HPCA 2025 Tutorial

Topic 1. Introduction of Janus Quantum Cloud Platform and Installing JanusQ

Speaker: Liqiang Lu

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Zhejiang University (ZJU)

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

Presenter

Liqiang Lu
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Liqiang Lu is a ZJU100 Young Professor in the College of Computer Science, Zhejiang University. His research interests include quantum computing, computer architecture, deep learning accelerator, and software-hardware codesign. He has authored more than 30 scientific publications in premier international journals and conferences in related domains, including ISCA, MICRO, HPCA, ASPLOS, FCCM, DAC, IEEE Micro, and TCAD. He also serves as a TPC member in the premier conferences in the related domain, including DAC, ICCAD, FPT, HPCC, etc.

[HPCA 2025] Debin Xiang, Qifan Jiang, **Liqiang Lu**, et al. “Choco-Q: Commute Hamiltonian-based QAOA for Constrained Binary Optimization”.
[ASPLOS 2024] Siwei Tan, **Liqiang Lu**, Hanyu Zhang, et al. “QuFEM: Fast and Accurate Quantum Readout Calibration Using the Finite Element Method”.
[MICRO 2021] Liqiang Lu, Yicheng Jin, Hangrui Bi, et al. “Sanger: A Co-Design Framework for Enabling Sparse Attention using Reconfigurable Architecture”.
[ISCA 2021] Liqiang Lu, Naiqing Guan, Yuyue Wang, et al. “TENET: A Framework for Modeling Tensor Dataflow Based on Relation-centric Notation”.

Presenter

Siwei Tan
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Siwei Tan received the Ph.D. degree in computer science from Zhejiang University (ZJU) in 2024 and keep staying at Zhejiang University as a Tenure-track Assistant Professor. He is interested in the quantum software, quantum hardware, and machine learning. He has published more than 20 papers in top international journals and conferences such as ASPLOS, MICRO, HPCA, DAC, ICCAD, FSE, TVCG, et al.

[FSE 2025] Siwei Tan, Liqiang Lu, Debin Xiang, et al. “HornBro: Homotopy-like Method for Automated Quantum Program Repair”.
[ASPLOS 2024] Siwei Tan, Debing Xiang, Liqiang Lu, et al. “MorphQPV: Exploiting Isomorphism in Quantum Programs to Facilitate Confident Verification”.
[HPCA 2023] Siwei Tan, Mingqian Yu, Liqiang Lu, et al. “HyQSAT: A Hybrid Approach for 3-SAT Problems by Integrating Quantum Annealer with CDCL”.
[MICRO 2023] Siwei Tan, Congliang Lang, Liang Xiang, et al. “QuCT: A Framework for Analyzing Quantum Circuit by Extracting Contextual and Topological Features”.

Presenter

Tianyao Chu

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Tianyao Chu is a first-year PhD student at the College of Computer Science, Zhejiang University. His research interests include multi-node quantum computing and quantum networking system. He is currently working on the quantum network-on-chip based on enhanced QST.

Presenter

Kaiwen Zhou

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Kaiwen Zhou is a first-year PhD student at the College of Computer Science, Zhejiang University. He is interested in quantum computer architecture and high-performance computing. He is currently working on designing a QLDPC decoding accelerator.

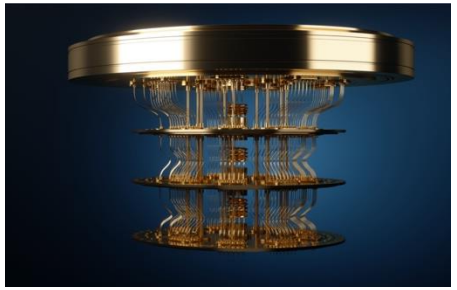
Outline of Presentation

- **Background Knowledge**
- Mathematical Model of Quantum Computing
- Janus (Taiyuan) Quantum Cloud Platform
- Installing JanusQ

