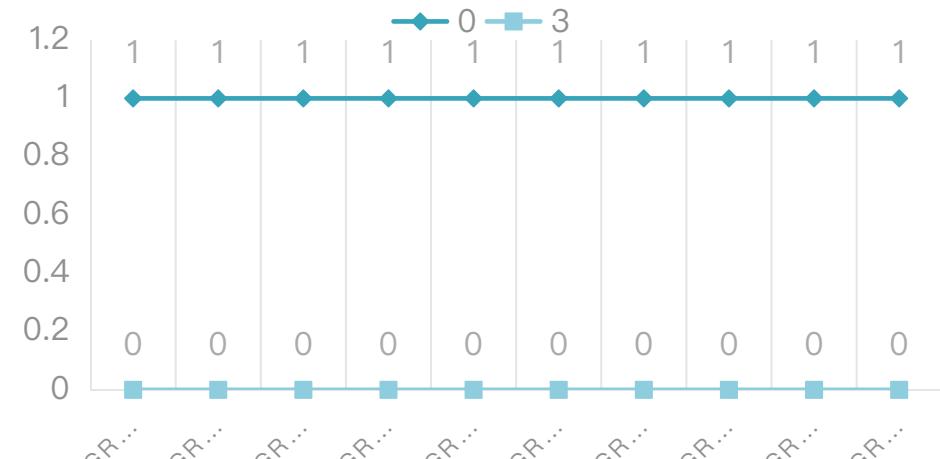
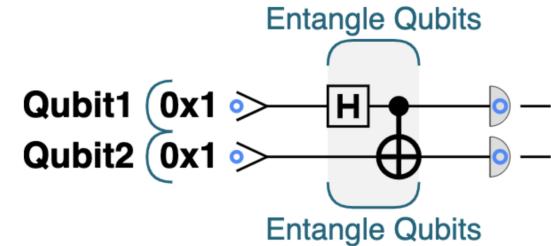
Test Oracle – Output Probability Oracle (OPO)

- 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.



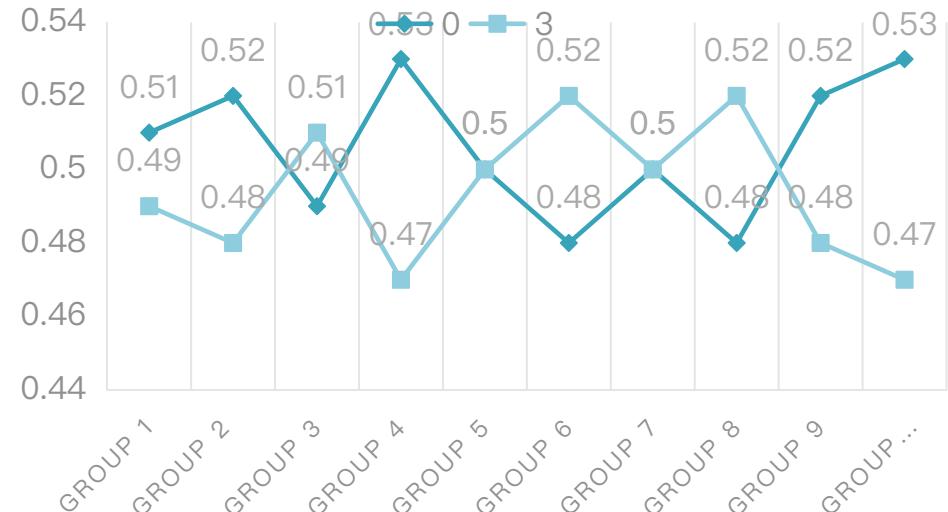
Test Oracle – Output Probability Oracle (OPO)

Valid Input	Valid Output 1	Probability 1	Valid Output 2	Probability 2
0	0	50%	3	50%
1	0	50%	3	50%



