HPCA 2025 Tutorial

Topic 2. QuCT: A Framework for Analyzing Quantum Circuit by Extracting Contextual and Topological Features

Lab

JanusQ
Cloud

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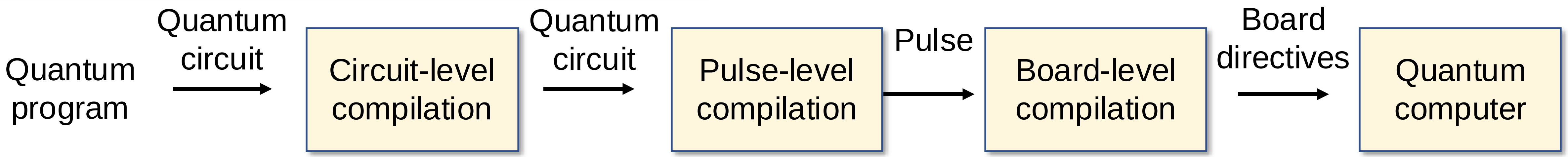
https://janusq.github.io/HPCA_2025_Tutorial/

Outline of Presentation

- **Background and challenges**
- QuCT overview
- Upstream model: Circuit feature extraction
- Downstream model 1: Circuit fidelity prediction
- Downstream model 2: Unitary decomposition

Compilation of a quantum program



Circuit-level compilation:

- Input: quantum circuit   Output: Quantum circuit that satisfies the constraints

Pulse-level compilation:

- Input: quantum circuit   Output: Pulses received by qubits

Board-level compilation:

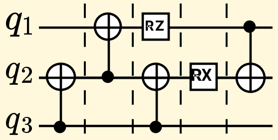
- Input: pulses   Output: Board directives

Background

Key passes of quantum circuit compilation

Quantum program $\xrightarrow{\text{Quantum circuit}}$ **Circuit-level compilation** $\xrightarrow{\text{Quantum circuit}}$ **Pulse-level compilation** $\xrightarrow{\text{Pulse}}$ **Board-level compilation** $\xrightarrow{\text{Board directives}}$ **Quantum computer**

Pass 1: Unitary decomposition

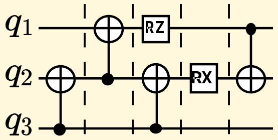


compute → **small complexity**

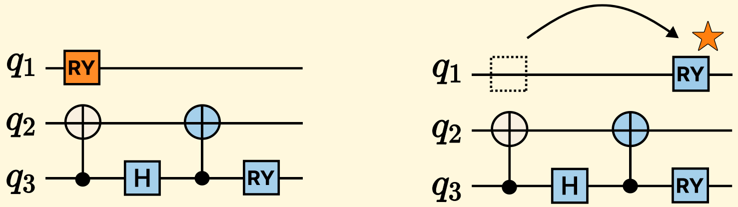
$$\begin{bmatrix} 0 & e^{i-\pi/2} & 0 & 0 \\ 0 & 0 & 0 & e^{i-\pi/2} \\ e^{i\pi/2} & 0 & 0 & 0 \\ 0 & 0 & 0 & e^{i\pi/2} \end{bmatrix}$$

$$\begin{bmatrix} 0 & e^{i-\pi/2} & 0 & 0 \\ 0 & 0 & 0 & e^{i-\pi/2} \\ e^{i\pi/2} & 0 & 0 & 0 \\ 0 & 0 & 0 & e^{i\pi/2} \end{bmatrix}$$

decompose → **large complexity**



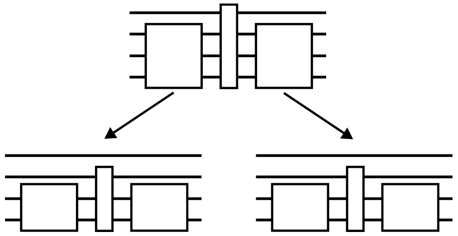
Pass 2: Fidelity prediction and optimization



Optimize the noise while keeping the equivalence of circuits

Challenges of Unitary Decomposition

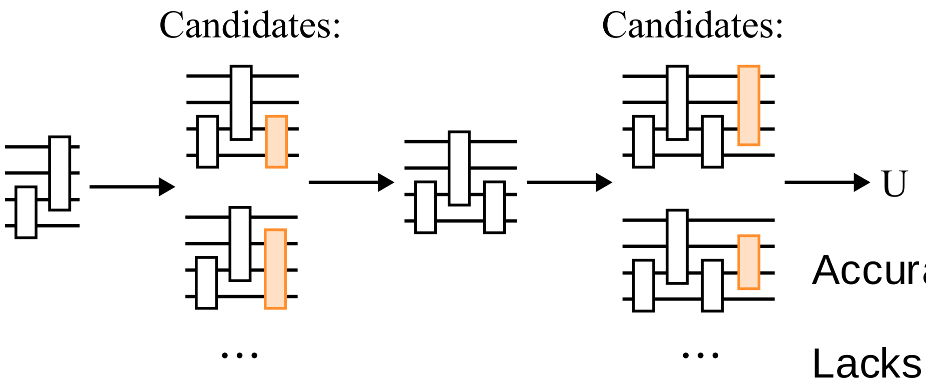
Unitary decomposition



Template-based method

Fast but

Leads to numerous redundant gates



Search-based method

Accurate but

Lacks a heuristic to prune candidate space.

Category	Template-based		Search-based	
Method	CCD [1]	QSD [2]	QFAST [3]	Squander [4]
Time	3.6 s	2.1 s	**511.2 h**	**426.2 h**
#Gate	**3,592**	**3,817**	806	887

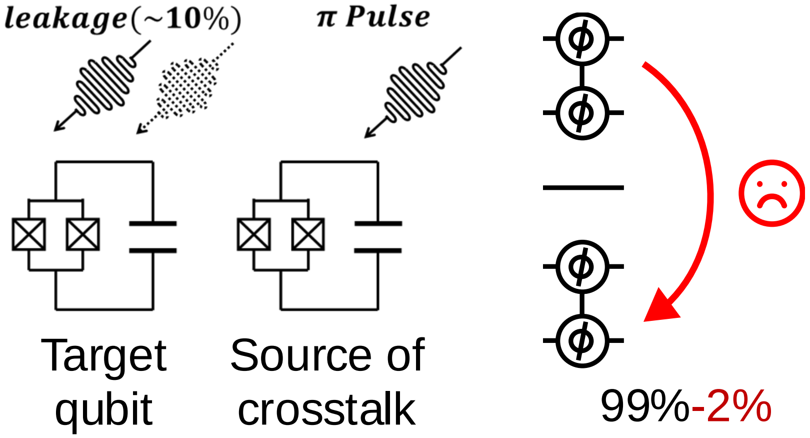
O(4^N) #Gate **O(4^N) Time**

5-qubit unitary decomposition

[1] R. Iten, et al. PRA. 2016
[2] V. Shende, et al. ASP-DAC. 2005
[3] E. Younis, et al. QCE. 2021.
[4] P. Rakyta , et al. Quantum, 2022

Challenges

Fidelity prediction



Related to the circuit structure

Category	RB [5]	XEB [6]	Cycle bench. [7]	Noisy simulat. [8]
Gate-independent error	√	√	√	√
Crosstalk, Pulse distortion	×	×	√	√
Inaccuracy (IBMQ Manila)	**4-28%**	**3-36%**	**2-12%**	**3-17%**

Fidelity prediction

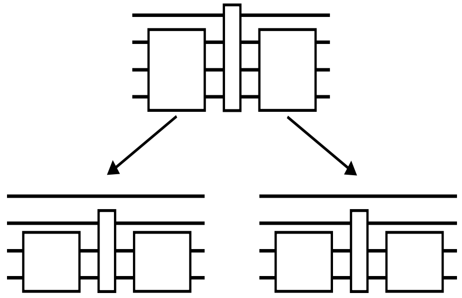
Not one-shot

[5] E. Knill , et al. D. PRA. 2008.
[6] F. Arute, et al. Nature. 2019
[7] A. Erhard, et al. Nature communications. 2019
[8] Isakov, et al ArXiv. 2021.

Current Compilation Methods

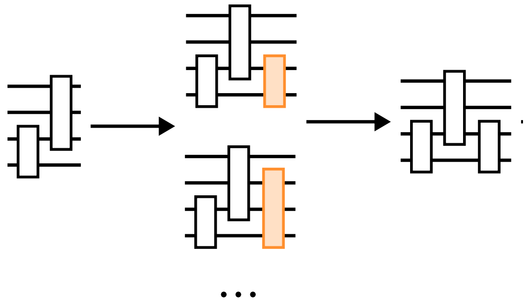
Unitary decomposition

Template-based method



Fast by not accurate:
10-qubit unitary ->
20,000 gate

Search-based method



Accurate but slow:
10-qubit unitary->
one year

Fidelity prediction

Method	Independent noise	Dependent noise	Inaccuracy
RB	√	×	4-28%
XEB	√	×	3-36%
CB	√	√	2-12%
Noisy Simulat.	√	√	3-17%

Fast by inaccurate:
cannot model
dependent noise

Accurate but slow:
require repeated
executions

They face a trade-off between the efficiency and accuracy

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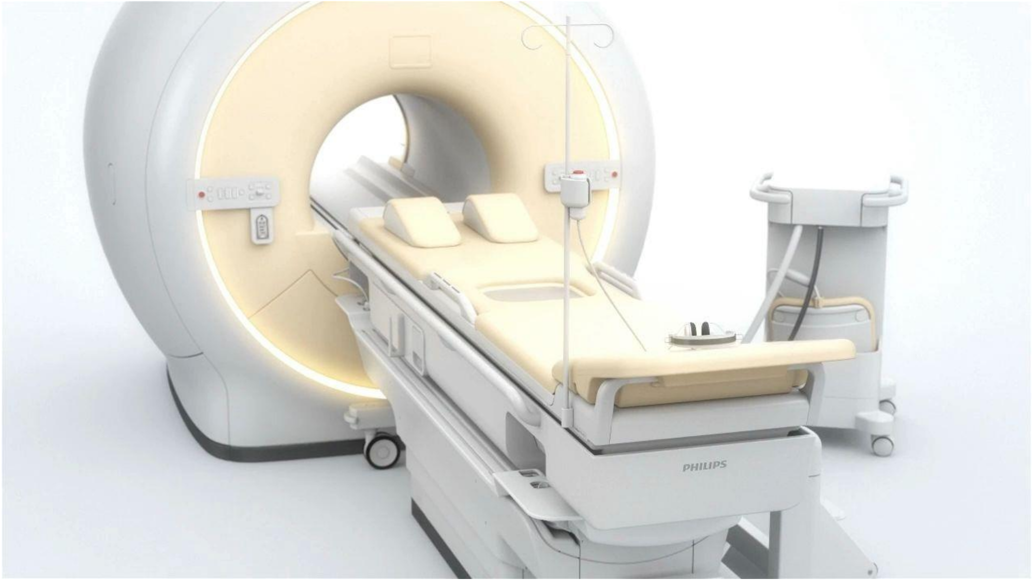
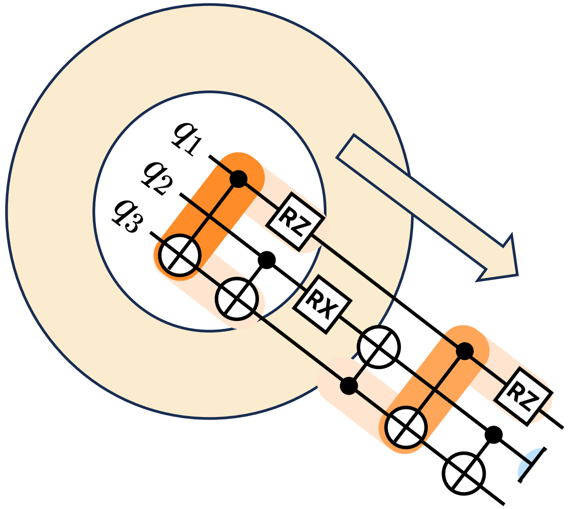
QuCT Overview