Background Knowledge

Development of
Classical Computing

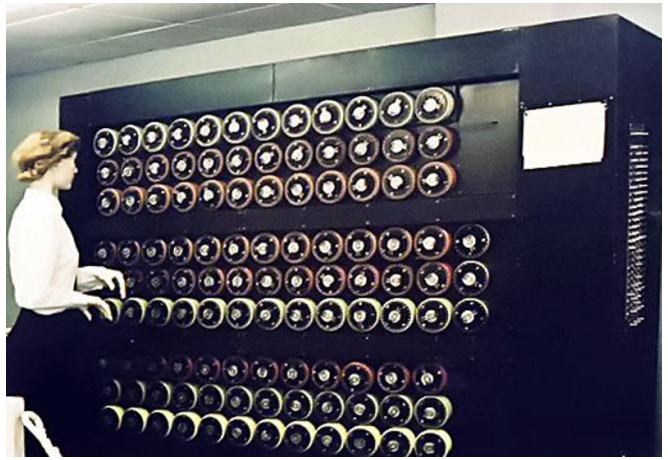
Motivation of
Quantum Computing



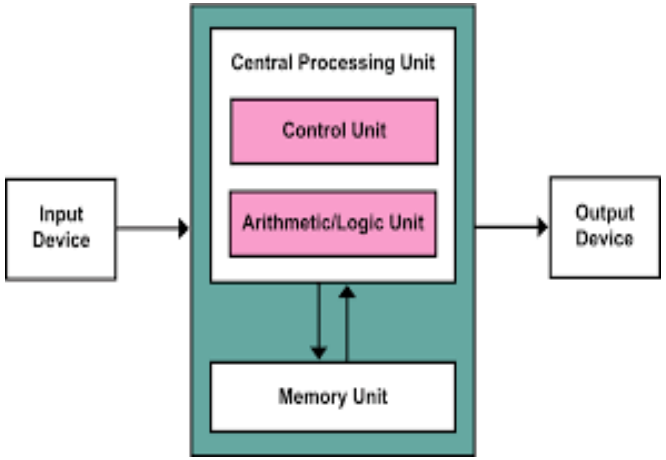
Development of
Quantum Computing

Development Of Classical Computing

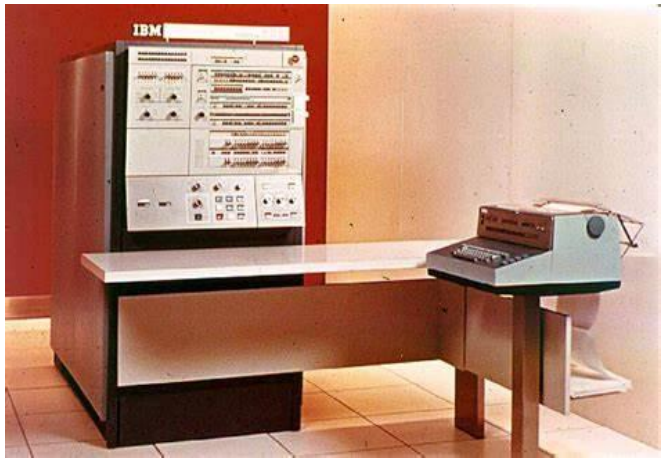
Domain-specific calculator （1939）



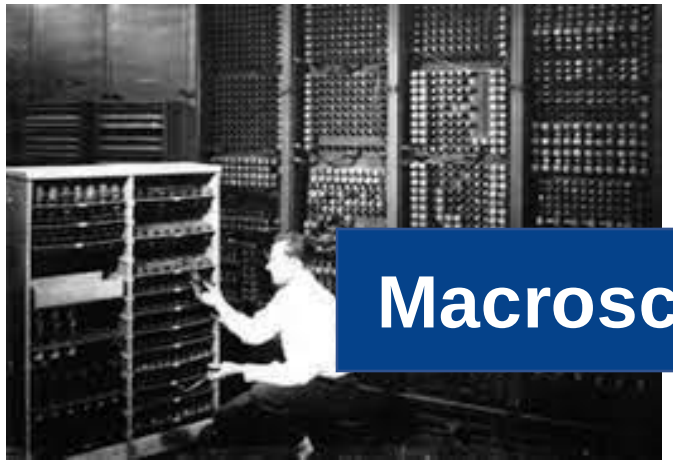
Von Neumann architecture (1947)



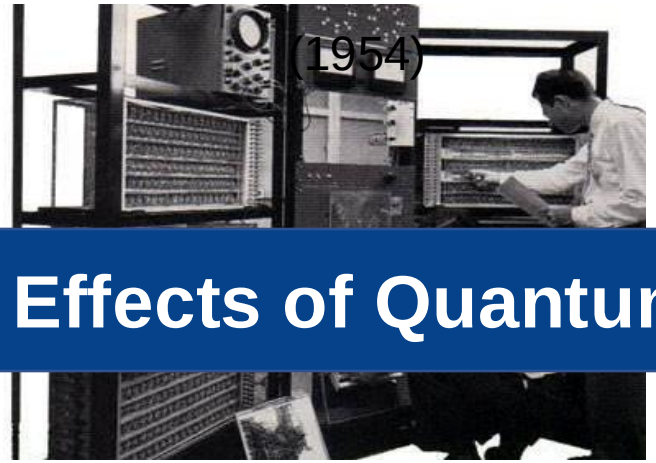
IBM360 Integrated Circuit (1964)



