WELCOME TO TUTORIAL

Session 3 JanusQ-CT: A Framework for Analyzing Quantum Circuit by Extracting Contextual and Topological Features

ACES Lab
ADVANCED COMPUTING AND EMERGING SERVICE LAB

JanusQ Cloud

浙江大学 计算机科学与技术学院
COLLEGE OF COMPUTER SCIENCE AND TECHNOLOGY
ZHEJIANG UNIVERSITY

https://janusq.github.io/tutorials/

College of Computer Science and Technology,
Zhejiang University

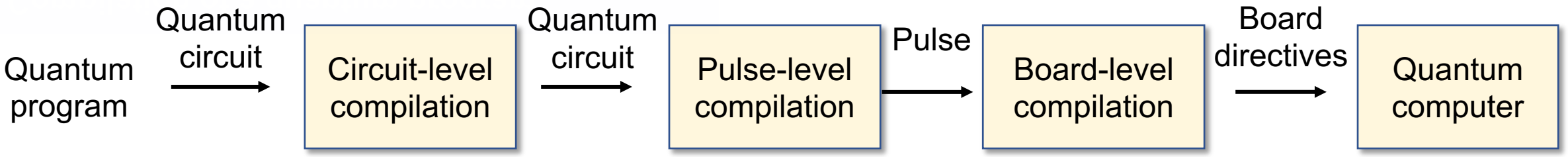
ASPLOS 2024

Outline of Presentation

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

Background

Compilation of a quantum program



Circuit-level compilation:

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

Pulse-level compilation:

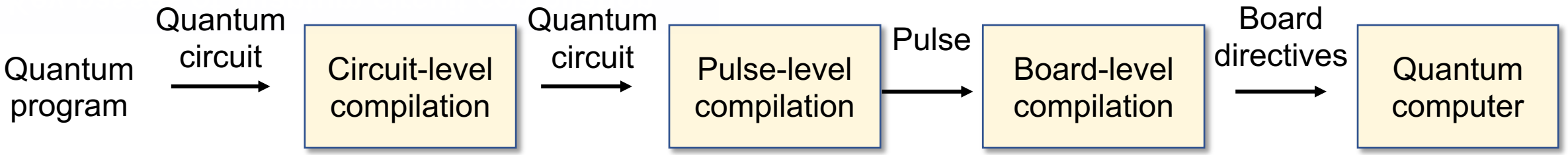
- Input: quantum circuit — Output: Pulses received by qubits

Board-level compilation:

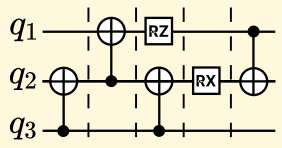
- Input: pulses — Output: Board directives

Background

Key passes of quantum circuit compilation



Pass 1: Unitary decomposition



compute

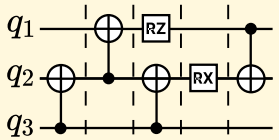
small complexity

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

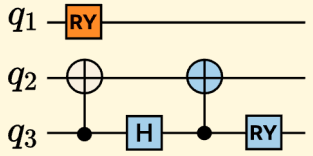
$$\begin{bmatrix} 0 & e^{i-\pi/2} & 0 & 0 \\ 0 & 0 & 0 & e^{i-\pi/2} \\ e^{i\pi/2} & 0 & 0 & 0 \\ 0 & 0 & 0 & e^{i\pi/2} \end{bmatrix}$$

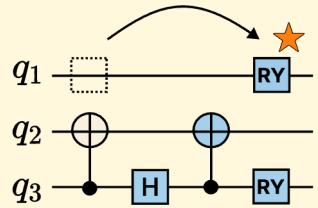
decompose

large complexity



Pass 2: Fidelity prediction and optimization

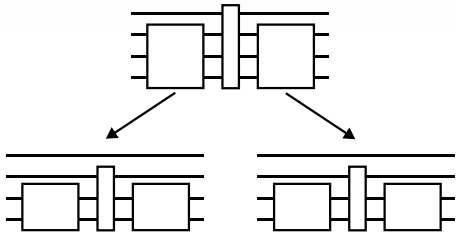




Optimize the noise while keeping the equivalence of circuits

Challenges of Unitary Decomposition

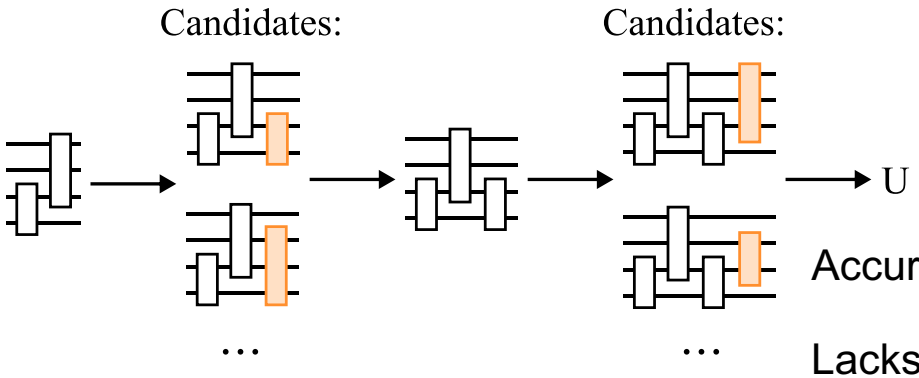
Unitary decomposition



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

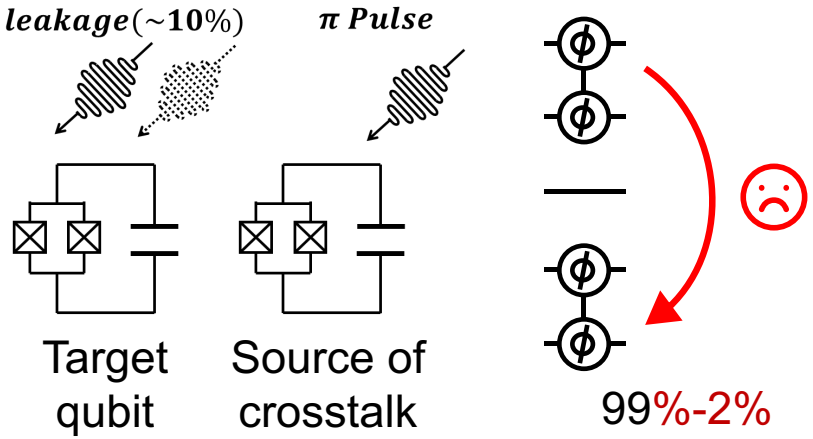
$O(4^N)$ #Gate **$O(4^N)$ Time**

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



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

Fidelity prediction

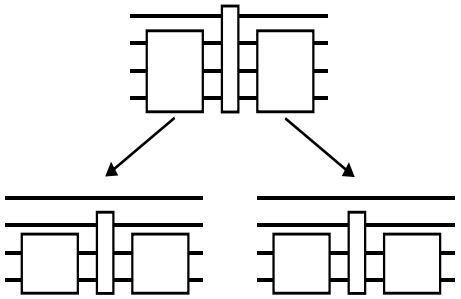
Not one-shot

[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

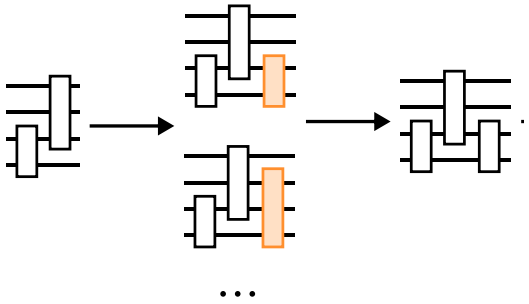
Unitary decomposition

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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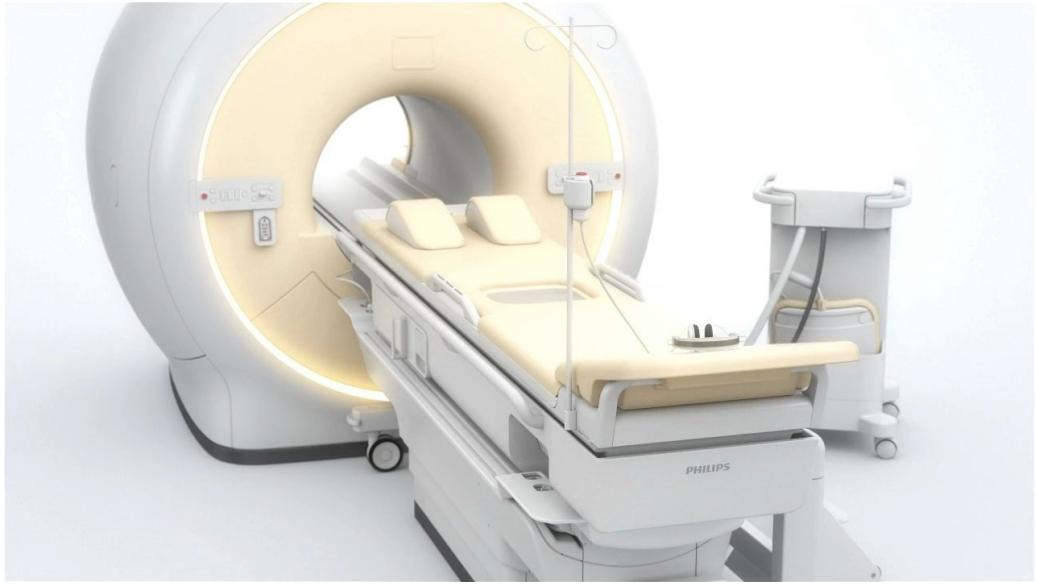
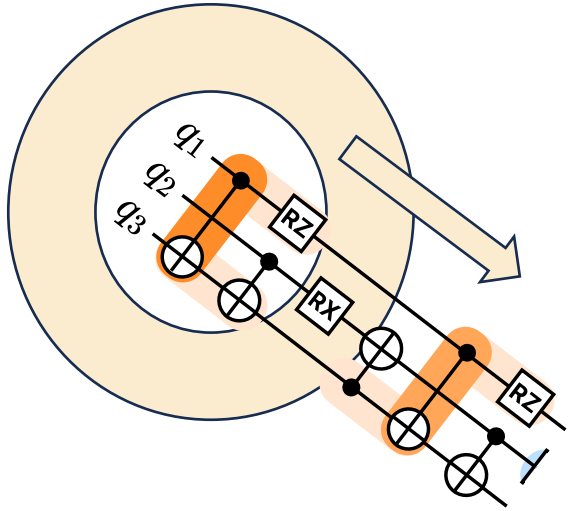
- **Janus-CT overview**
- Upstream model: Circuit feature extraction
- Downstream model 1: Circuit fidelity prediction
- Downstream model 2: Unitary decomposition