Origin of the name



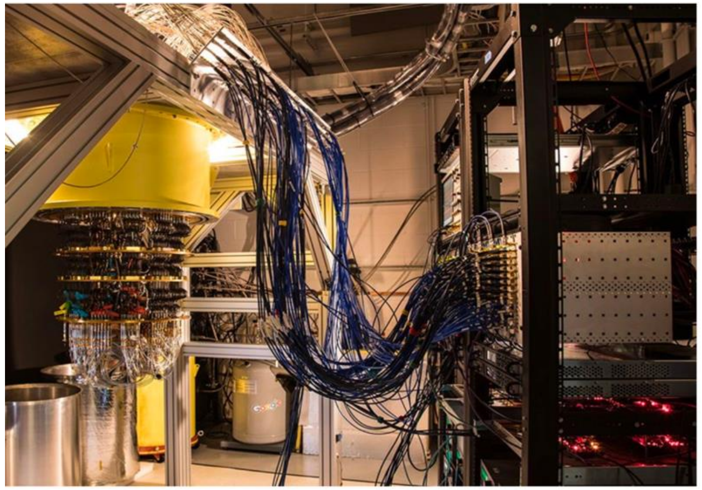
Computerized Tomography

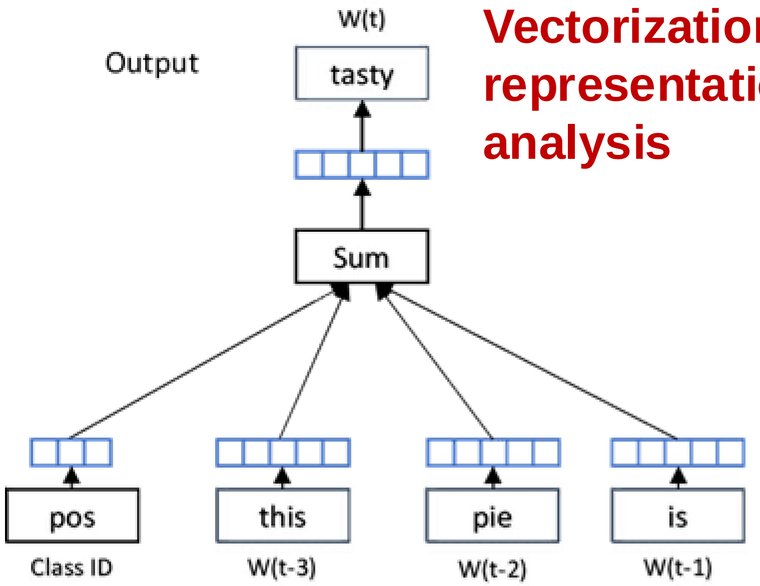


Analyzing Quantum Circuit by Contextual and Topological Features

QuCT Insight

Solution: Implement circuit topology and context-aware gate vectorization





Vectorization is a more efficient representation for further analysis

Quantum	NLP
Fidelity prediction	grammar analysis
Circuit generation	Test generation

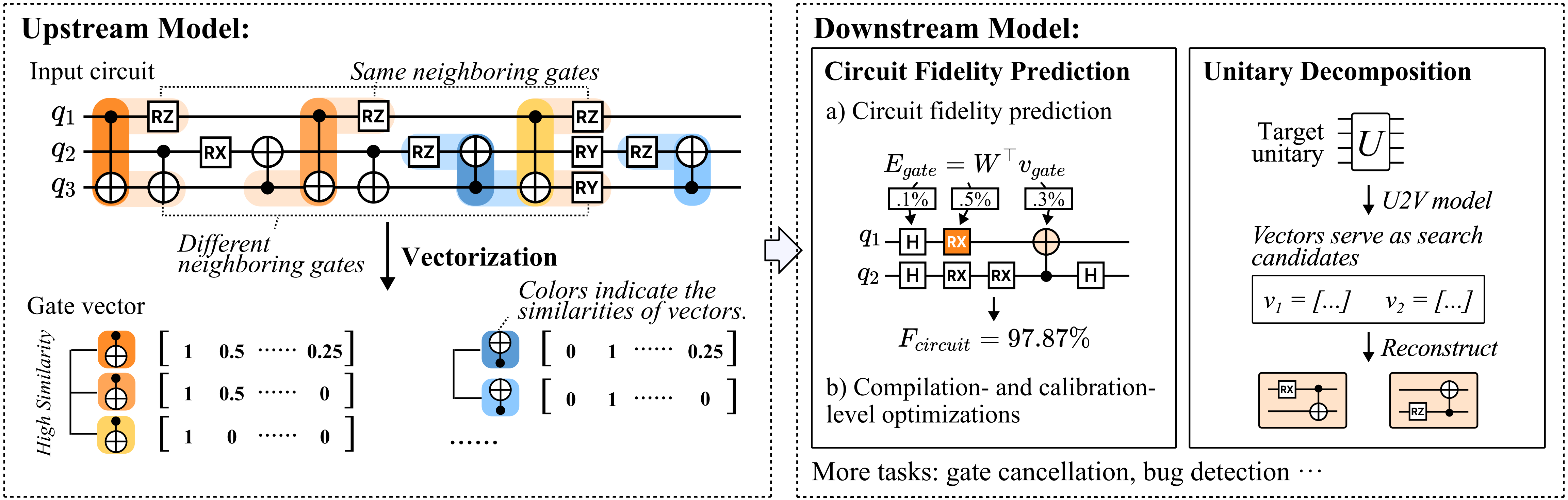
Quantum circuits are implemented via pulses. There are **interactions between wirings of qubits.**

Context extraction is common in **natural language processing (NLP)** and **classical program analysis**

Quantum program analysis and NLP have similar tasks

QuCT Overview

Each model is one-shot generated

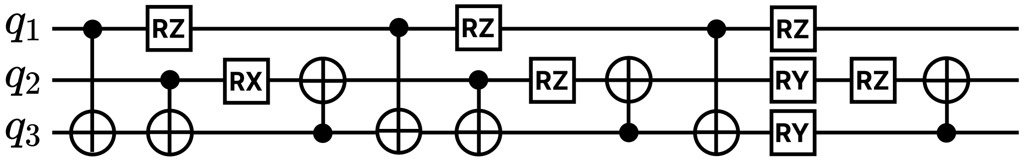


Random walk → Vectorization → Fidelity prediction or Unitary decomposition

QuCT Overview

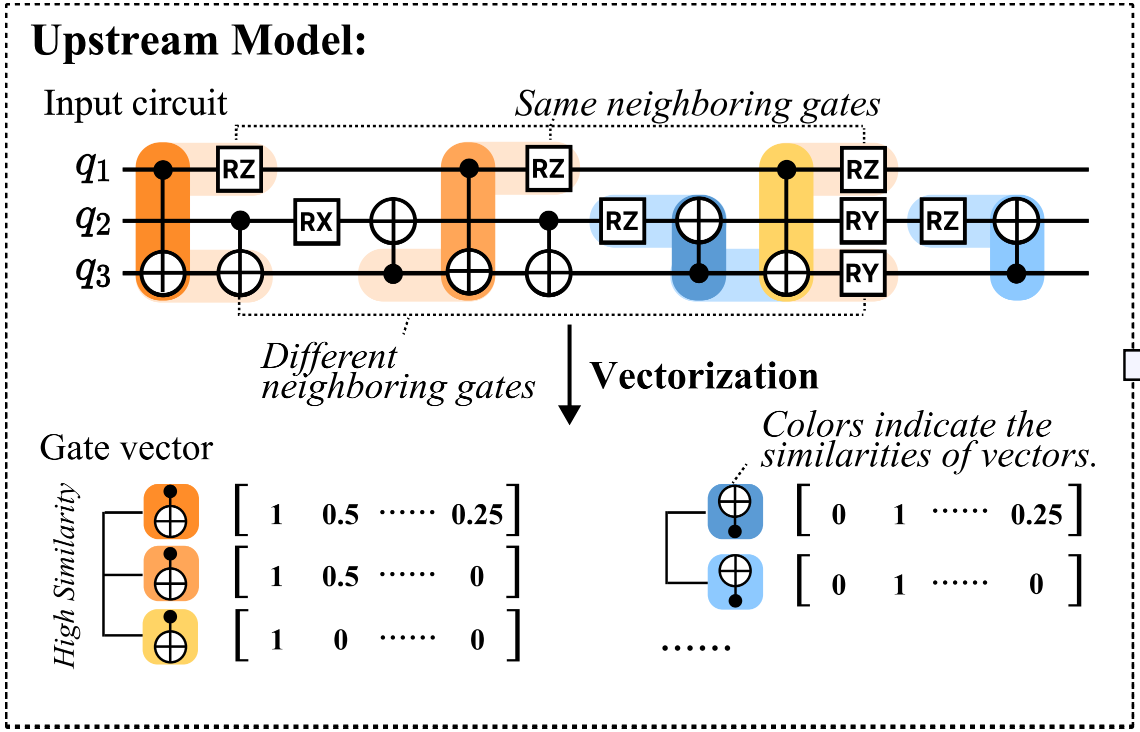
Upstream Model:

Input circuit



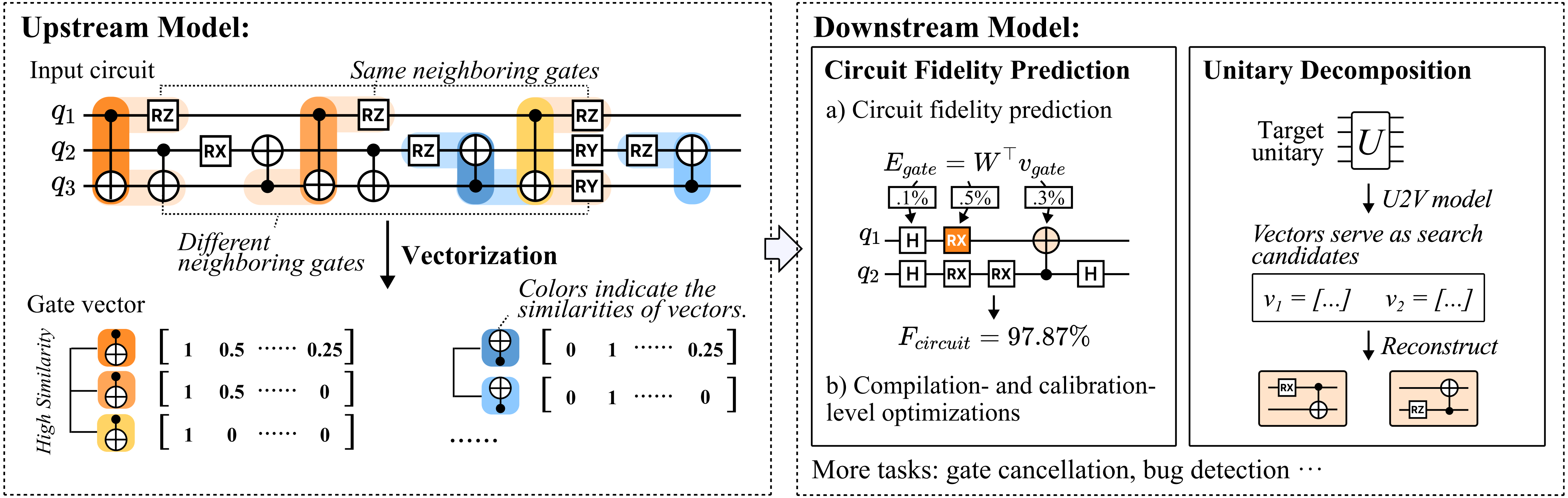
Random walk

QuCT Overview



Random walk → Vectorization

QuCT Overview



Random walk → Vectorization → Fidelity prediction or Unitary decomposition

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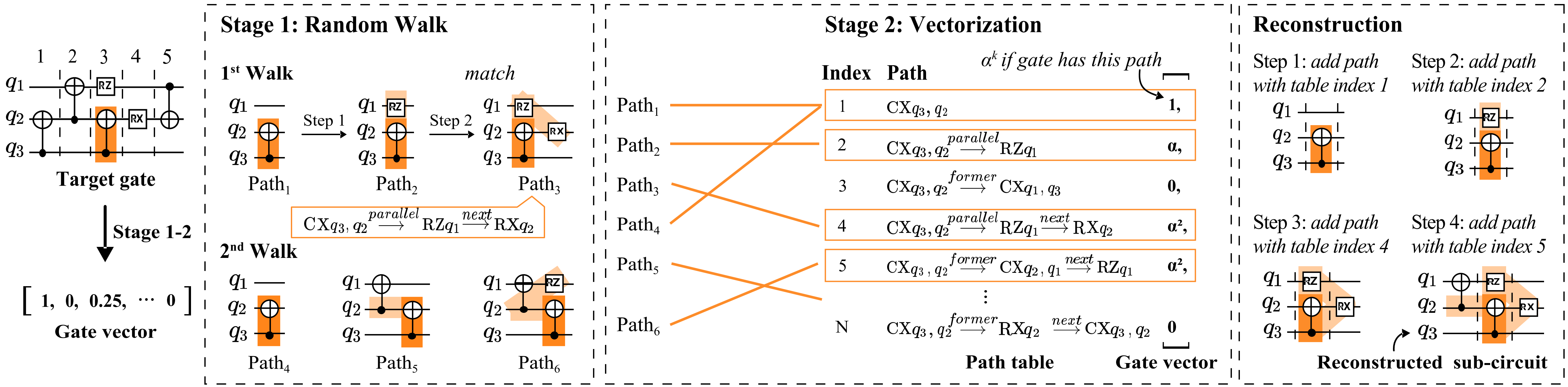
Upstream Model: Circuit Feature Extraction

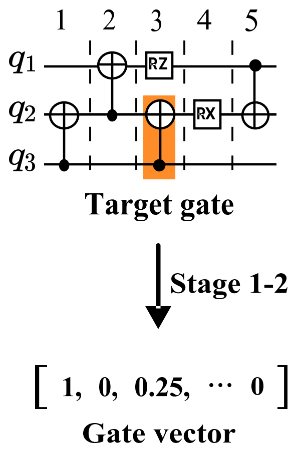
Two-step vectorization flow



Upstream Model: Circuit Feature Extraction

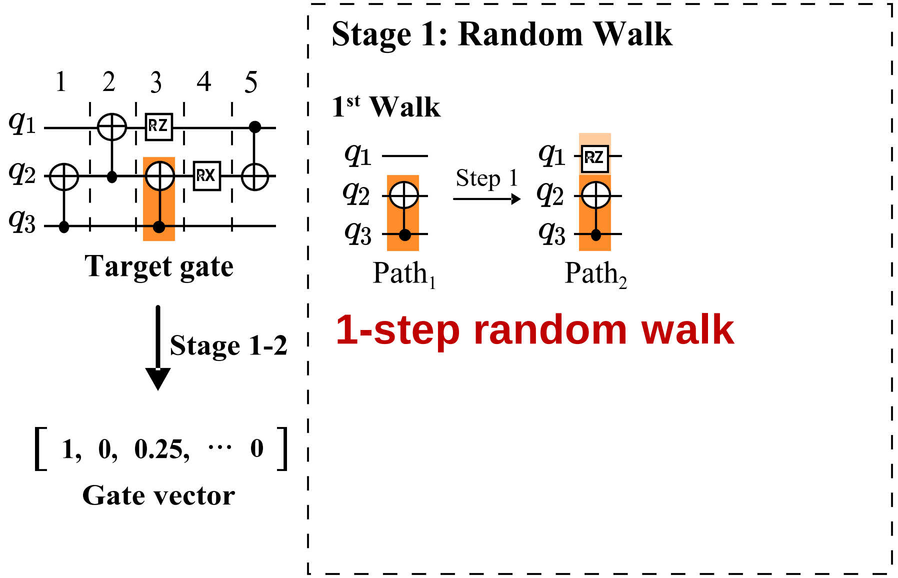
Two-step vectorization flow

For each gate



Upstream Model: Circuit Feature Extraction

Two-step vectorization flow

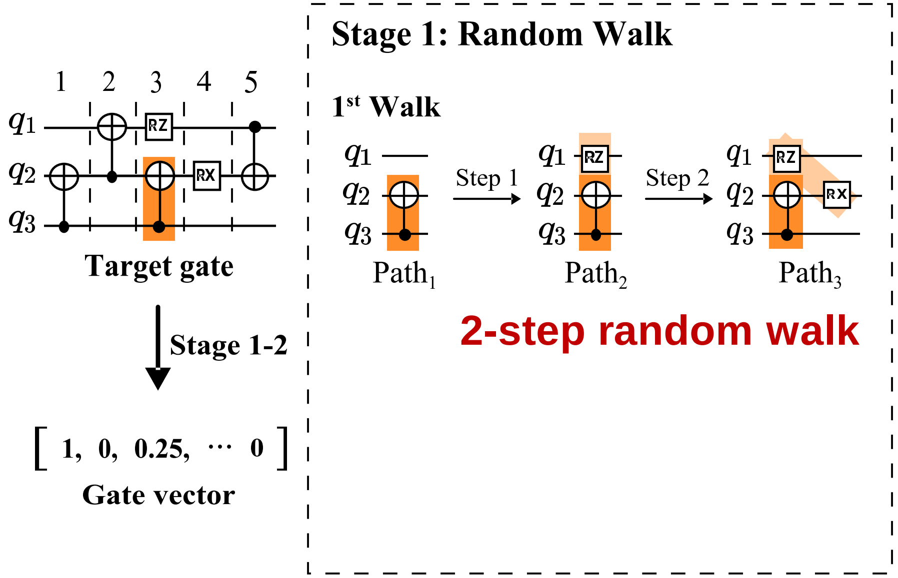


1-step random walk

Step 1: Extract features as paths.

Upstream Model: Circuit Feature Extraction

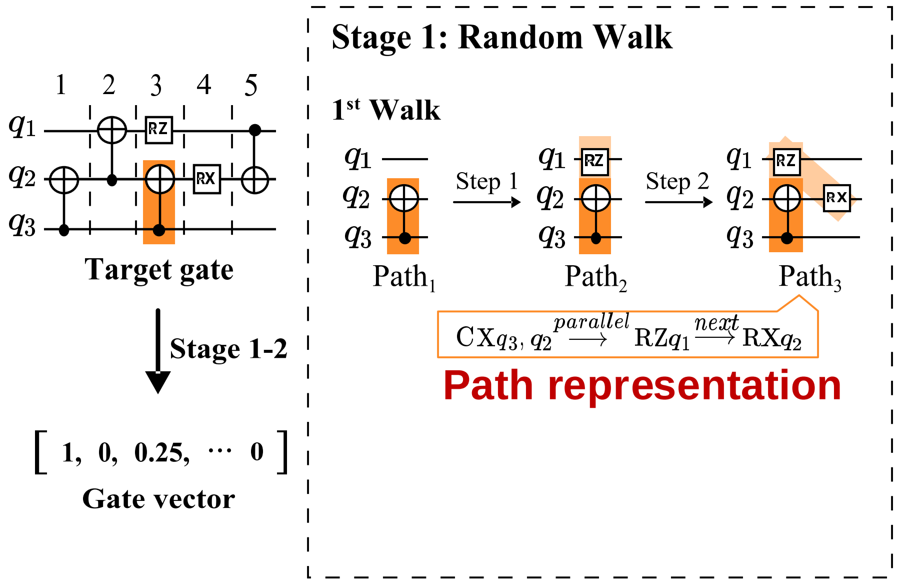
Two-step vectorization flow



Step 1: Extract features as paths.