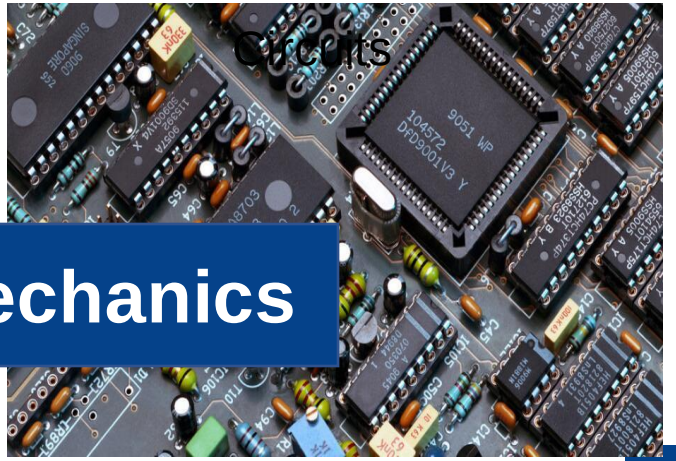
Vacuum Tube Computer ENIAC (1942)



Transistor Computer TRADIC (1954)



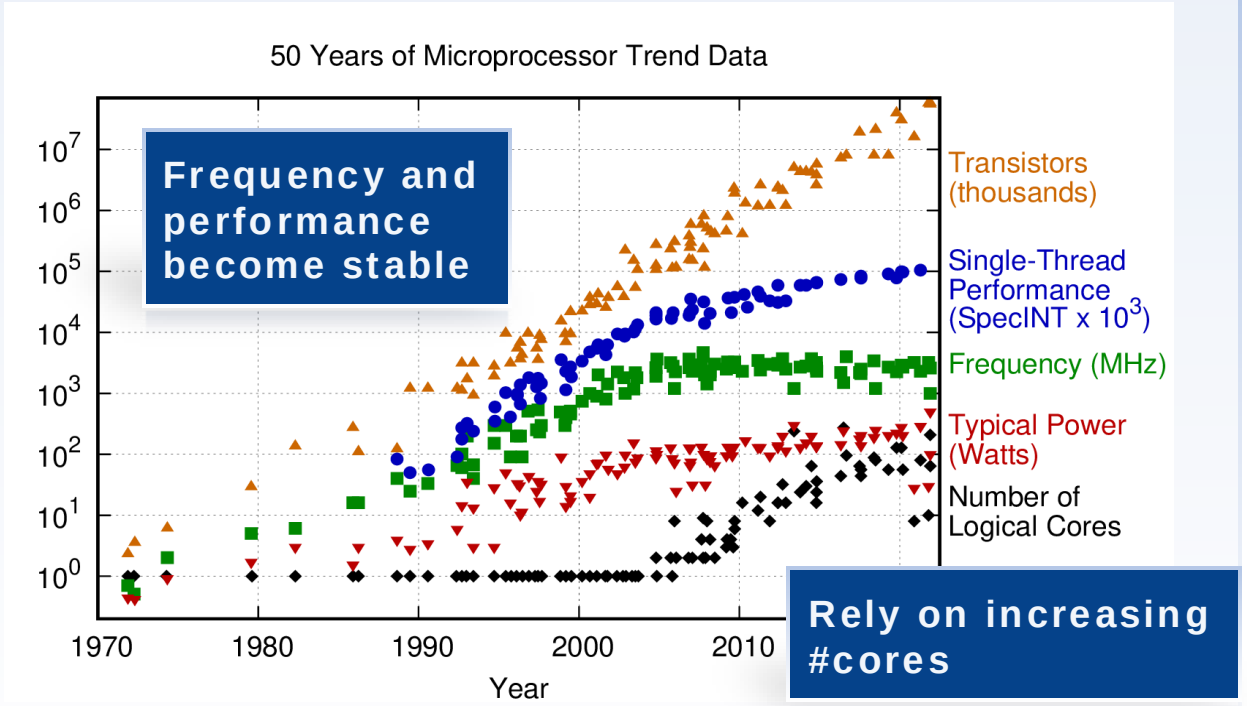
Large Scale Integrated Circuits



Macroscopic Effects of Quantum Mechanics

Motivation Of Quantum Computing

Computation barrier

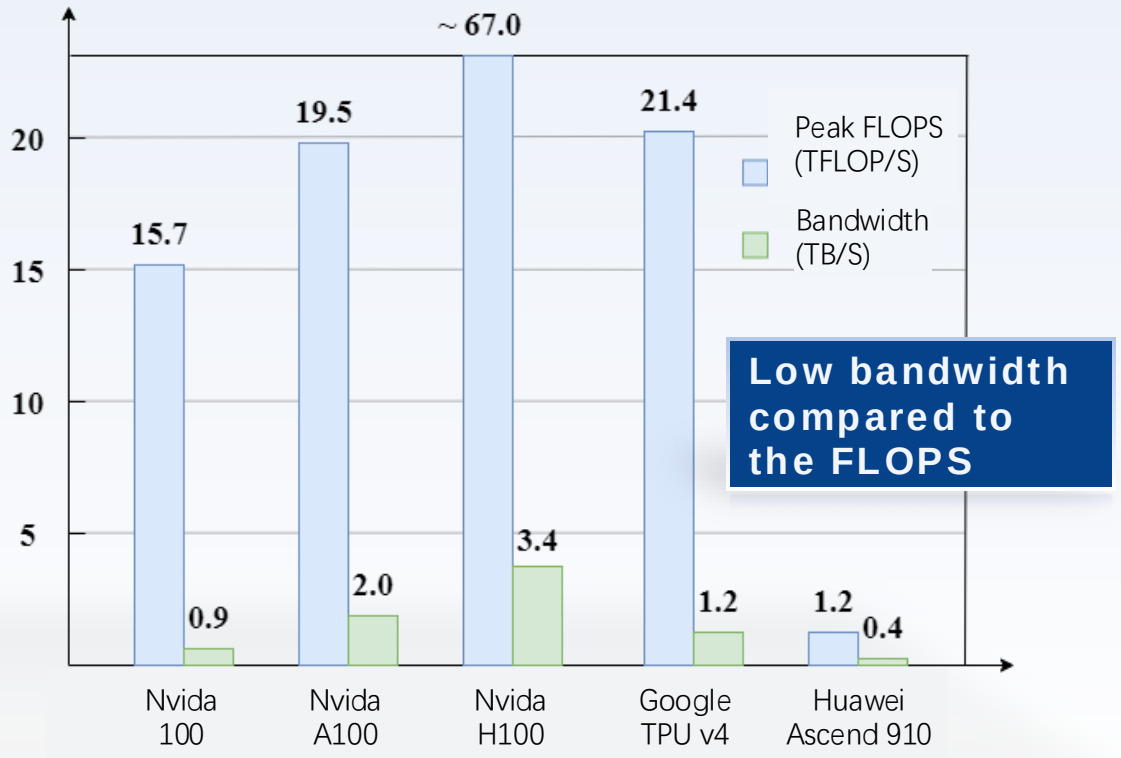


Original dalta up to the year 2010 colecled and plolted by M. Horowitz, F. Labonle, 0. Shacham, K. Olukolun, L. Hammond, and c. BalienNew plot and dala collected for 2010-2021 by K.Rupp

- The research costs and cycles of advanced chip processes are continuously increasing, Moore's Law is approaching obsolescence.
- The computing systems cannot rely solely on the development of traditional single chips. Instead, it requires new chip design methods and computing principles.