Janus-CT Overview

Origin of the name



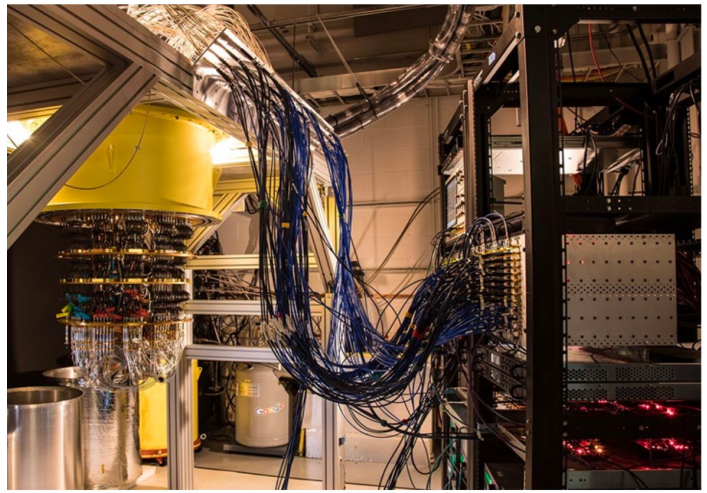
Computerized Tomography



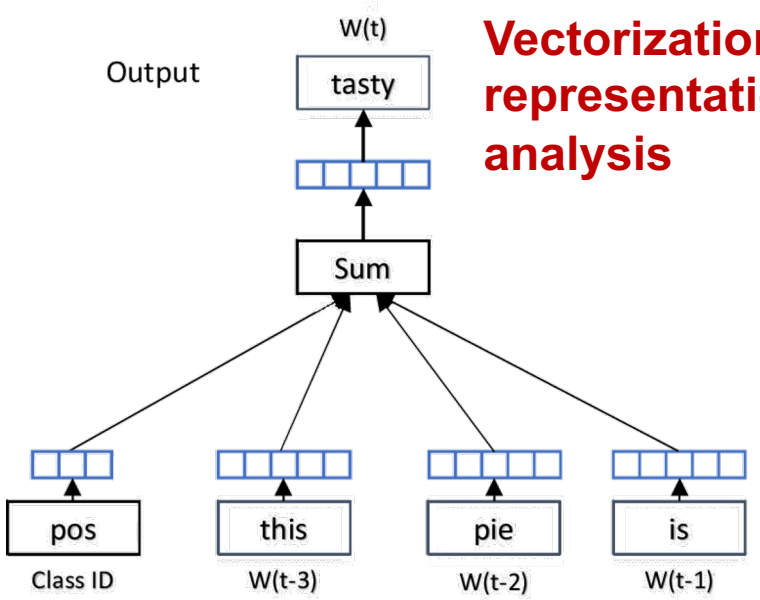
Analyzing Quantum Circuit by
Contextual and Topological Features

Janus-CT Insight

Solution: Implement circuit topology and context-aware gate vectorization



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



Vectorization is a more efficient representation for further analysis

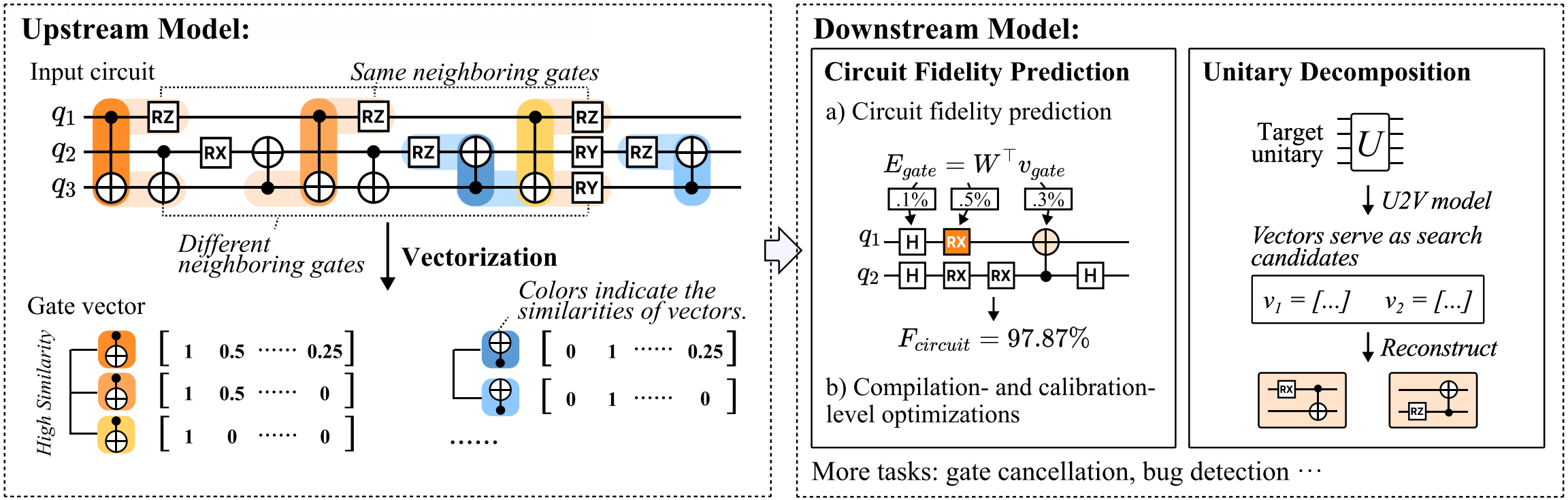
Context extraction is common in **natural language processing (NLP)** and **classical program analysis**

Quantum	NLP
Fidelity prediction	grammar analysis
Circuit generation	Test generation

Quantum program analysis and NLP have similar tasks

Janus-CT Overview

Each model is one-shot generated

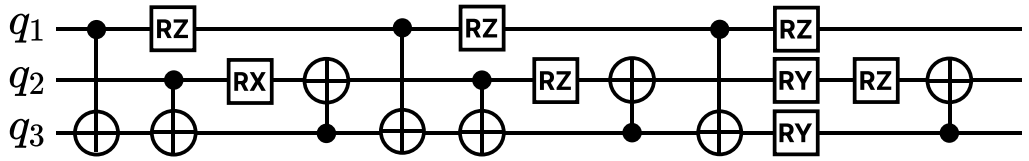


Random walk → Vectorization → Fidelity prediction or Unitary decomposition

Janus-CT Overview

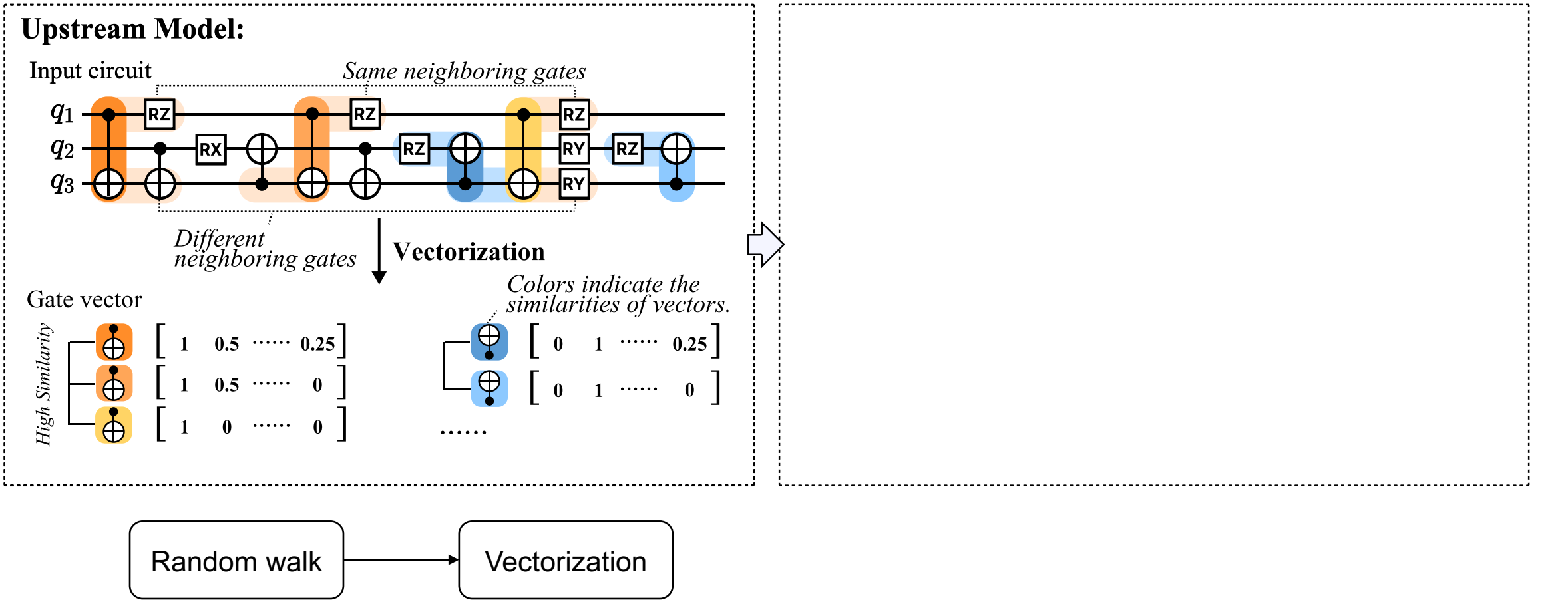
Upstream Model:

Input circuit



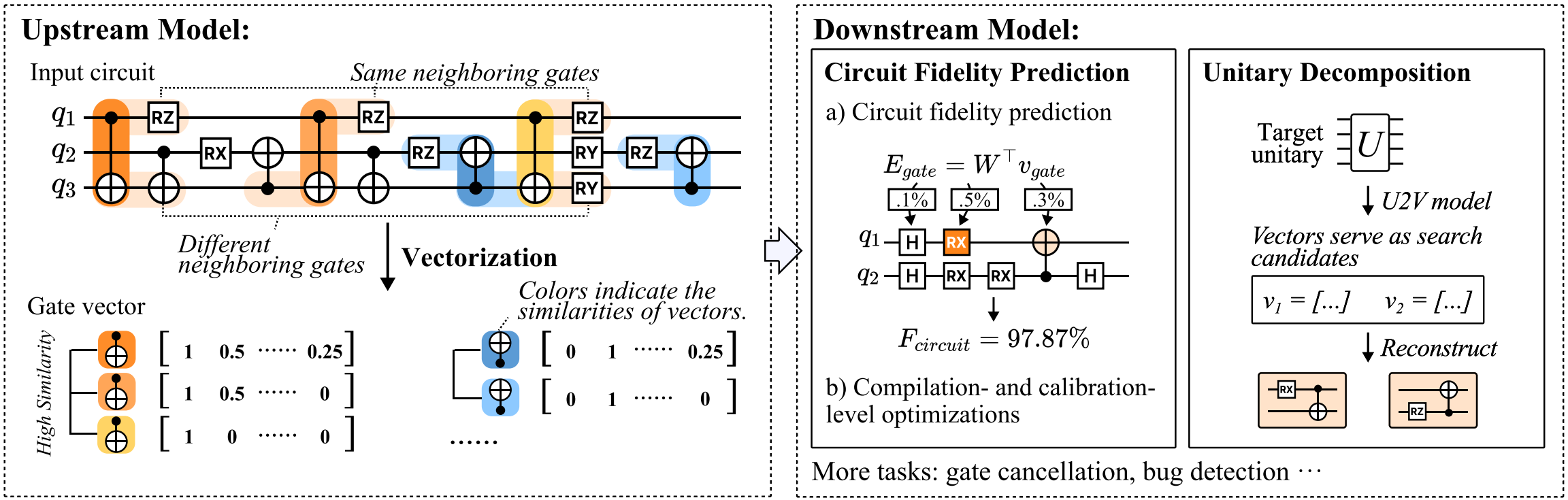
Random walk

Janus-CT Overview



Random walk → Vectorization

Janus-CT Overview



Random walk → Vectorization → Fidelity prediction or Unitary decomposition

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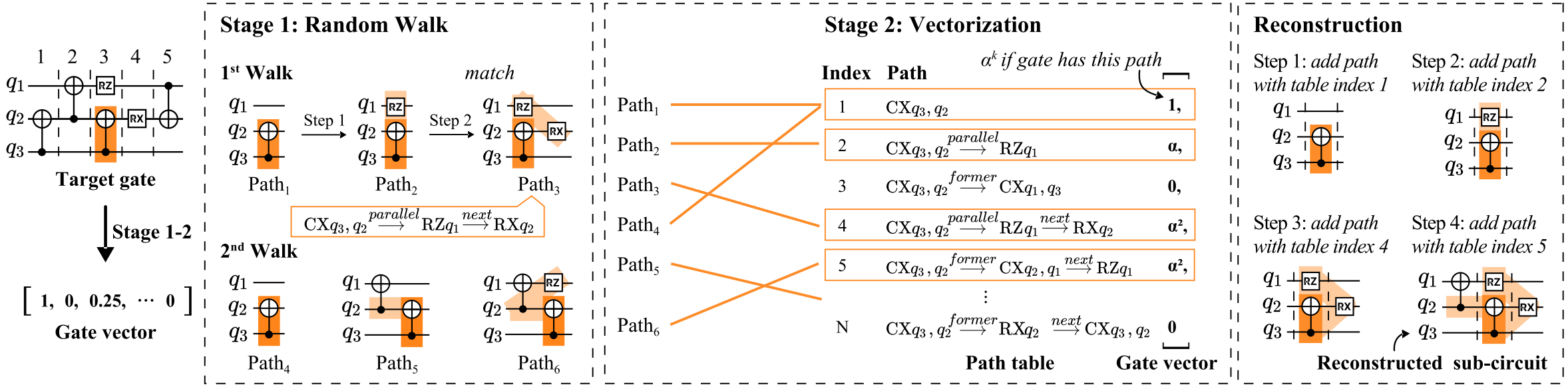
- Background and challenges
- Janus-CT overview
- **Upstream model: Circuit feature extraction**
- Downstream model 1: Circuit fidelity prediction
- Downstream model 2: Unitary decomposition
- Experiment

Upstream Model: Circuit Feature Extraction

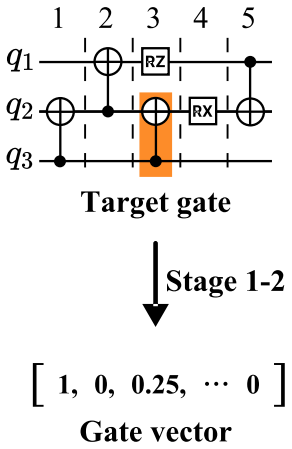
Two-step vectorization flow



Upstream Model: Circuit Feature Extraction

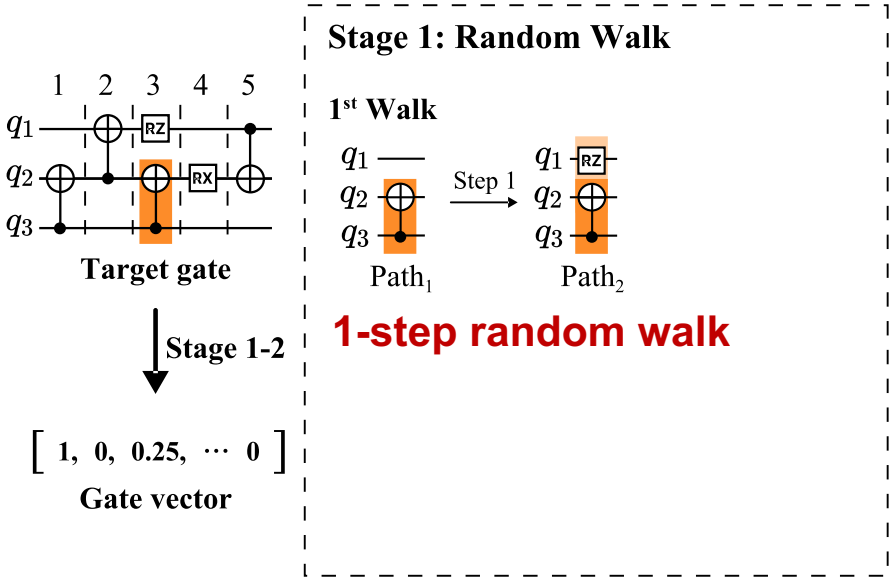
Two-step vectorization flow

For each gate



Upstream Model: Circuit Feature Extraction

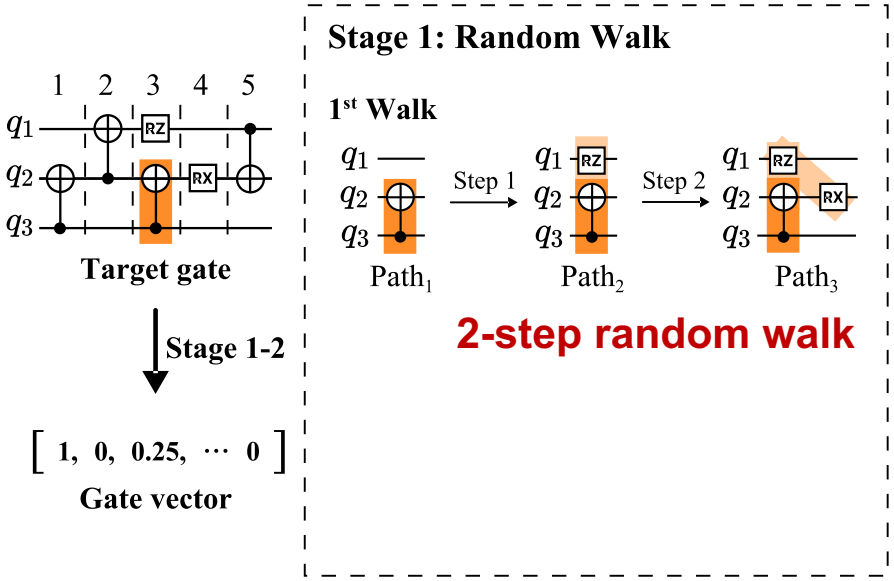
Two-step vectorization flow



Step 1: Extract features as paths.

Upstream Model: Circuit Feature Extraction

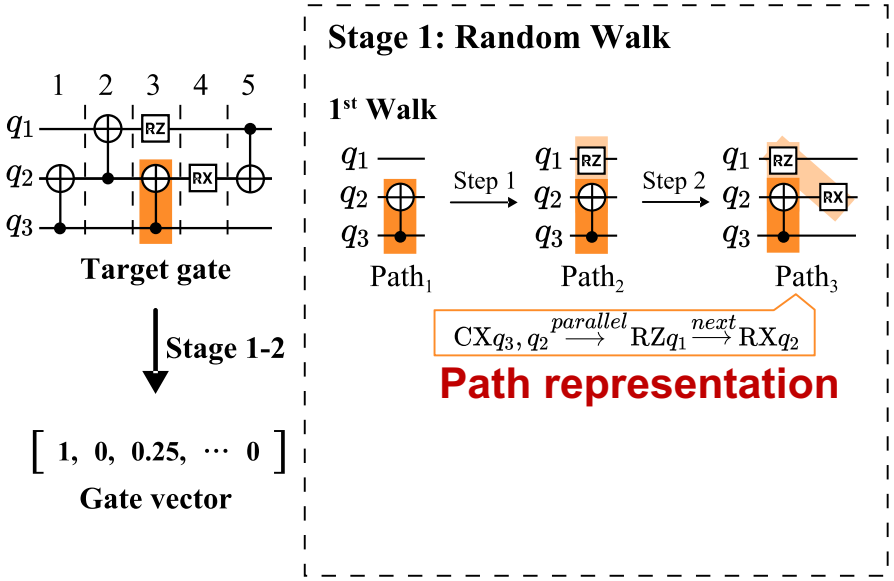
Two-step vectorization flow



Step 1: Extract features as paths.