(0,0): $p - \text{value} < 10^{-4}$
(0,3): $p - \text{value} < 10^{-4}$

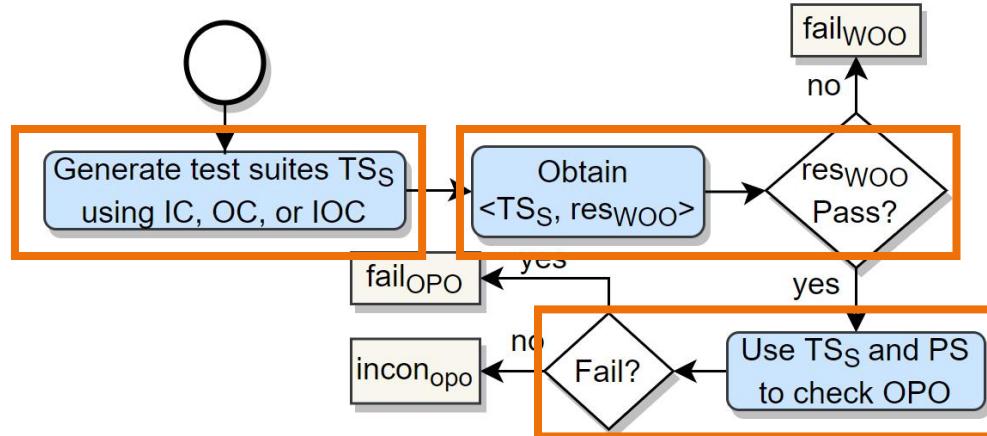
Likely Fail



(0,0): $p - \text{value} > 0.01$
(0,3): $p - \text{value} > 0.01$

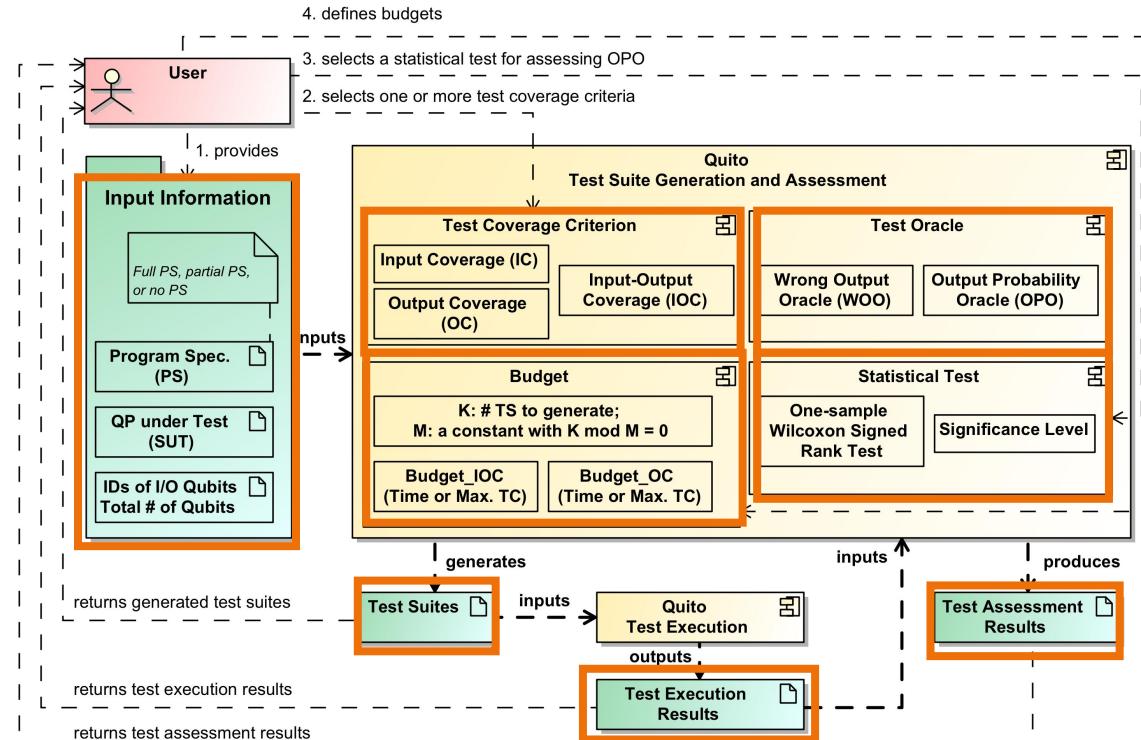
Inconclusive

Test Generation and Assessment



Hands on Quito and exercises

Overview



Installation

- Clone the current repository `git clone https://github.com/Simula-COMPLEX/quito.git`
- Install R environment. <https://cran.r-project.org>
- Install Anaconda. <https://www.anaconda.com/>

Installation

- Create a conda environment (e.g., with name "quantum_env"):

```
conda create -n quantum_env python=3.9
```