Motivation Of Quantum Computing

Storage barrier

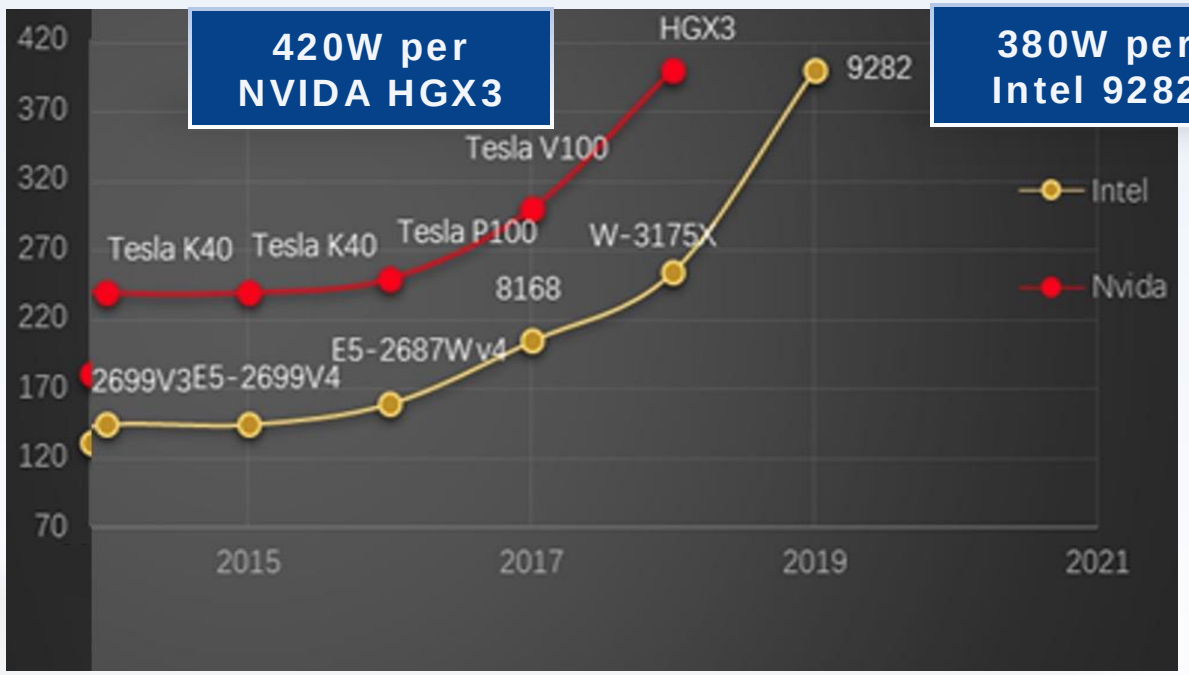


- Computation power and bandwidth is not matched.
- Latency of memory access is high, limiting CPU performance.
- Quantum computing is in memory.
- Non-von Neumann architectures.

Motivation Of Quantum Computing

Power wall

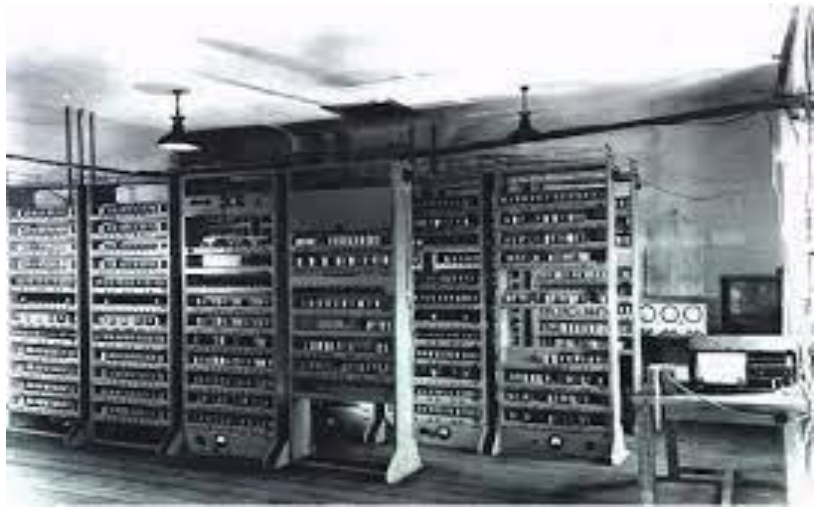
Thermal design power exponentially increases.