Upstream Model: Circuit Feature Extraction

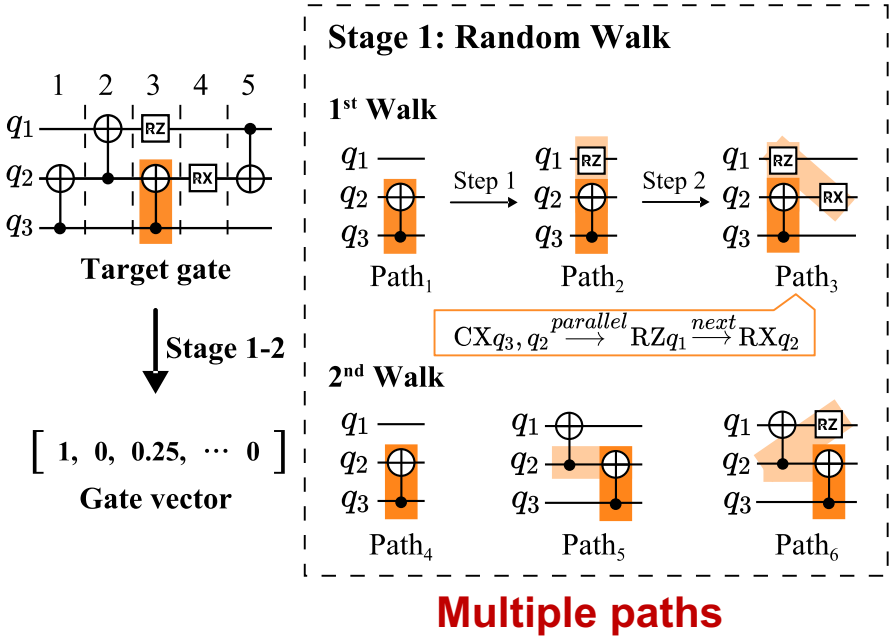
Two-step vectorization flow



Step 1: Extract features as paths.

Upstream Model: Circuit Feature Extraction

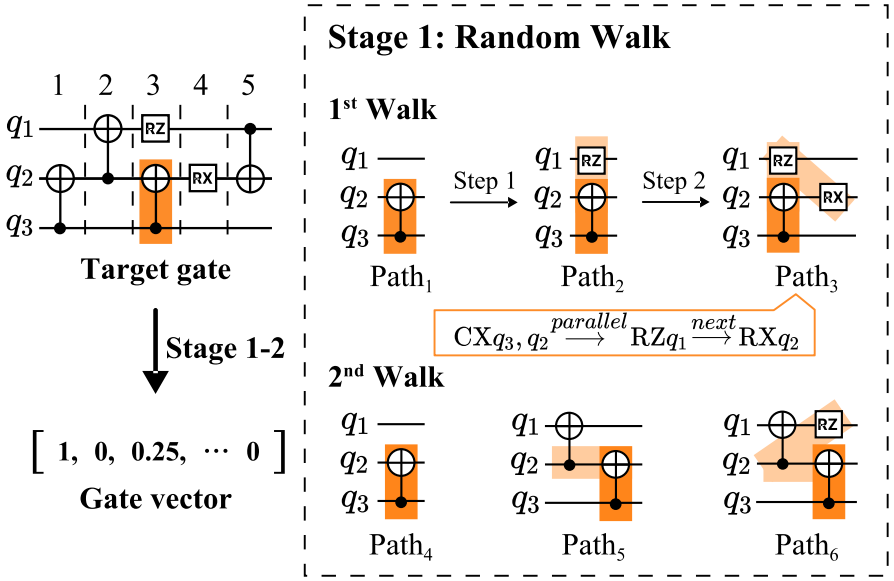
Two-step vectorization flow



Step 1: Extract features as paths.

Upstream Model: Circuit Feature Extraction

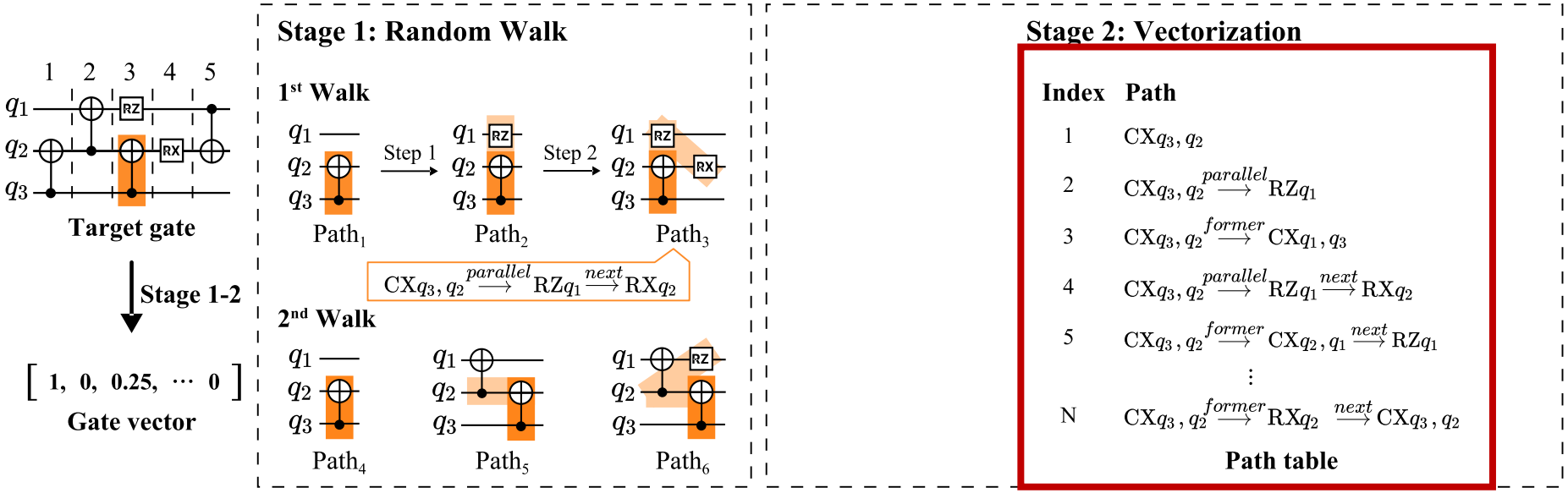
Two-step vectorization flow



Obtain vector.

Upstream Model: Circuit Feature Extraction

Two-step vectorization flow

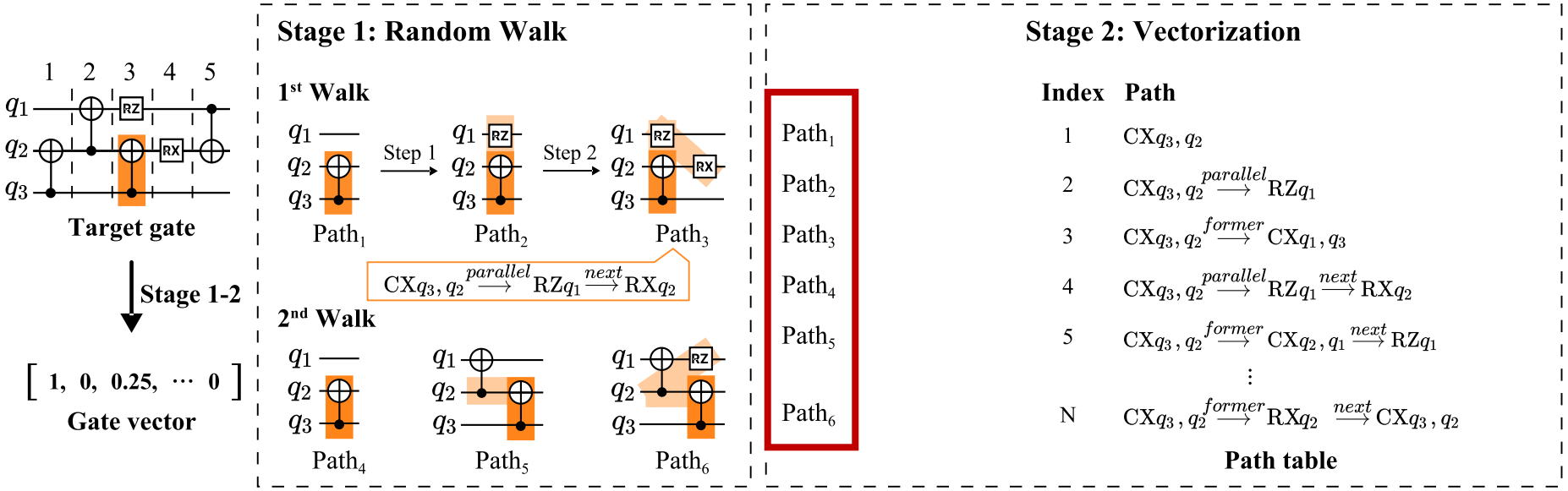


Pre-generated

Obtain vector.