- Activate the environment and install Qiskit and rpy2

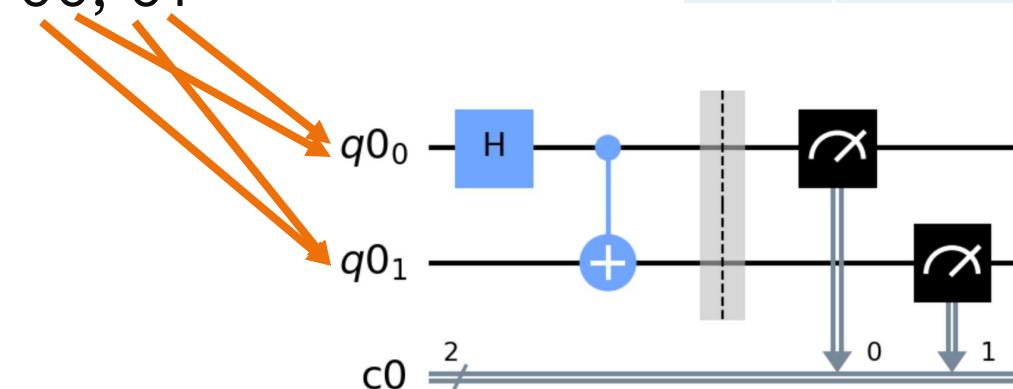
```
conda activate quantum_env
```

Example

- Program
 - ✓ Entanglement
- Partial specs. inputs
 - ✓ 00, 01

- Program specification

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



Example

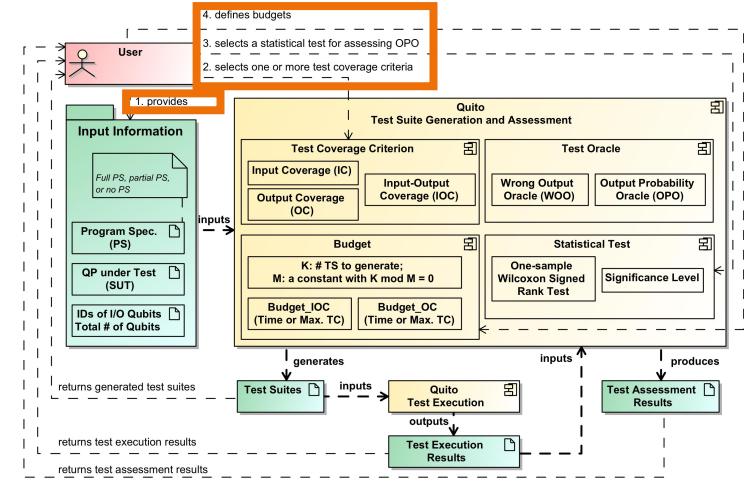
```
entanglement.ini
```

```
[program]
root=/Users/xinyi/Documents/NordIQuEst/quito-main/tutorial/example/entanglement.py
num_qubit=2
inputID=0,1
outputID=0,1

[program_specification_category]
ps_category=full

[quito_configuration]
coverage_criterion=IC
K=200
M=10
BUDGET=20
confidence_level=0.01
statistical_test=one-sample Wilcoxon signed rank test

[program_specification]
00,00=0.5
00,11=0.5
01,00=0.5
01,11=0.5
```



Example

```

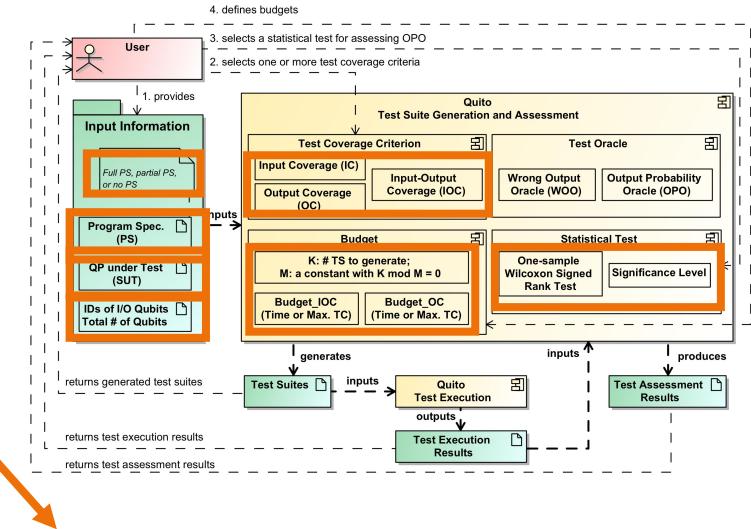
entanglement.ini

[program]
root=/Users/xinyi/Documents/NordIQuEst/quito-main/tutorial/example
num_qubit=2
inputID=0,1
outputID=0,1

[program_specification_category]
ps_category=full

[quito_configuration]
coverage_criterion=IC
K=200
M=10
BUDGET=20
confidence_level=0.01
statistical_test=one-sample Wilcoxon signed rank test

[program_specification]
00,00=0.5
00,11=0.5
01,00=0.5
01,11=0.5
  
```



```

entanglement.py

def run(qc):
    qc.h(0)
    qc.cx(0,1)
    qc.draw(output='mpl', filename='mpl')
    qc.measure([0,1],[0,1])
  