Upstream Model: Circuit Feature Extraction

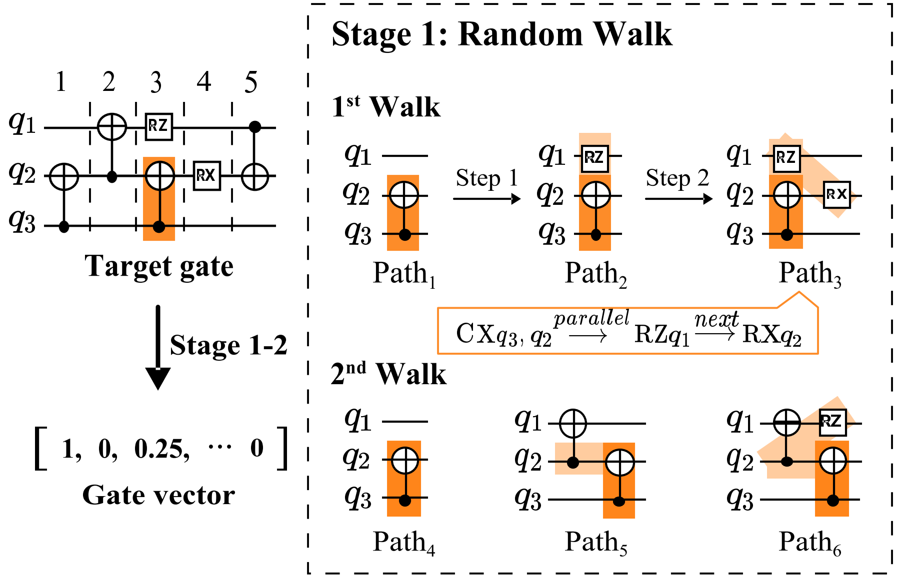
Two-step vectorization flow



Step 1: Extract features as paths.

Upstream Model: Circuit Feature Extraction

Two-step vectorization flow

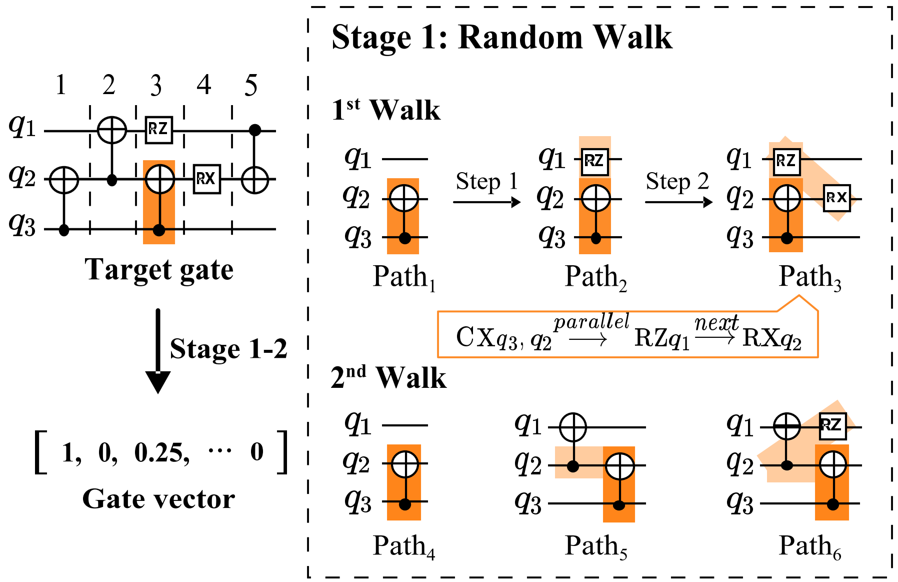


Multiple paths

Step 1: Extract features as paths.

Upstream Model: Circuit Feature Extraction

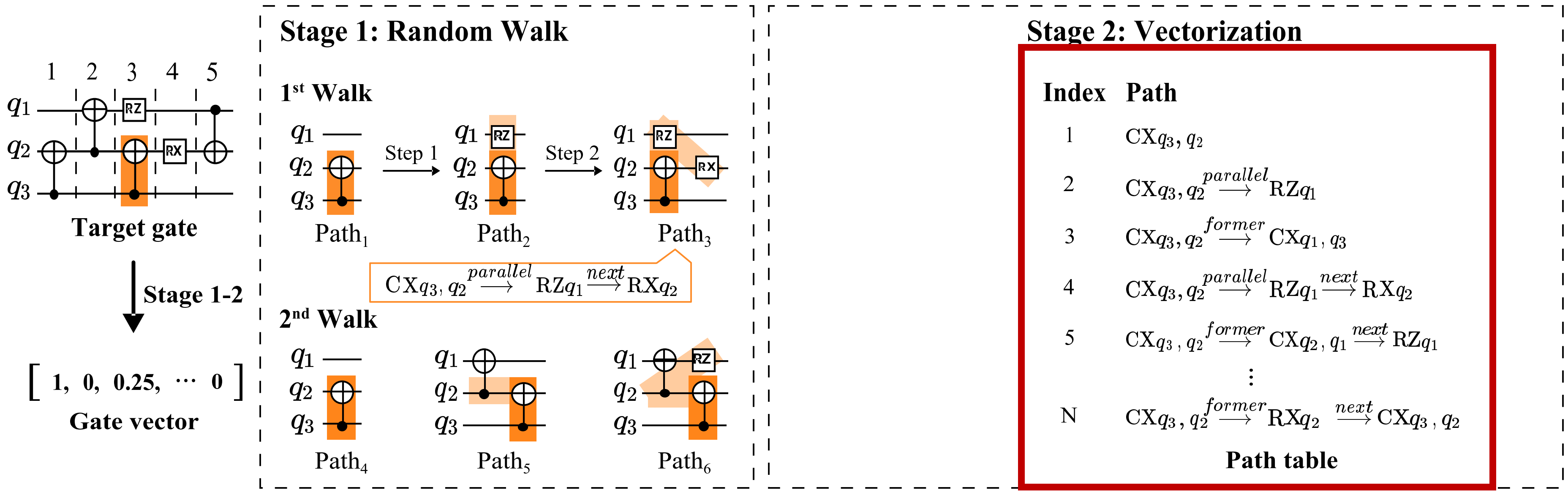
Two-step vectorization flow



Obtain vector.

Upstream Model: Circuit Feature Extraction

Two-step vectorization flow

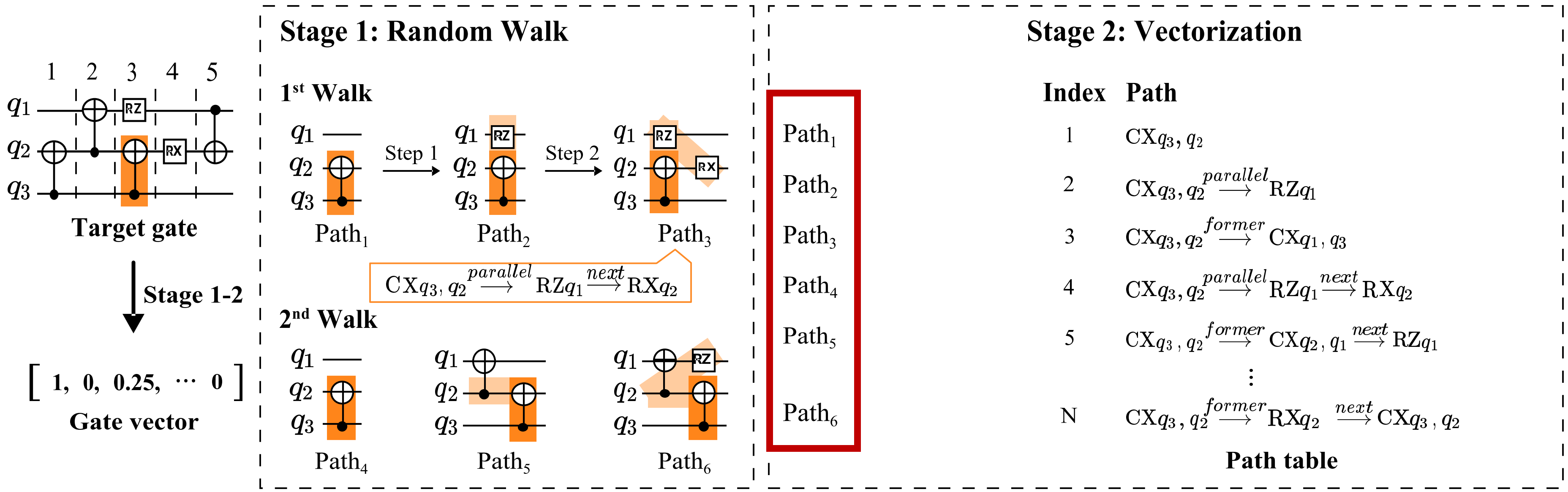


Pre-generated

Obtain vector.

Upstream Model: Circuit Feature Extraction

Two-step vectorization flow

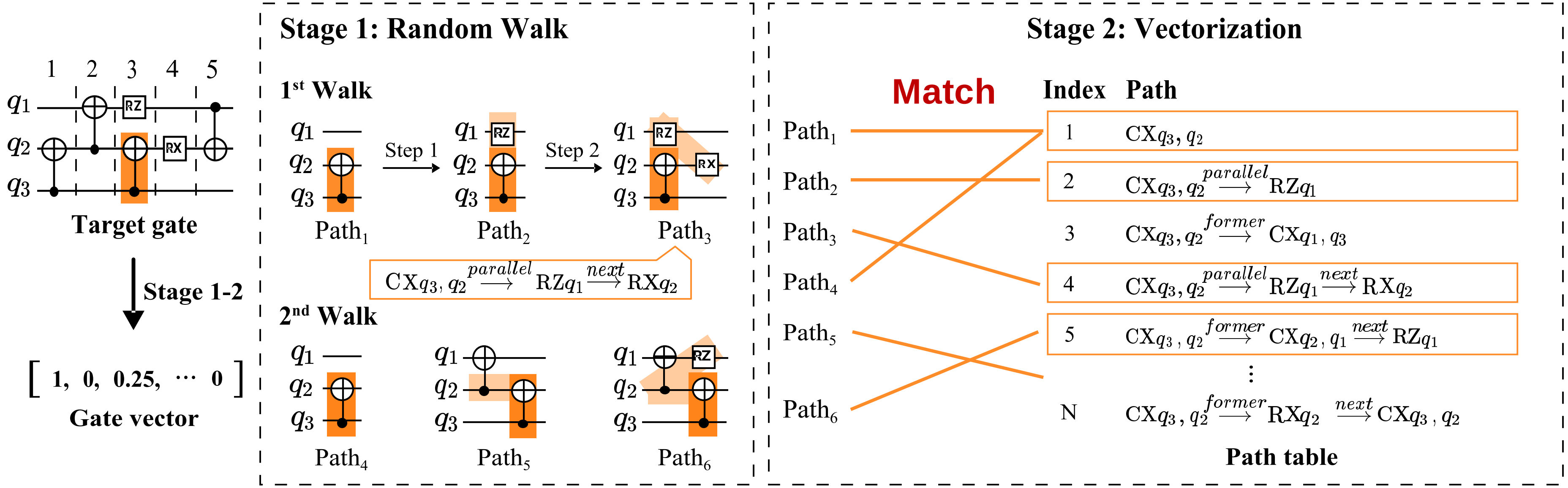


From random walk **Pre-generated**

Obtain vector.