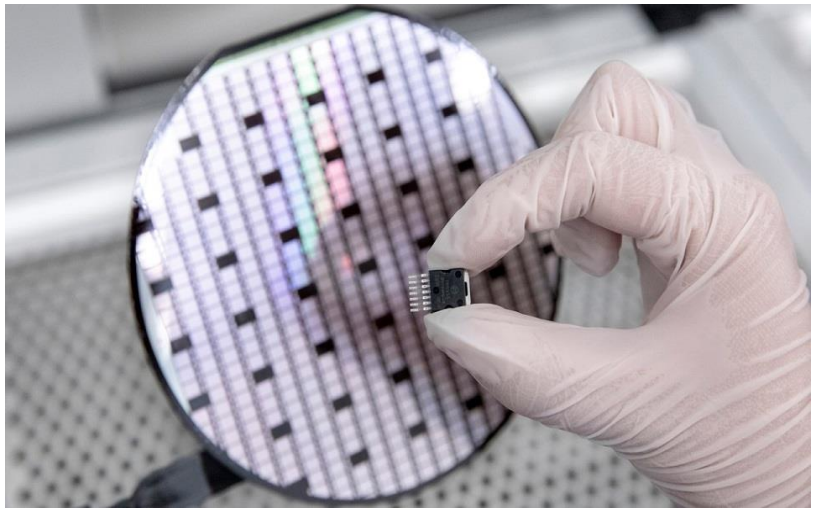


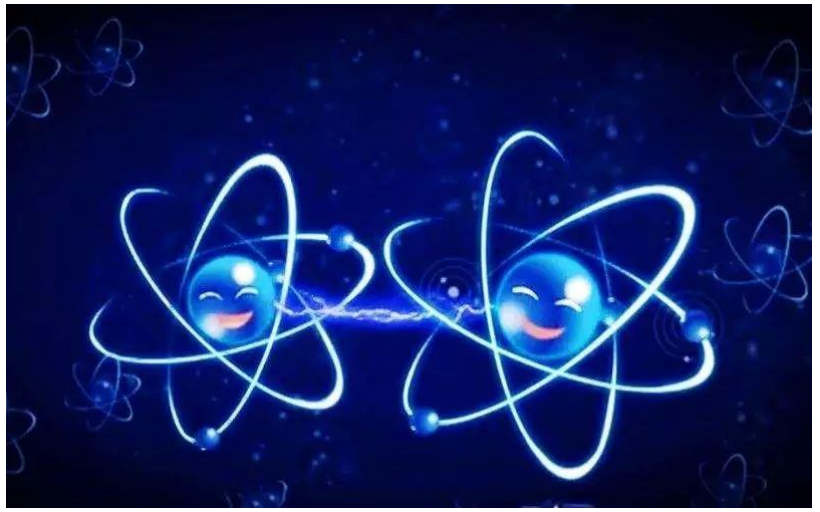
From https://www.blueocean-china.net/faq3/241.html

- The power consumption increases exponentially with computing power.
- Energy consumption restricts computing power.
- Systematical resource scheduling at the architectural level.

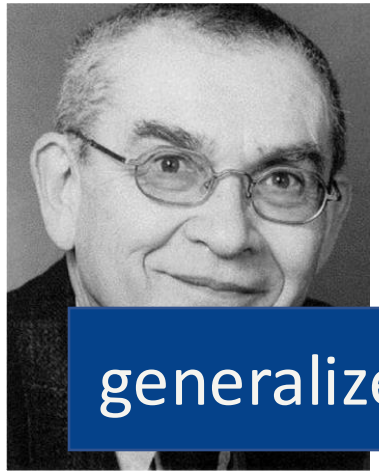
Proposal of Quantum Computing







- Classical physics is no longer able to fully describe the underlying physical mechanisms at its core.



Yuri Manin

- Algebraic Geometry
- Discrete Geometry (Diophantine Geometry)
- Manin (1980) and Feynman

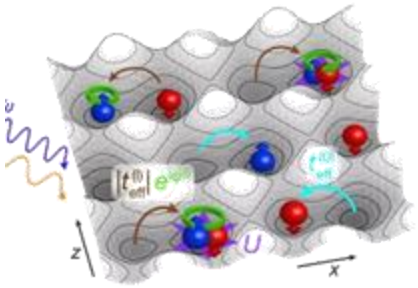
Richard Feynman

- Feynman Path Integral, Feynman Diagram, Feynman Parton Model
- Quantum Electrodynamics, Nobel Prize in Physics

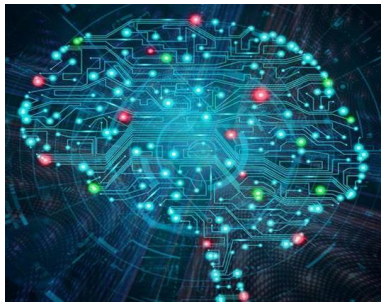
generalize to other domains such as the database search and cryptography

vely

Basic Concepts of Quantum Computing

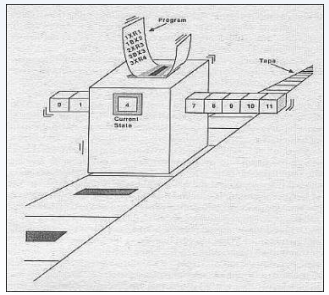
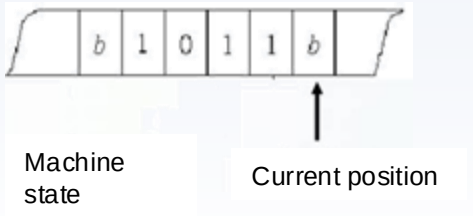
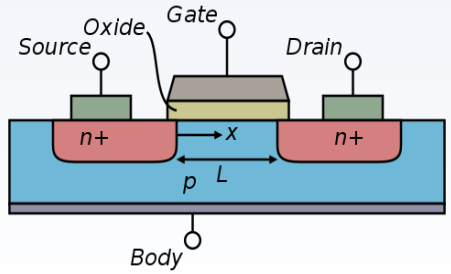
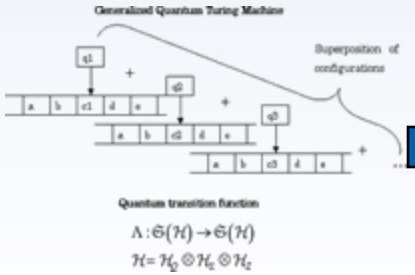
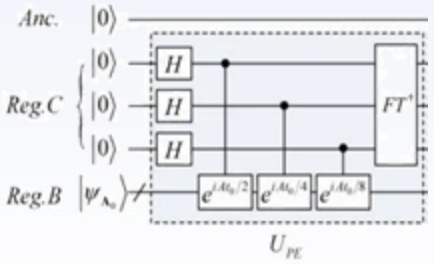
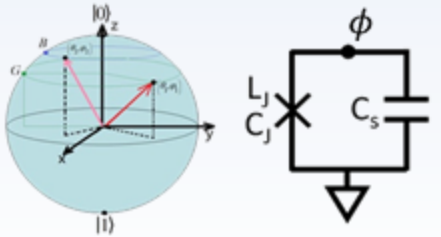