Upstream Model: Circuit Feature Extraction

Two-step vectorization flow



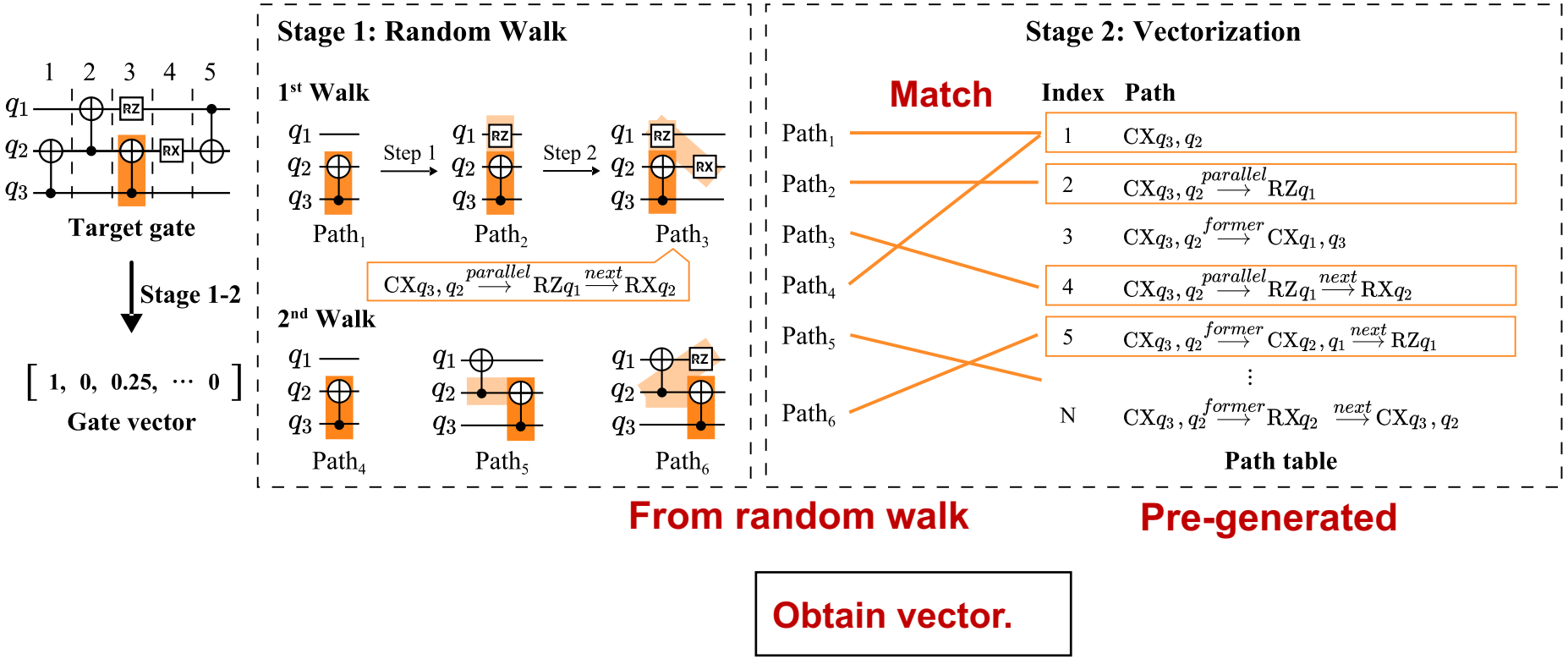
From random walk

Pre-generated

Obtain vector.

Upstream Model: Circuit Feature Extraction

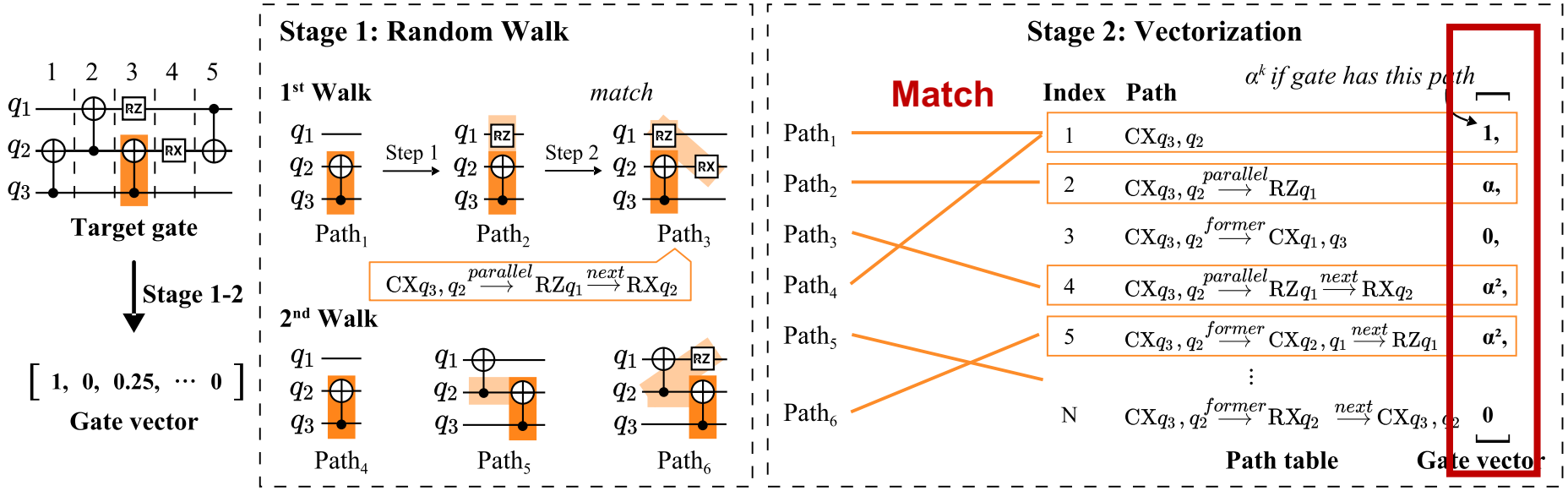
Two-step vectorization flow



Obtain vector.

Upstream Model: Circuit Feature Extraction

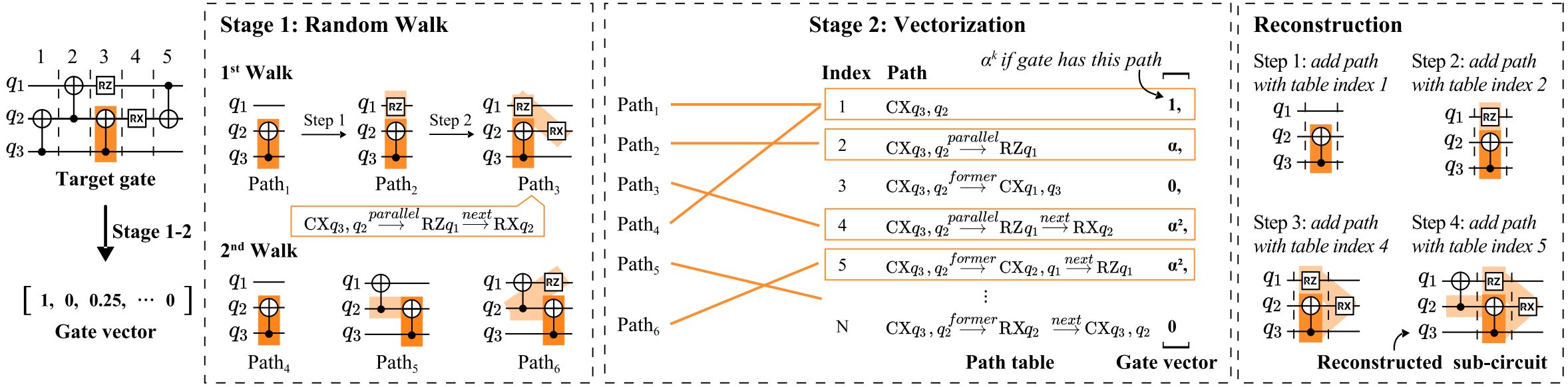
Two-step vectorization flow



Obtain vector.

Upstream Model: Circuit Feature Extraction

Two-step vectorization flow



Reconstruct circuit.

API to Construct Upstream Model

File:
- examples/2-1.vectorization.ipynb
- https://janusq.github.io/tutorials/Demonstrations/2-1.vectorization.ipynb

define backend

generate fidelity dataset

construct model using random walk

```
from janusq.analysis.vectorization import RandomwalkModel, extract_device
from janusq.data_objects.backend import GridBackend, FullyConnectedBackend, LinearBackend
# define the information of the quantum device
n_qubits = 6
backend = GridBackend(2, 3)

# generate a dataset including varous random circuits
from janusq.data_objects.random_circuit import random_circuits, random_circuit
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)

print('length of the path table is', len(up_model.pathtable))
```

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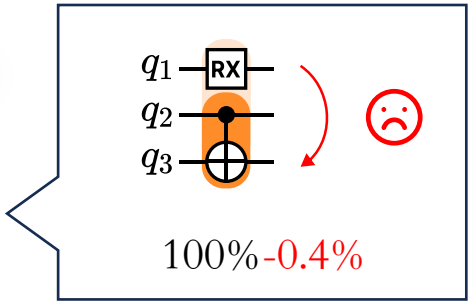
Downstream Model 1: Circuit Fidelity Prediction

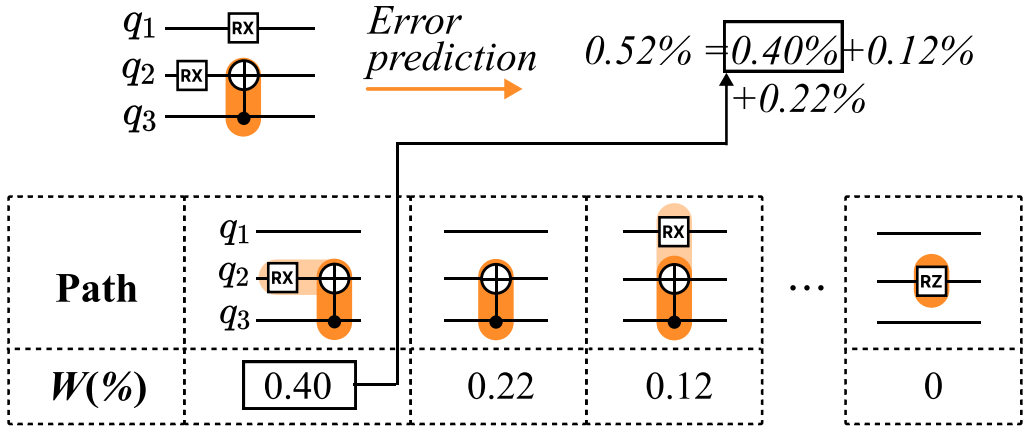
Gate error prediction

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



Model dependent error

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



Downstream Model 1: Circuit Fidelity Prediction

Gate error prediction

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

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

Circuit fidelity prediction

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

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

The probability that all gates are correct.