Upstream Model: Circuit Feature Extraction

Two-step vectorization flow



From random walk

Pre-generated

Obtain vector.

Upstream Model: Circuit Feature Extraction

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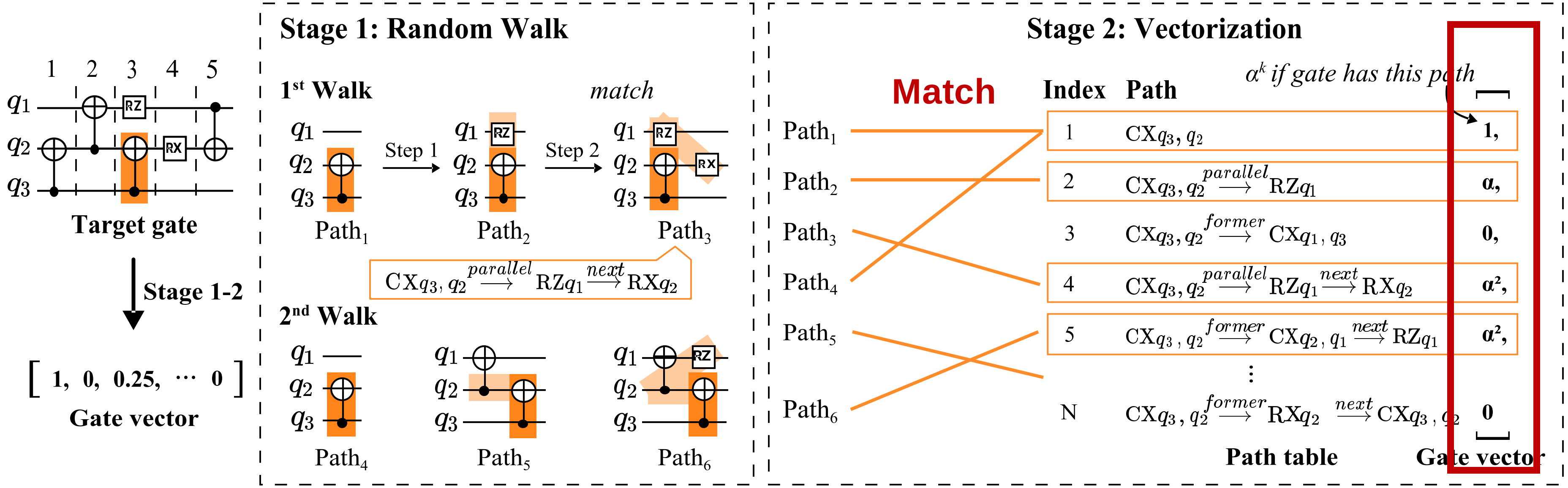
Two-step vectorization flow

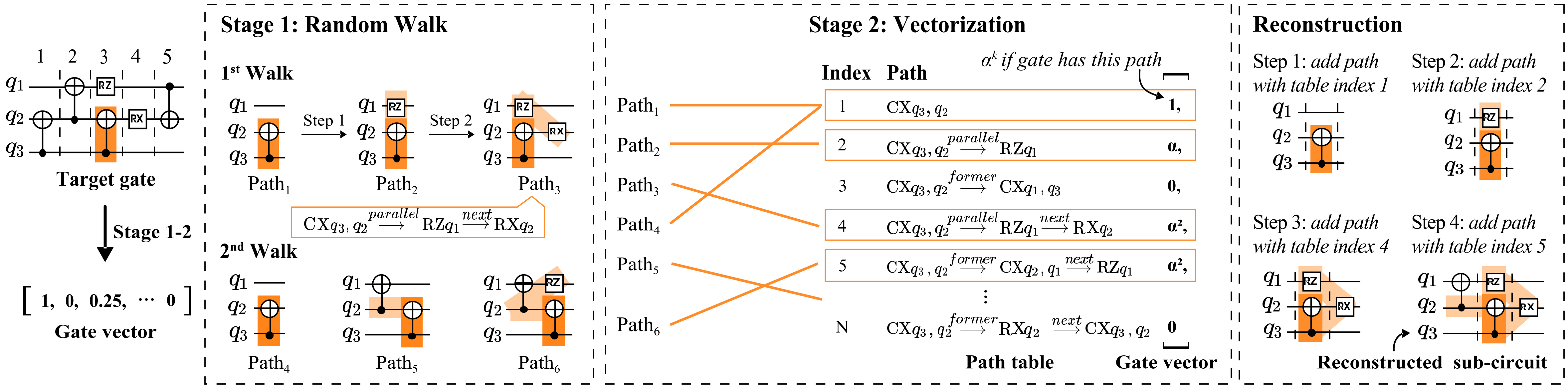


From random walk **Pre-generated**

Obtain vector.

Upstream Model: Circuit Feature Extraction

Two-step vectorization flow



Reconstruct circuit.

API to Construct Upstream Model

File:
- JanusQ/examples/ipynb/2_1_vectorization.ipynb
- https://janusq.github.io/tutorials/demo/2_1_vectorization

define backend

generate fidelity dataset

construct model using random walk

```
from janusq.analysis.vectorization import RandomwalkModel
from janusq.objects.backend import GridBackend
from janusq.objects.random_circuit import random_circuits

# define the information of the quantum device
n_qubits = 6
backend = GridBackend(2, 3)

# generate a dataset including varous random circuits
circuit_dataset = random_circuits(backend, n_circuits=100, n_gate_list=[30, 50, 100],
two_qubit_prob_list=[.4], reverse=True)

# apply random work to consturct the vectorization model with a path table
n_steps, n_walks = 1, 100
up_model = RandomwalkModel(n_steps = n_steps, n_walks = n_walks, backend = backend,
decay= 0.5, circuits = circuit_dataset )
up_model.train(circuit_dataset, multi_process=False)
```

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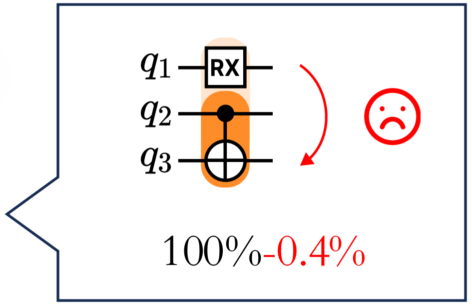
Downstream Model 1: Circuit Fidelity Prediction

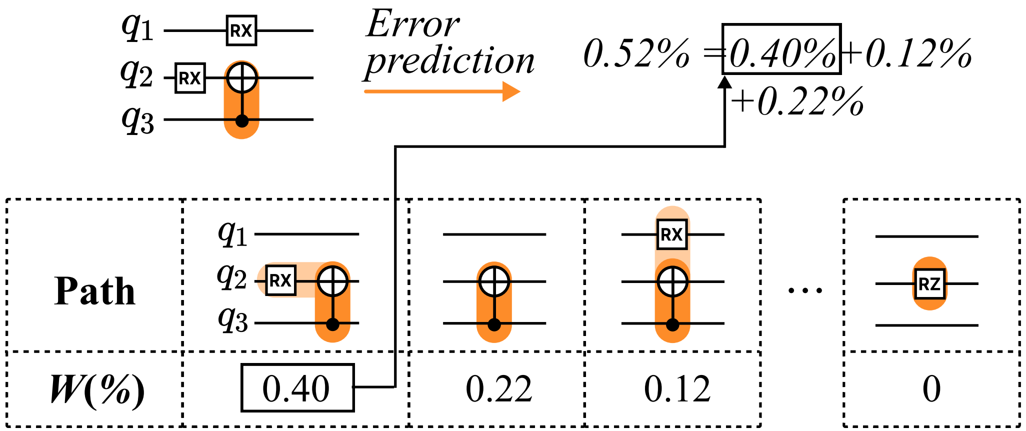
Gate error prediction

$$E(v_i) = W^\intercal v_i$$



Model dependent error

v_i : gate vector. W : weight vector obtained via training.



Downstream Model 1: Circuit Fidelity Prediction

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Gate error prediction

$$E(v_i) = W^\intercal v_i$$

v_i : gate vector. W : weight vector obtained via training.

Circuit fidelity prediction

$$F_{circuit} = \prod_{g_i \in G} (1 - E(v_i)) \prod_{q \in Q} MF_q$$

G : gate set， Q : qubit set， MF_q : measurement fidelity

The probability that all gates are correct.

Downstream Model 1: Circuit Fidelity Prediction

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Gate error prediction

$$E(v_i) = W^{\intercal} v_i$$

v_i : gate vector. W : weight vector obtained via training.

Circuit fidelity prediction

$$F_{circuit} = \prod_{g_i \in G} (1 - E(v_i)) \prod_{q \in Q} MF_q$$

G : gate set, Q : qubit set, MF_q : measurement fidelity

Training process of weight vector W :

Obtain fidelity dataset (*circuit,* $F_{ground-truth}$) ⋯, $F_{ground-truth}$: ground-truth circuit fidelity on the target quantum device.

$$\min_{W} | F_{circuit} - F_{ground-truth} |$$

Minimize the distance between the prediction and ground-truth fidelity.