Physical Simulation

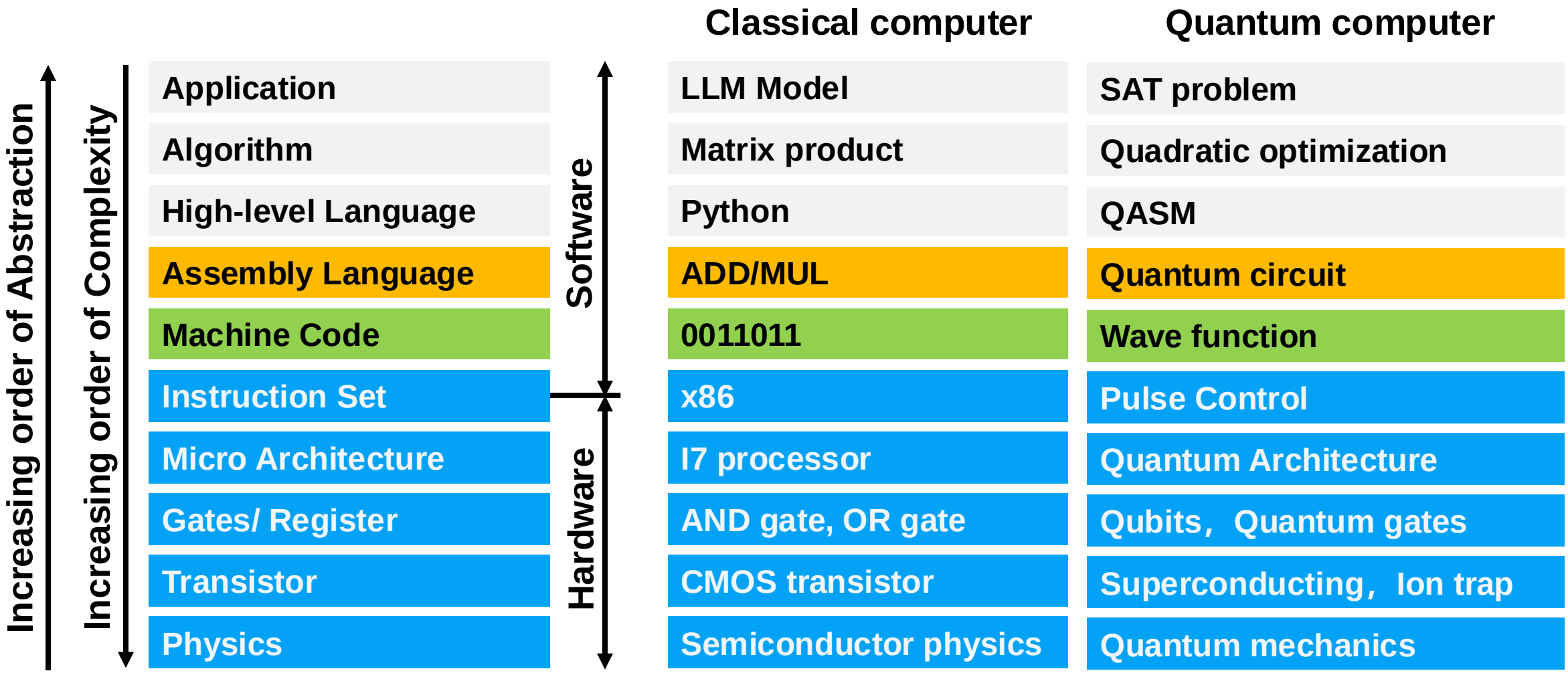


Factor

Application

	Computing theory	Encoding	Physical implementation
Classical program	**Classical Turing machine** 	**Program based on binary encoding** 	**CMOS (0/1)** 
Quantum program	**Quantum Turing machine** 	**Circuit-based quantum program** 	**Superconducting, photon (superposition state)**  Josephson junction
	lead to high computational advantages via parallelism.	*suffer from complexity due to quantum collapse and entanglement*	*has low energy consumption due to reversibility and superconductivity.*