Downstream Model 1: Circuit Fidelity Prediction

Gate error prediction

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

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

Circuit fidelity prediction

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

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

Training process of weight vector W :

Obtain fidelity dataset (*circuit,* $F_{ground-truth}$) $\cdots$, $F_{ground-truth}$: 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:
- examples/2-2.fidelity_prediction_simulator.ipynb
- https://janusq.github.io/tutorials/Demonstrations/2-2.fidelity_prediction_simulator.ipynb

Load the fidelity dataset

```
from janusq.dataset import real_qc_5bit
circuits, fidelities = real_qc_5bit
print(len(circuits))
```

Construct upstream model

```
from janusq.analysis.vectorization import RandomwalkModel
from janusq.data_objects.backend import FullyConnectedBackend
backend = FullyConnectedBackend(5)
up_model = RandomwalkModel(n_steps = 1, n_walks = 10, backend = backend, circuits =
circuits)
```

Construct fidelity prediction model

```
from janusq.analysis.fidelity_prediction import FidelityModel
fidelity_model = FidelityModel(up _model)
fidelity_model.train((cirucits, fidelities), multi_process = False)
```

Predict the fidelity of the given circuit

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

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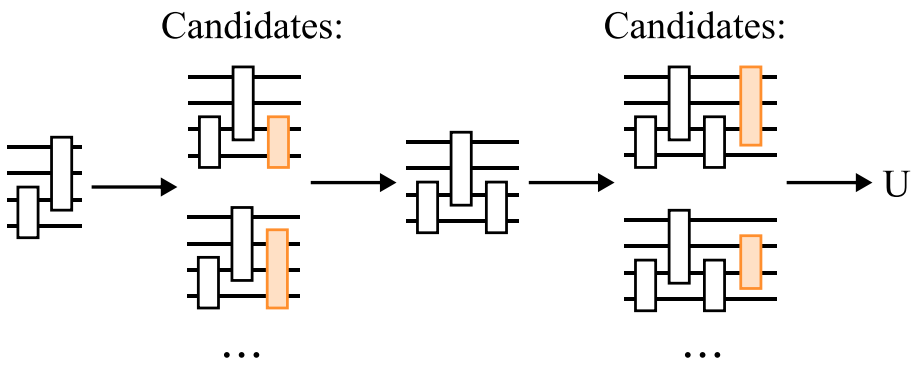
Downstream Model 2: Unitary Decomposition

Improve the current search-based method



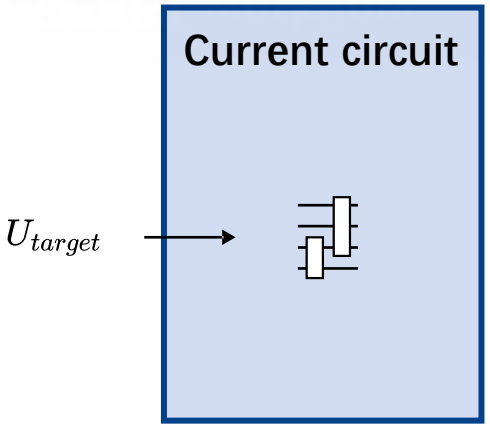
Search-based method

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

5-qubit unitary decomposition

Downstream Model 2: Unitary Decomposition

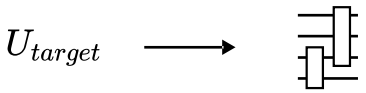
QFAST workflow



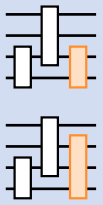
Downstream Model 2: Unitary Decomposition

QFAST workflow

Current circuit

U_{target} 

Step 1. enumerate candidates



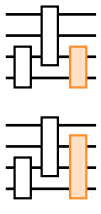
Downstream Model 2: Unitary Decomposition

QFAST workflow

Current circuit

U_{target} ⟶ 

Step 1. enumerate candidates



…

Step 2. calculate distance

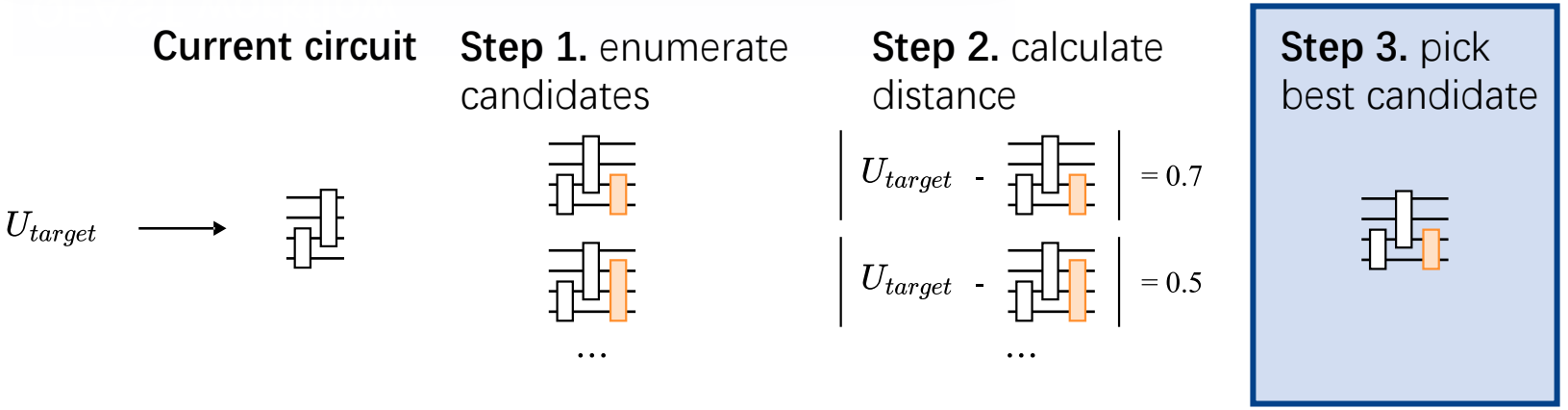
$\left| U_{target} - \right| = 0.7$

$\left| U_{target} - \right| = 0.5$

…

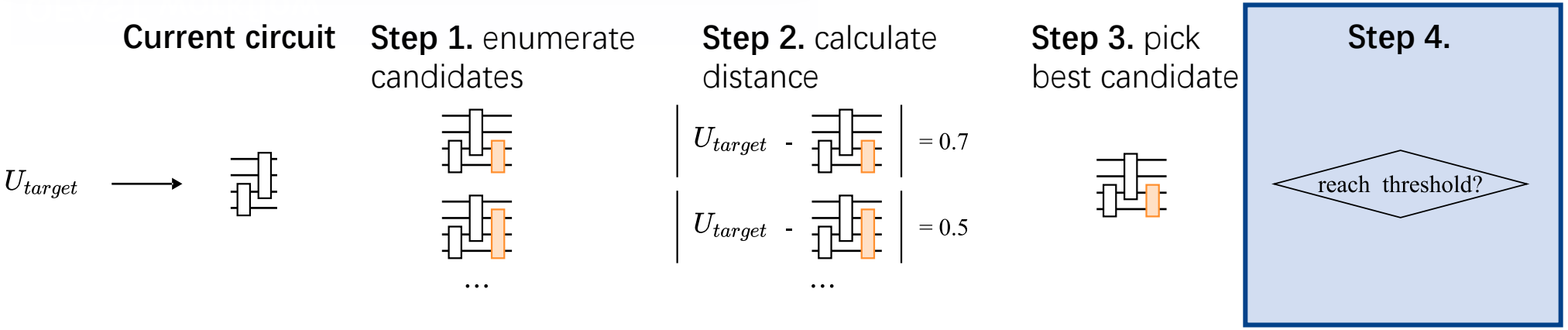
Downstream Model 2: Unitary Decomposition

QFAST workflow



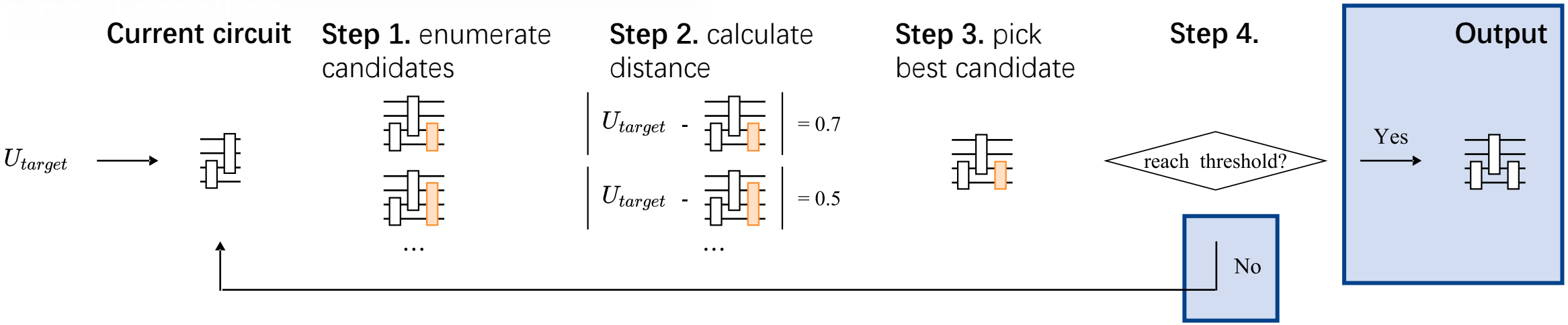
Downstream Model 2: Unitary Decomposition