API to Construct Fidelity Prediction Model

File:
- JanusQ/examples/ipynb/2_2_fidelity_prediction_simulator.ipynb
- https://janusq.github.io/tutorials/demo/2_2_fidelity_prediction_simulator

```
from janusq.dataset import real_qc_5bit
from janusq.objects.backend import FullyConnectedBackend
from janusq.analysis.fidelity_prediction import FidelityModel

circuits, fidelities = real_qc_5bit
backend = FullyConnectedBackend(5)
up_model = RandomwalkModel(n_steps = 1, n_walks = 10, backend = backend,
circuits = circuits)

fidelity_model = FidelityModel(up_model)
fidelity_model.train((circuits, fidelities), multi_process = False)

circuit = random_circuit(backend, n_gates = 100, two_qubit_prob = 0.5 )
fidelity_model.predict_circuit_fidelity(circuit)
```

construct upstream model

construct fidelity prediction model

predict the fidelity of the given circuit

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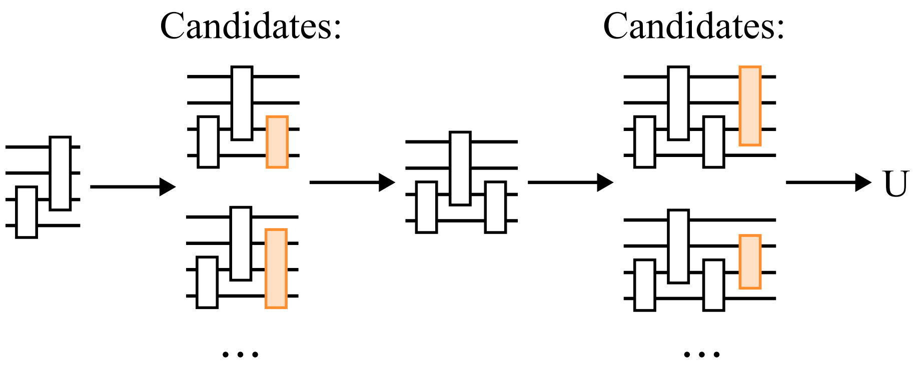
Downstream Model 2: Unitary Decomposition

Improve the current search-based method



Search-based method

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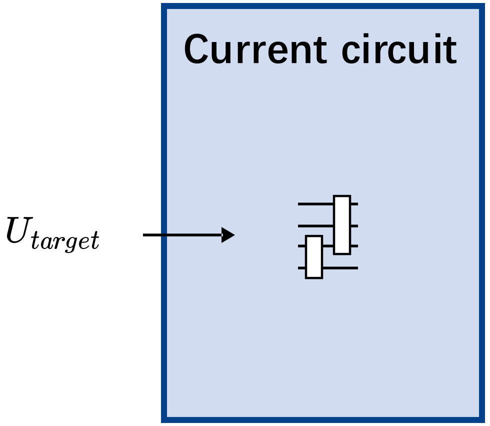
5-qubit unitary decomposition

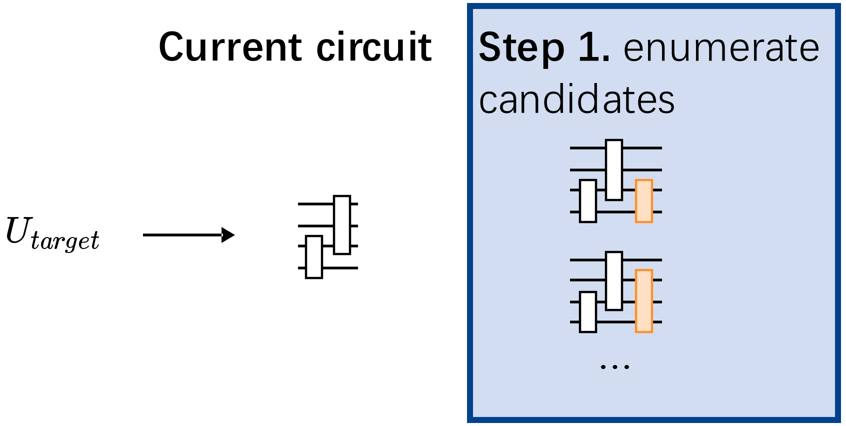
Downstream Model 2: Unitary Decomposition

QFAST workflow



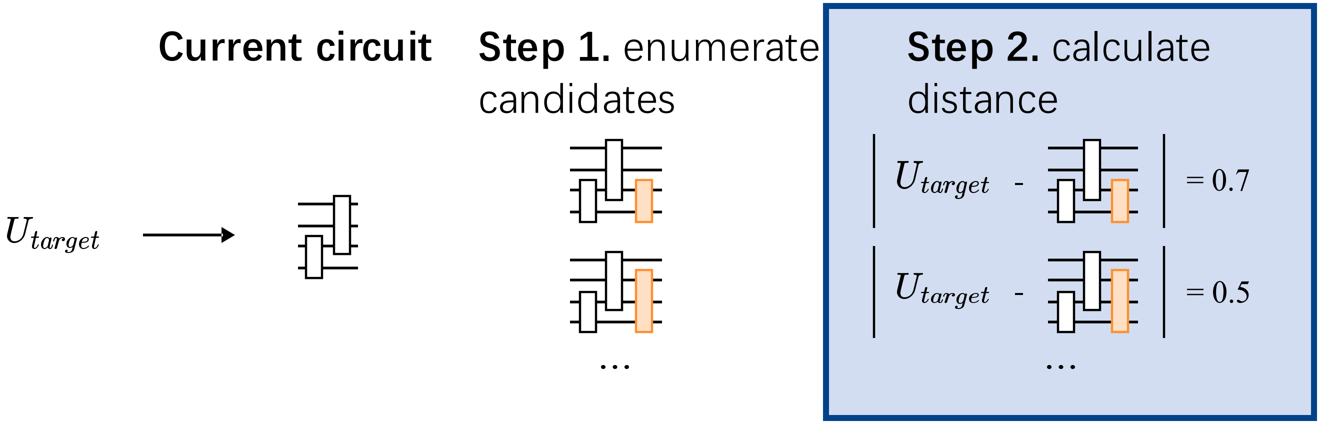
Downstream Model 2: Unitary Decomposition

QFAST workflow



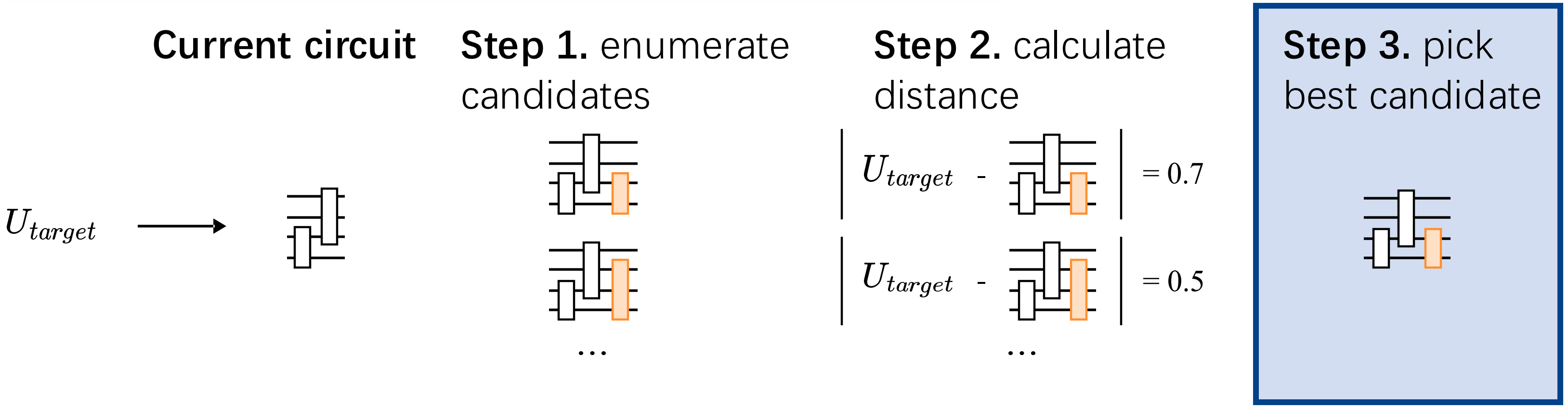
Downstream Model 2: Unitary Decomposition

QFAST workflow



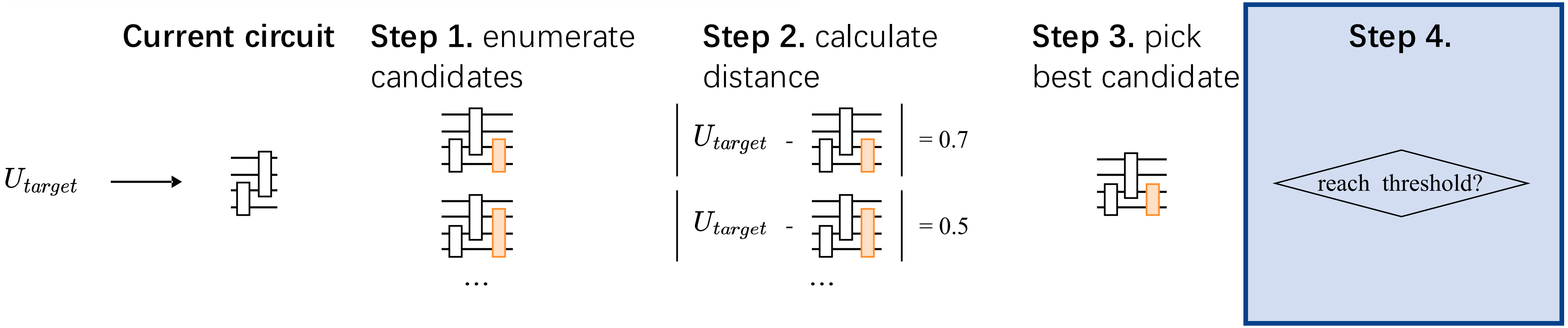
Downstream Model 2: Unitary Decomposition

QFAST workflow



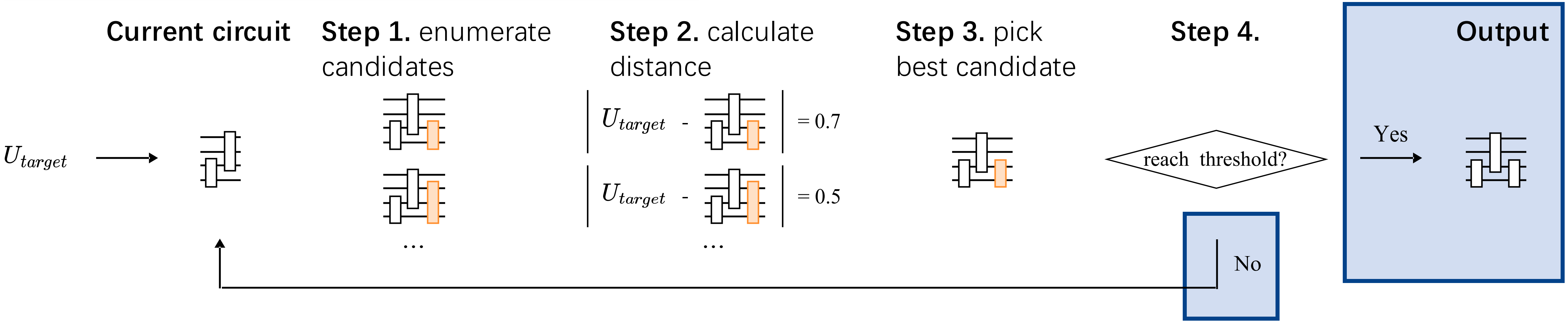
Downstream Model 2: Unitary Decomposition