```

Qiskit

Example

Test suites

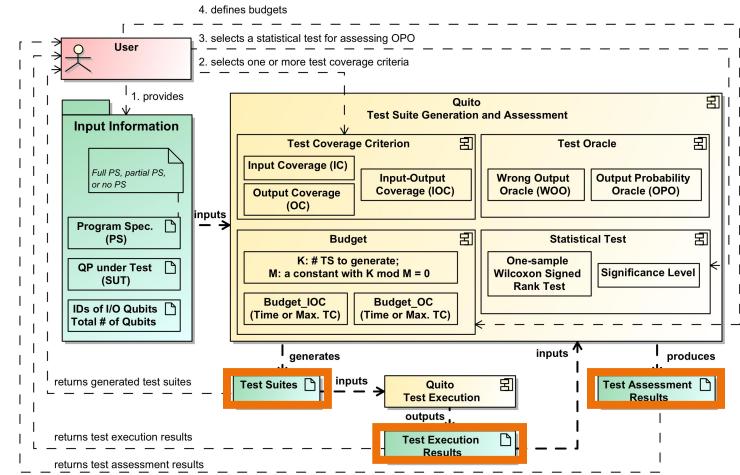
 ASSESSMENT_input_coverage_entanglement.txt

Test Execution Results

 INPUTS_input_coverage_entanglement.txt

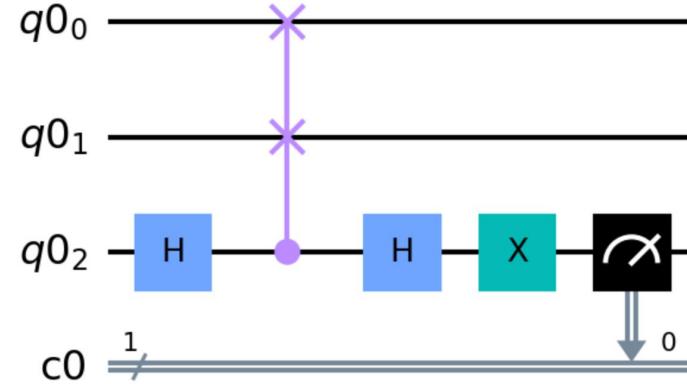
Assessment Results (for full and partial program specification)

 RESULTS_input_coverage_entanglement.txt



Exercise

- Program
 - ✓ Swap
- Description
 - ✓ If q_{0_0} and q_{0_1} are in the same state, measure qubit will be 0 with 100% probability.
 - ✓ Otherwise, there will be 50% probability for the measure qubit to be either 0 or 1.



Exercise

- Step 1
 - ✓ Write quantum program file

```
def run(qc):  
    qc.h(2)  
    qc.cswap(2,0,1)  
    qc.h(2)  
    qc.x(2)  
  
    qc.measure(2,0)
```

Exercise

- Step 2
 - ✓ Write the configuration file

[program]

root=

;(Required) ;

Description: The absolute root of your quantum program file.

num_qubit=

;(Required)

;Description: The total number of qubits of your quantum program.

inputID=

;(Required)

;Description: The ID of input qubits.

;Format: A non-repeating sequence separated by commas.

outputID=

;(Required)

;Description: The ID of output qubits.

;Format: A non-repeating sequence separated by commas.

Exercise

[program_spacification_category]

ps_category=

;(Required)

;Description: The category of your program specification.

;Choice: full/partial/no

Exercise

[quito_configuration]

coverage_criterion=

;Description: The coverage criterion.

;Choice: IC/OC/IOC

K=

;(Optional)

;Description: The total number of test suites, K=200 by default.

M=

;(Optional)

;Description: The number of test suite groups, M=20 by default.

BUDGET=

;(Optional)

;Description: The budget of test suite size, BUDGET=10*number of inputs by default.

confidence_level=

;(Optional)

;Description: The confidence level for statistic test, confidence_level=0.01 by default.

statistical_test=one-sample Wilcoxon signed rank test

;(Optional)

;Description: The statistical test for assessment
statistical_test=one-sample Wilcoxon signed rank test by default.

Exercise

[program_specification]

;(Required for full and partial program specification)

;Description: The program specification. ;Format:input string,output string=probability

Exercise

- Step 3
 - ✓ Activate the conda environment

```
conda activate quantum_env
```
- Step 4
 - ✓ Start the program from the repository root

```
python Quito_CoverageRunning/quito.py
```
- Step 5
 - ✓ Enter a number to select the operation and follow the instructions

Exercise

- Mutant

```
def run(qc):
    qc.x(0)
    qc.h(2)
    qc.cswap(2,0,1)
    qc.h(2)
    qc.x(2)

    qc.measure(2,0)
```