QFAST workflow



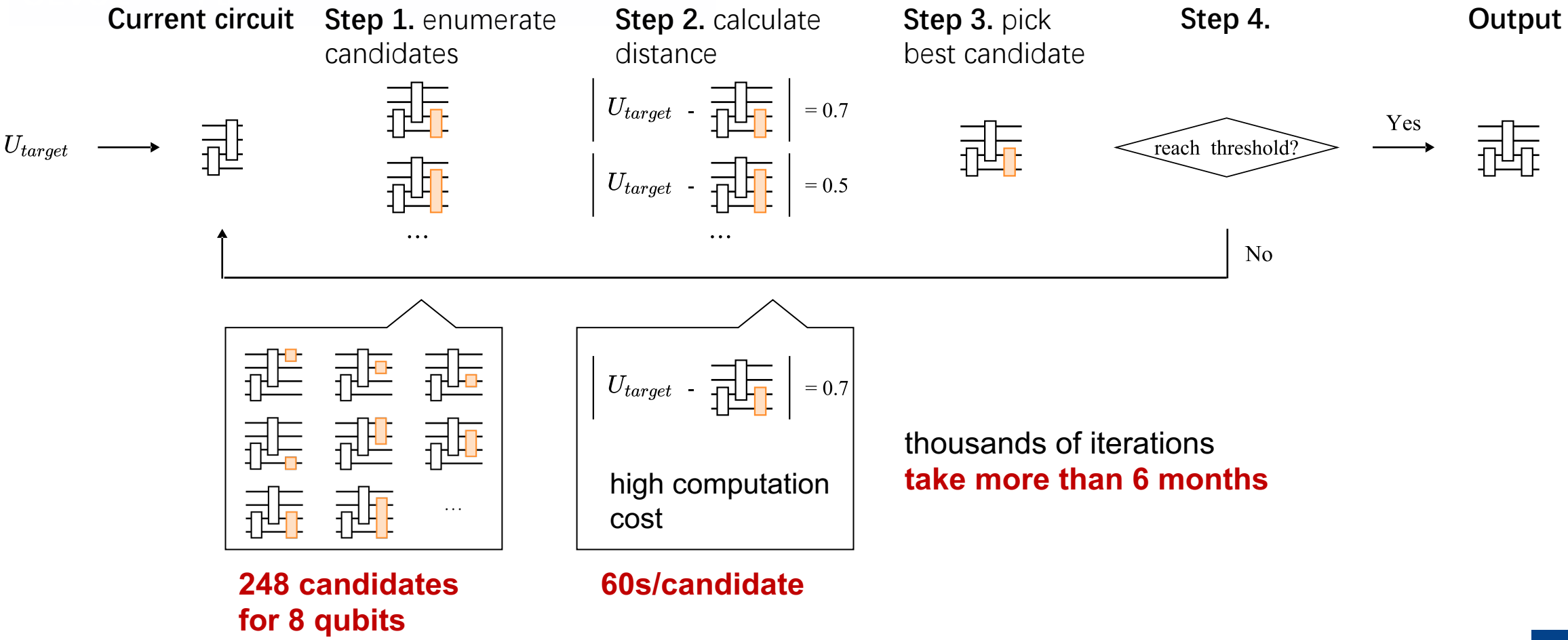
Downstream Model 2: Unitary Decomposition

QFAST workflow



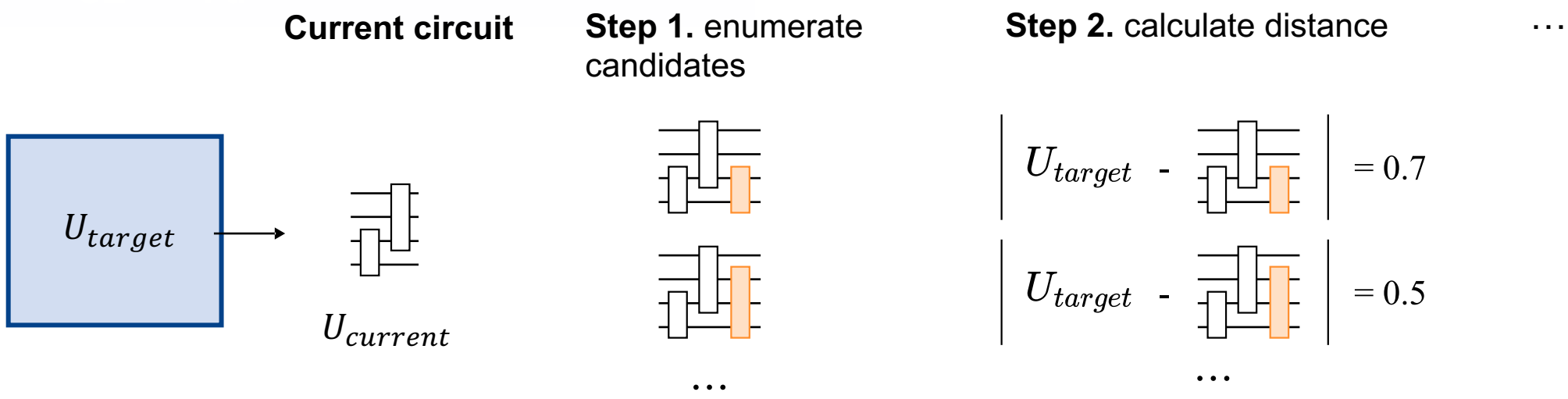
Downstream Model 2: Unitary Decomposition