QFAST workflow



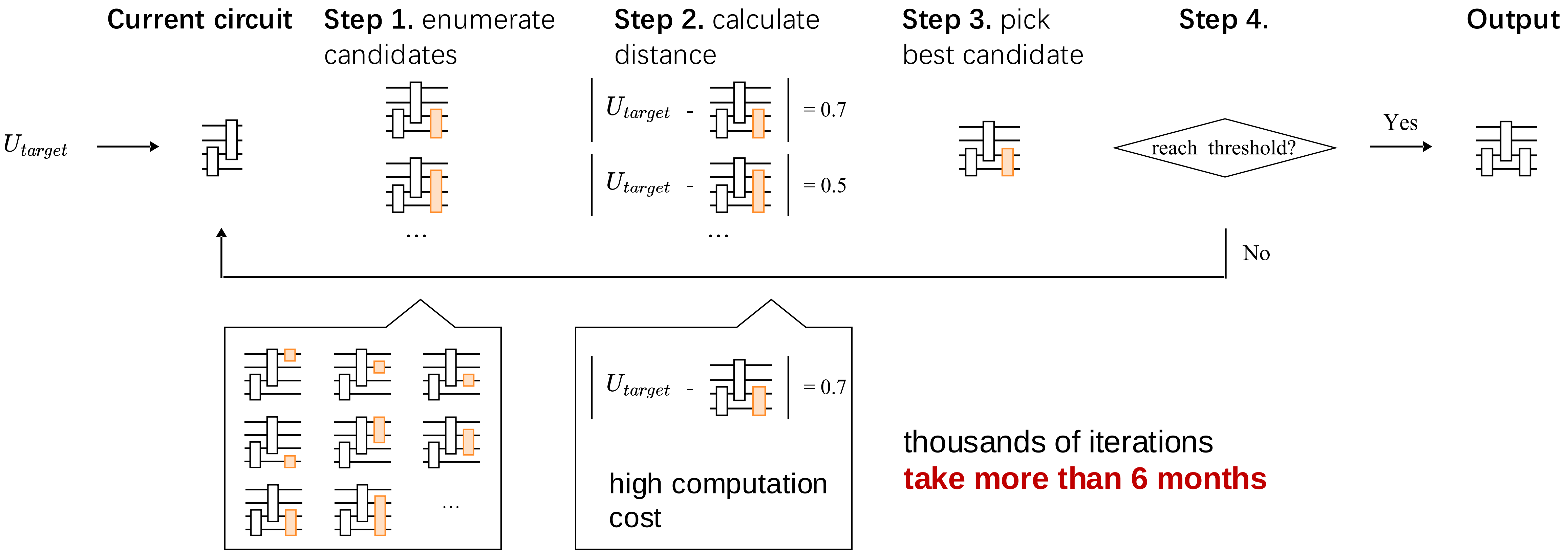
Downstream Model 2: Unitary Decomposition

QFAST workflow



Downstream Model 2: Unitary Decomposition

QFAST workflow



248 candidates for 8 qubits

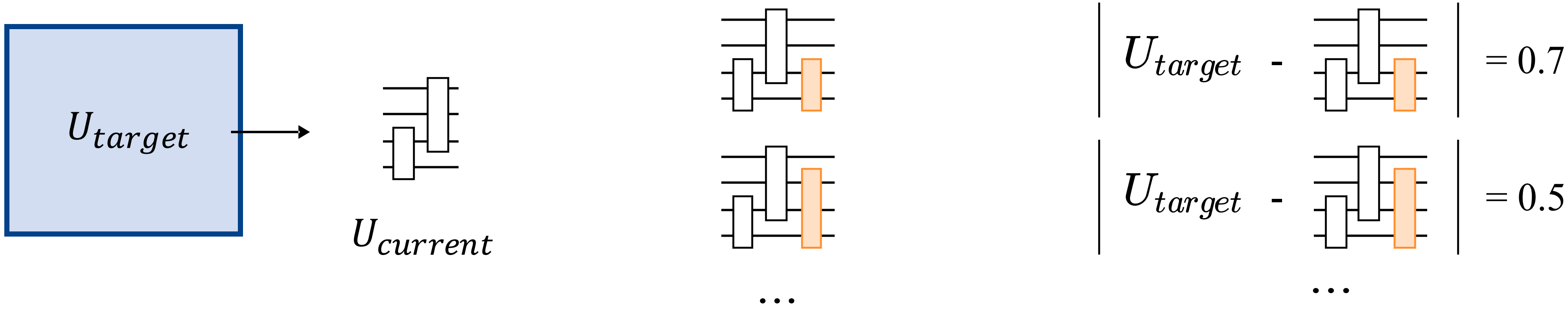
60s/candidate

thousands of iterations
take more than 6 months

Downstream Model 2: Unitary Decomposition

QuCT workflow

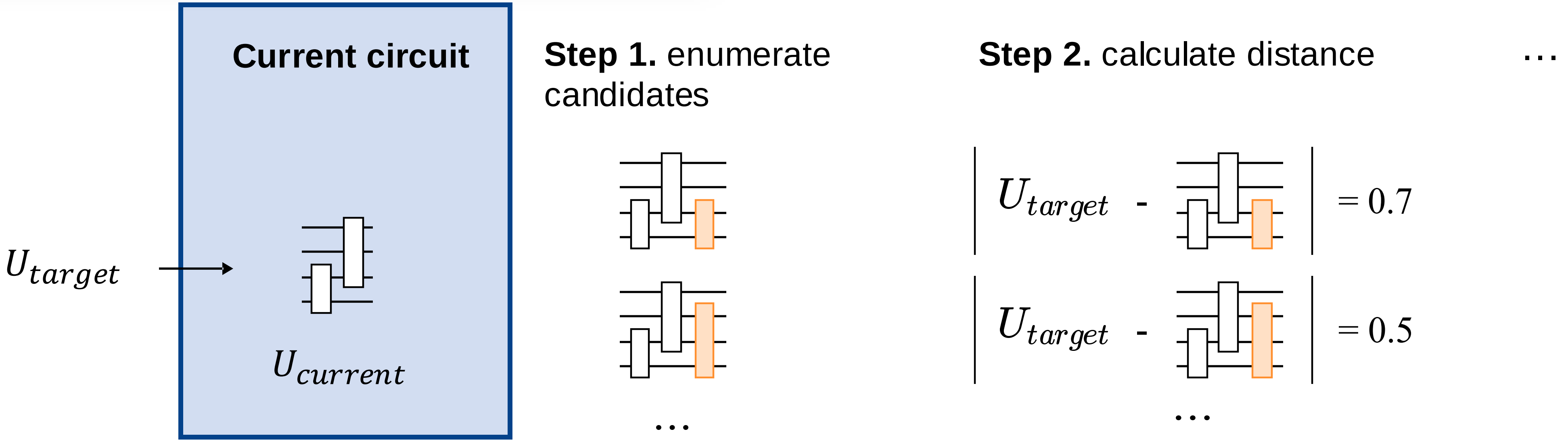
Current circuit | **Step 1.** enumerate candidates | **Step 2.** calculate distance | …



Candidates and should equal $U_{target}U_{current}^{-1}$

Downstream Model 2: Unitary Decomposition

QuCT workflow



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Downstream Model 2: Unitary Decomposition

QuCT workflow

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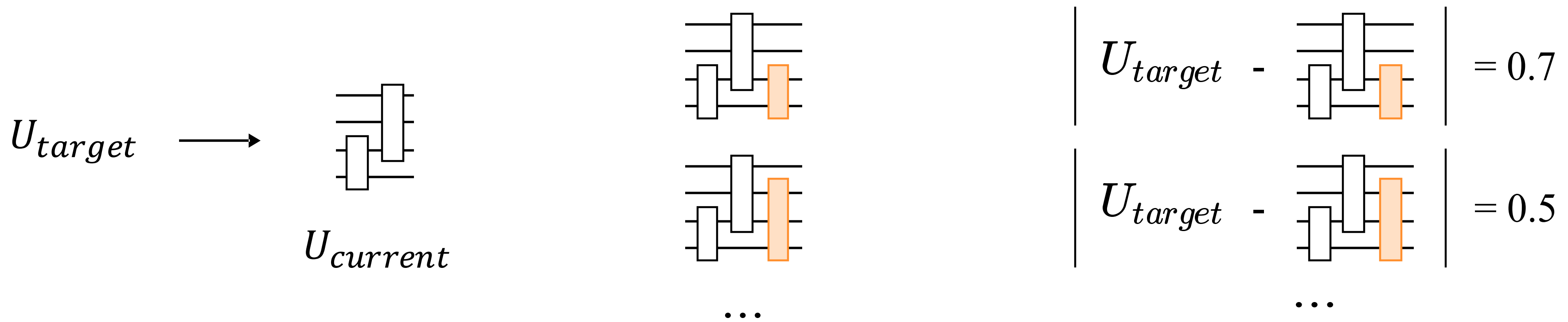

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Downstream Model 2: Unitary Decomposition

QuCT workflow

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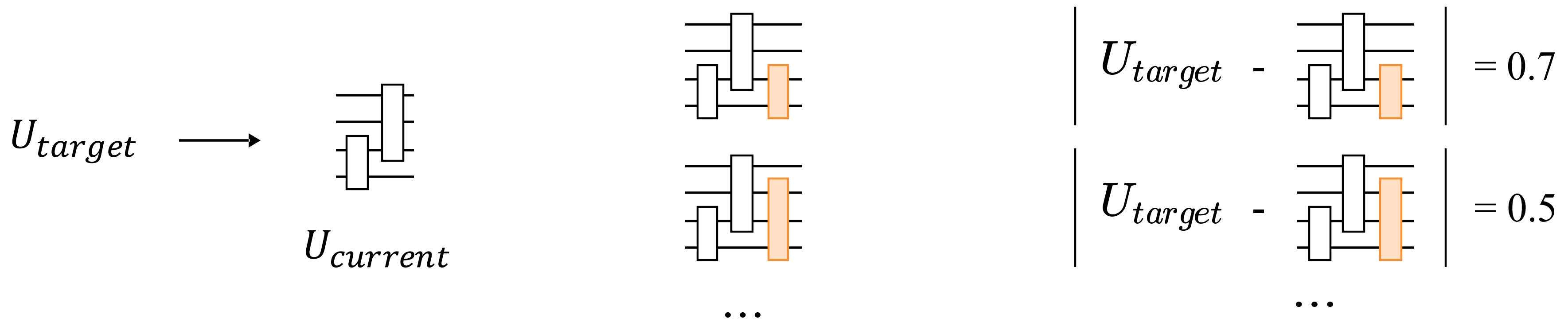