QFAST workflow



Downstream Model 2: Unitary Decomposition

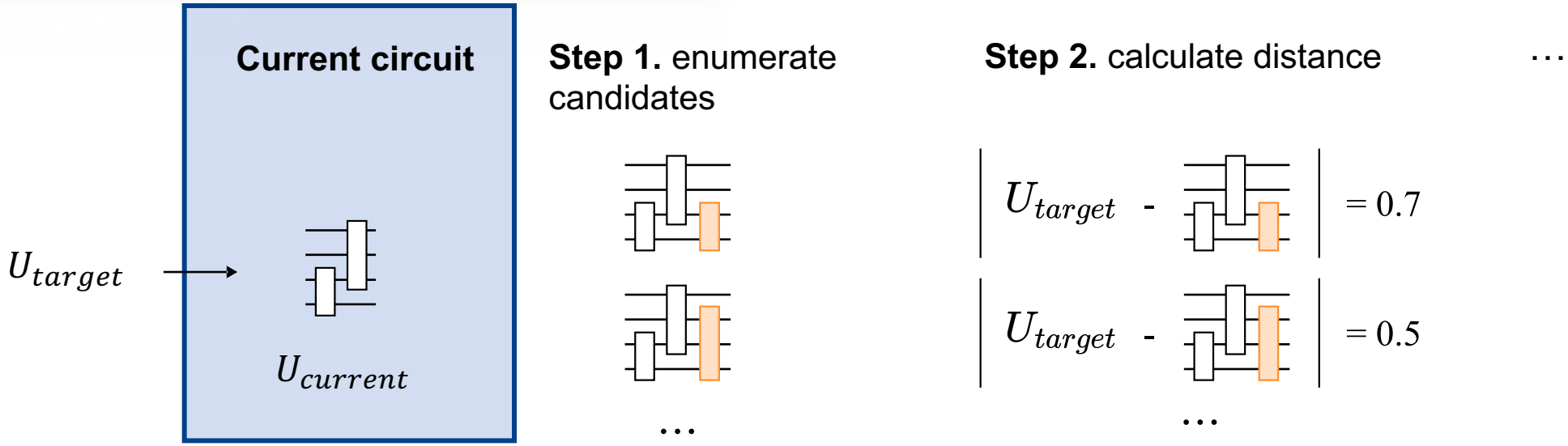
Janus-CT workflow



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

Downstream Model 2: Unitary Decomposition

Janus-CT workflow

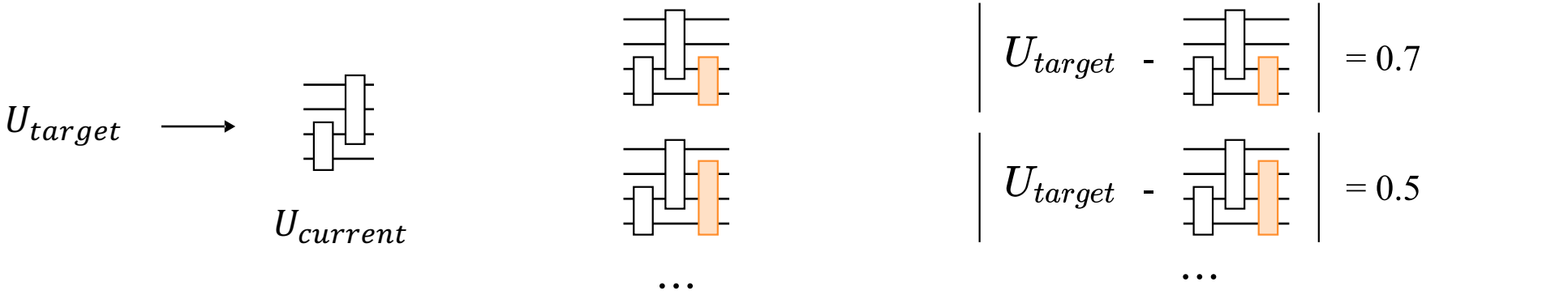


Candidates ▯ and ▯ should equal $U_{target}U_{current}^{-1}$

Downstream Model 2: Unitary Decomposition

Janus-CT workflow

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

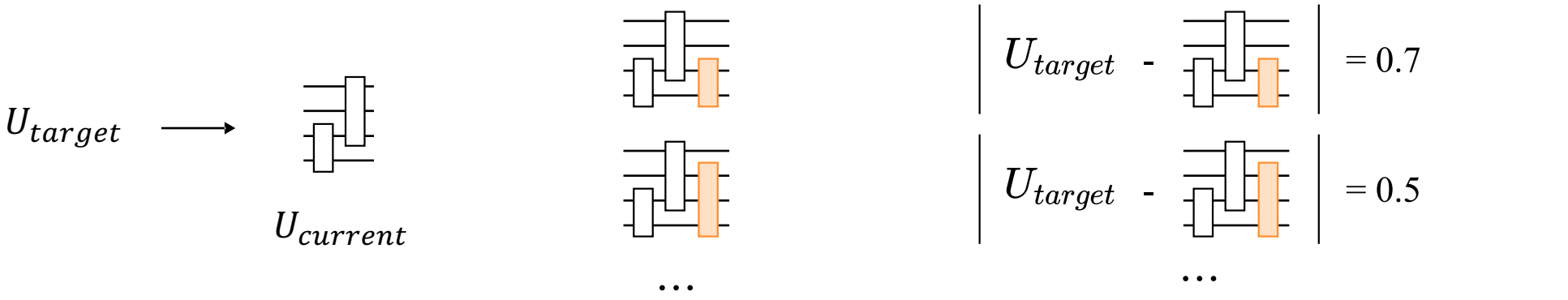


Candidates and should equal $U_{target}U_{current}^{-1}$

Downstream Model 2: Unitary Decomposition

Janus-CT workflow

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



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

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

Downstream Model 2: Unitary Decomposition

Janus-CT workflow

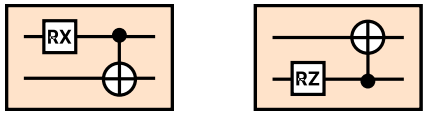
$$U_{target}U_{current}^{-1}$$

↓ U2V model

Gate vectors serve as search candidates

$$v_1 = [...] \quad v_2 = [...]$$

↓ Reconstruct

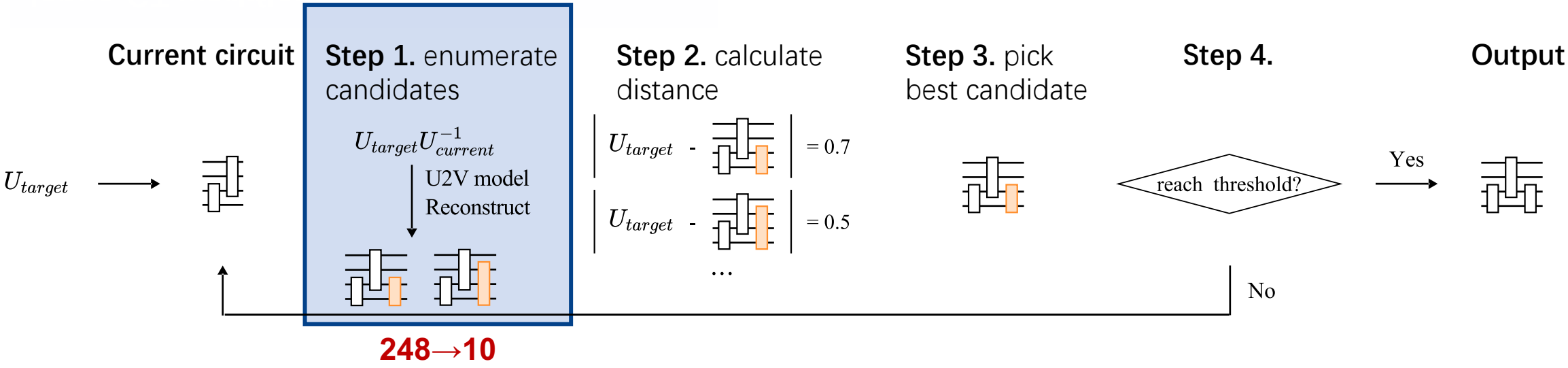


U2V model: a random forest model, trained by the pre-generated decomposition results.

Use gate vectors to construct good candidates.

Downstream Model 2: Unitary Decomposition

Janus-CT workflow



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:
- examples/ 2-5.unitary_decomposition.ipynb
- https://janusq.github.io/tutorials/Demonstrations/2-5.unitary_decomposition.ipynb

Construct the decomposition dataset

```
from janusq.data_objects.backend import LinearBackend
from janusq.data_objects.random_circuit import random_circuits
n_qubits = 4
backend = FullyConnectedBackend (n_qubits)
dataset = random_circuits(backend, n_circuits=50, n_gate_list=[30, 50, 100],
two_qubit_prob_list=[.4], reverse=True)
```

Construct unitary decomposition model

```
from janusq.analysis.unitary_decompostion import U2VModel
from janusq.analysis.vectorization import RandomwalkModel
vec_model = RandomwalkModel(2, 16, backend, directions=('parallel', 'next'))
vec_model.train(dataset, multi_process=True, remove_redundancy=False)
u2v_model = U2VModel(vec_model)
data = u2v_model.construct_data(dataset, multi_process=False)
u2v_model.train(data, n_qubits)
```

Generate a random unitary

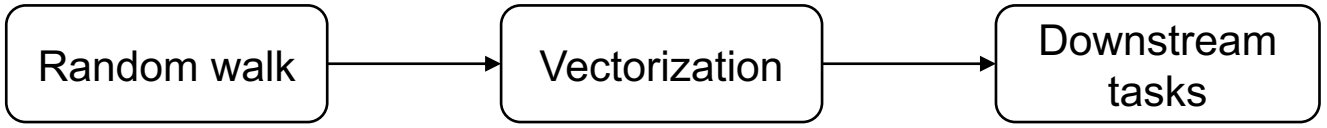
```
from qiskit.quantum_info import random_unitary
unitary = random_unitary(2**n_qubits).data
```

Apply decomposition

```
from janusq.analysis.unitary_decompostion import decompose
decompose(unitary, allowed_dist = 0.2, backend = backend, u2v_model = u2v_model)
```

Extending Janus-CT To More Downstream Tasks

File:
- examples/2-6.extend_framework_bug_identification.ipynb
- https://janusq.github.io/tutorials/Demonstrations/2-6.extend_framework_bug_identification




```
from janusq.analysis.vectorization import RandomwalkModel

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

Downstream task implementation

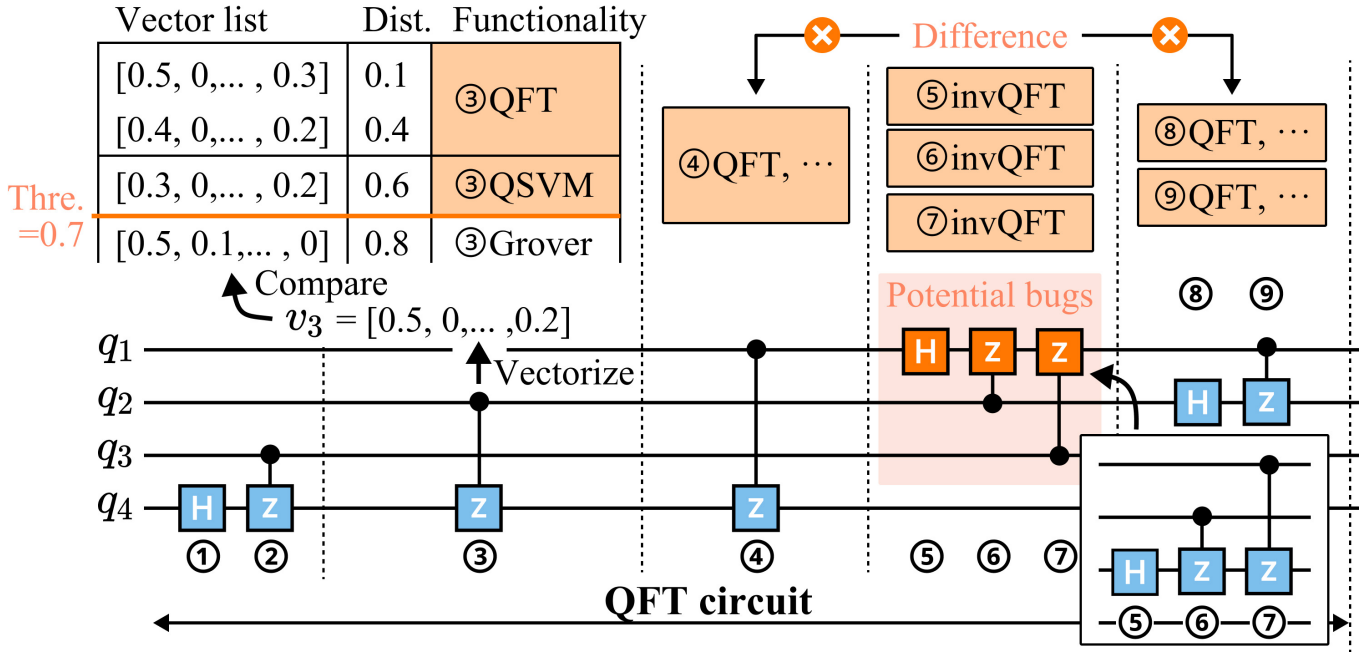
Extending Janus-CT To More Downstream Tasks

File:
- examples/2-6.extend_framework_bug_identification.ipynb
- https://janusq.github.io/tutorials/Demonstrations/2-6.extend_framework_bug_identification

For example: Bug Identification

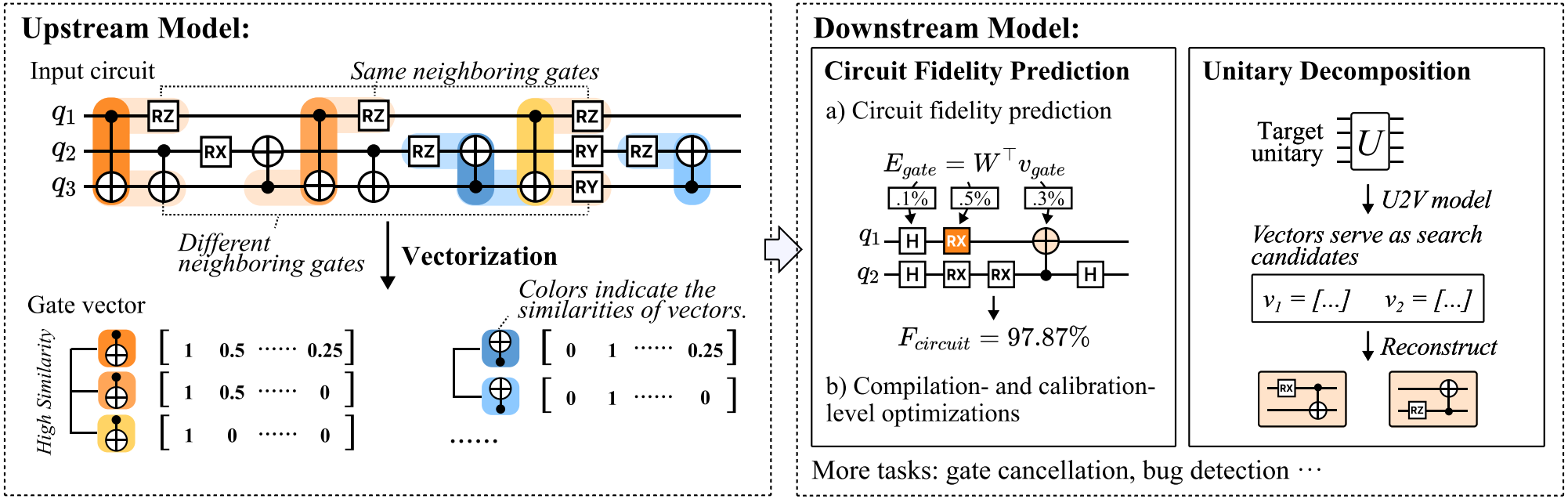
1. Identify the possible functionality

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.



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Thanks for listening

Janus-CT: A Framework for Analyzing Quantum Circuit by Extracting Contextual and Topological Features

Siwei Tan; Congliang Lang; Liang Xiang; Shudi Wang; Xinghui Jia; Ziqi Tan; Tingting Li; Jieming Yin; Yongheng Shang,
Andre Python, Liqiang Lu*, Jianwei Yin*