Candidates and should equal $U_{target}U_{current}^{-1}$

Instead of exhaustive search, QuCT only try the candidates that have high probability of equaling $U_{target}U_{current}^{-1}$

Downstream Model 2: Unitary Decomposition

QuCT workflow

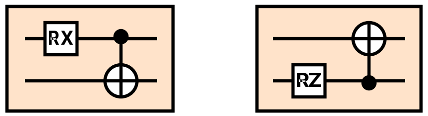
$$U_{target}U_{current}^{-1}$$

↓ U2V model

Gate vectors serve as search candidates

$v_1 = [...]$ $v_2 = [...]$

↓ Reconstruct

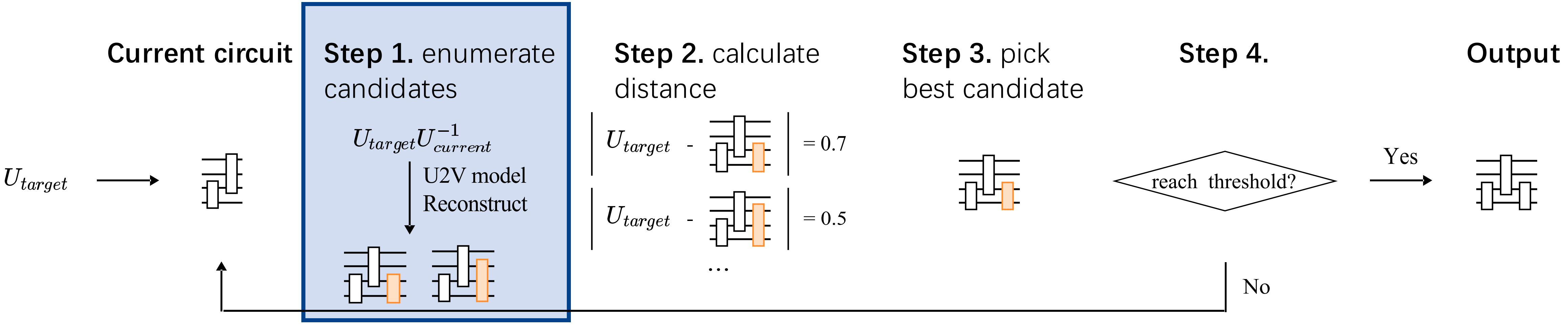


U2V model: a random forest model, trained by the pre-generated decomposition results.

Use gate vectors to construct good candidates.

Downstream Model 2: Unitary Decomposition

QuCT workflow



248→10

Comparison to the template-based method: template-based approach has smaller design space, as it can only selects candidates from a limited-size template library.

1.8 × speedup and 1.6 × gate reduction compared to the template-based method.

API to Construct Unitary Decomposition Model

File:
- JanusQ/examples/ipynb/2_5_unitary_decomposition.ipynb
- https://janusq.github.io/tutorials/demo/2_5_unitary_decomposition

```python
from qiskit.quantum_info import random_unitary
from janusq.objects.backend import FullyConnectedBackend
from janusq.analysis.unitary_decompostion import U2VModel
from janusq.analysis.unitary_decompostion import decompose

backend = FullyConnectedBackend(n_qubits=5)
dataset = random_circuits(backend = backend, n_circuits=50, n_gate_list=[30, 50, 100],
two_qubit_prob_list=[.4], reverse=True)

up_model = RandomwalkModel(n_step, 4 ** n_step, backend, directions=('parallel', 'next'))
u2v_model = U2VModel(up_model)
data = u2v_model.construct_data(dataset, multi_process=False)
u2v_model.train(data, n_qubits)

unitary = random_unitary(2**n_qubits).data
decompose(unitary, allowed_dist = 0.01, backend = backend, u2v_model = u2v_model ,
multi_process = True)
```

construct the decomposition dataset

construct unitary decomposition model

apply decomposition to random unitary

Extending QuCT To More Downstream Tasks

File:
- JanusQ/examples/ipynb/2_6_extend_framework_bug_identification.ipynb
- https://janusq.github.io/tutorials/demo/2_6_extend_framework_bug_identification

Random walk → Vectorization → Downstream tasks

```
from janusq.analysis.vectorization import RandomwalkModel

class DownstreamModel():
        def __init__(self, upstream_mdoel: RandomwalkModel) :
                self.upstream_mdoel = upstream_mdoel
```

Downstream task implementation

Extending QuCT To More Downstream Tasks

File:
- JanusQ/examples/ipynb/2_6_extend_framework_bug_identification.ipynb
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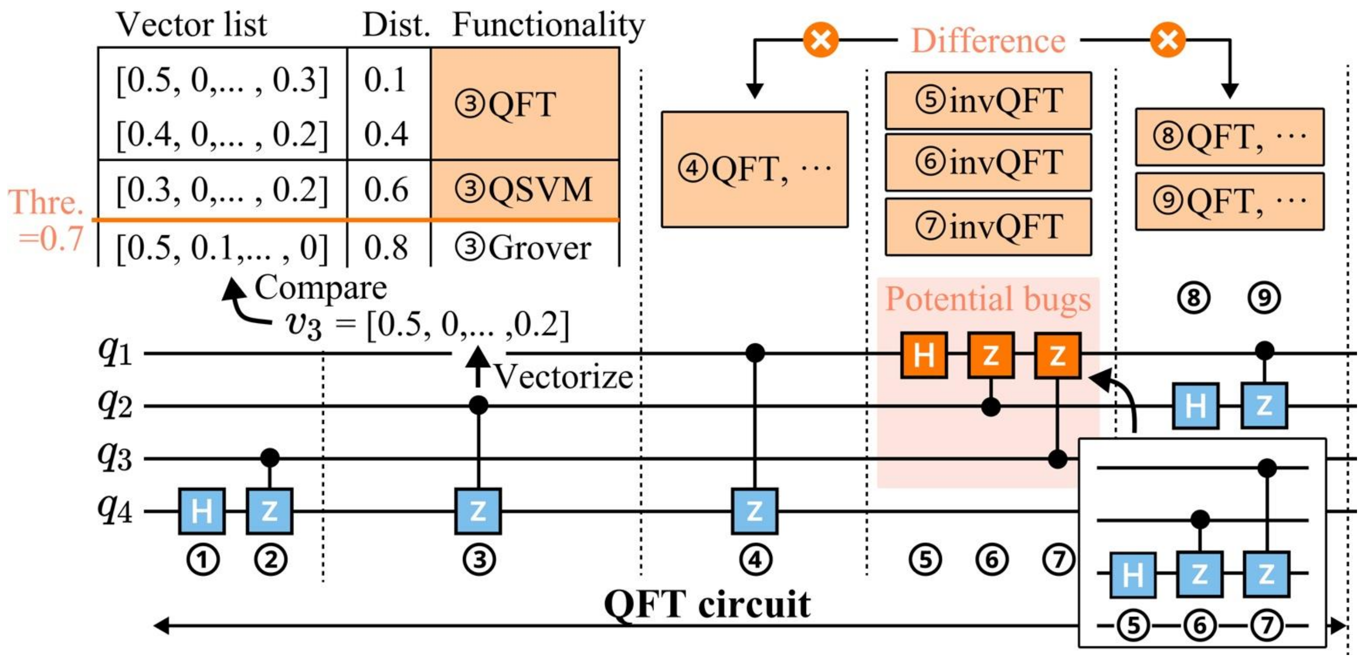
For example: Bug Identification

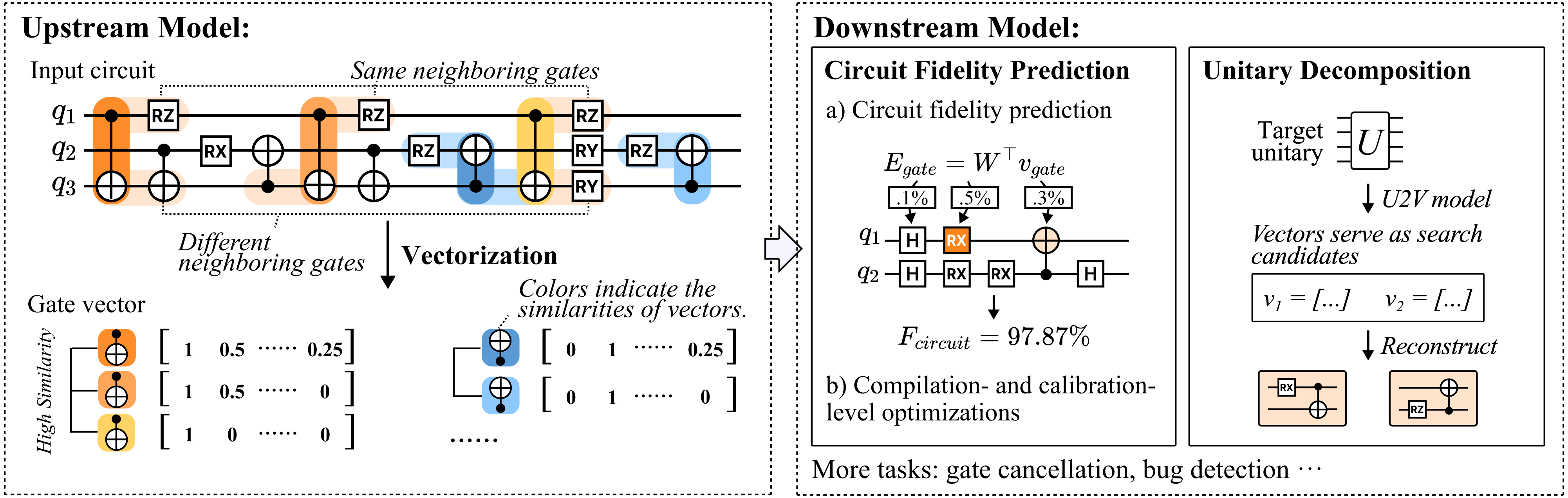
1. Identify the possible functionality

2. Identify the abnormal functionality (different from neighbors)



Conclusion

- Random walk-based method to extract contextual and topological circuit feature.
- Accurate circuit fidelity prediction via modeling gate interactions.
- Fast unitary decomposition via pruning candidate space.



Thanks for listening

QuCT: A Framework for Analyzing Quantum Circuit by Extracting Contextual and Topological Features

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