Quantum Computing Architecture

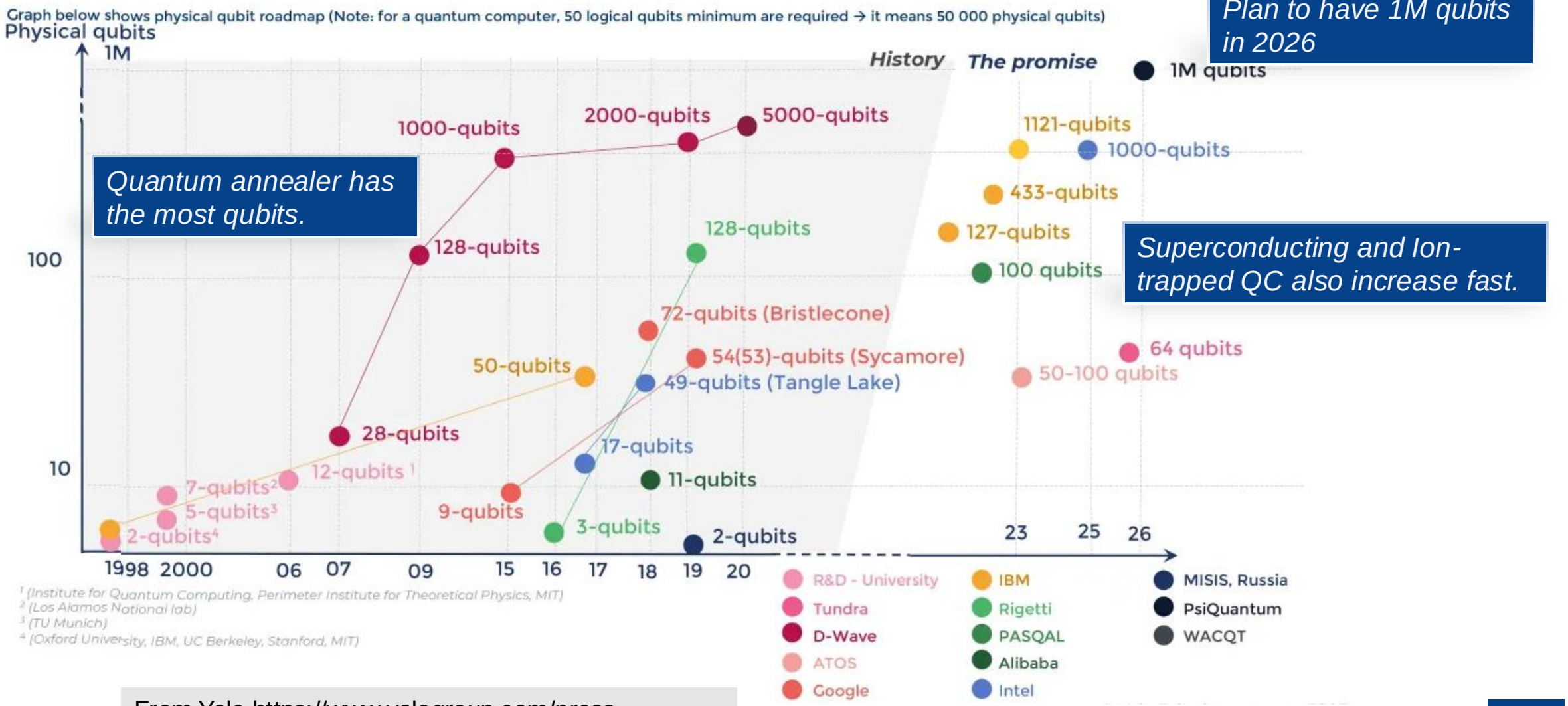


	Classical computer	Quantum computer
Application	LLM Model	SAT problem
Algorithm	Matrix product	Quadratic optimization
High-level Language	Python	QASM
Assembly Language	ADD/MUL	Quantum circuit
Machine Code	0011011	Wave function
Instruction Set	x86	Pulse Control
Micro Architecture	I7 processor	Quantum Architecture
Gates/ Register	AND gate, OR gate	Qubits，Quantum gates
Transistor	CMOS transistor	Superconducting，Ion trap
Physics	Semiconductor physics	Quantum mechanics

From https://www.secplicity.org/2018/09/19/understanding-the-layers-of-a-computer-system/

Classical and quantum computing has similar architecture

Development of Quantum Computer



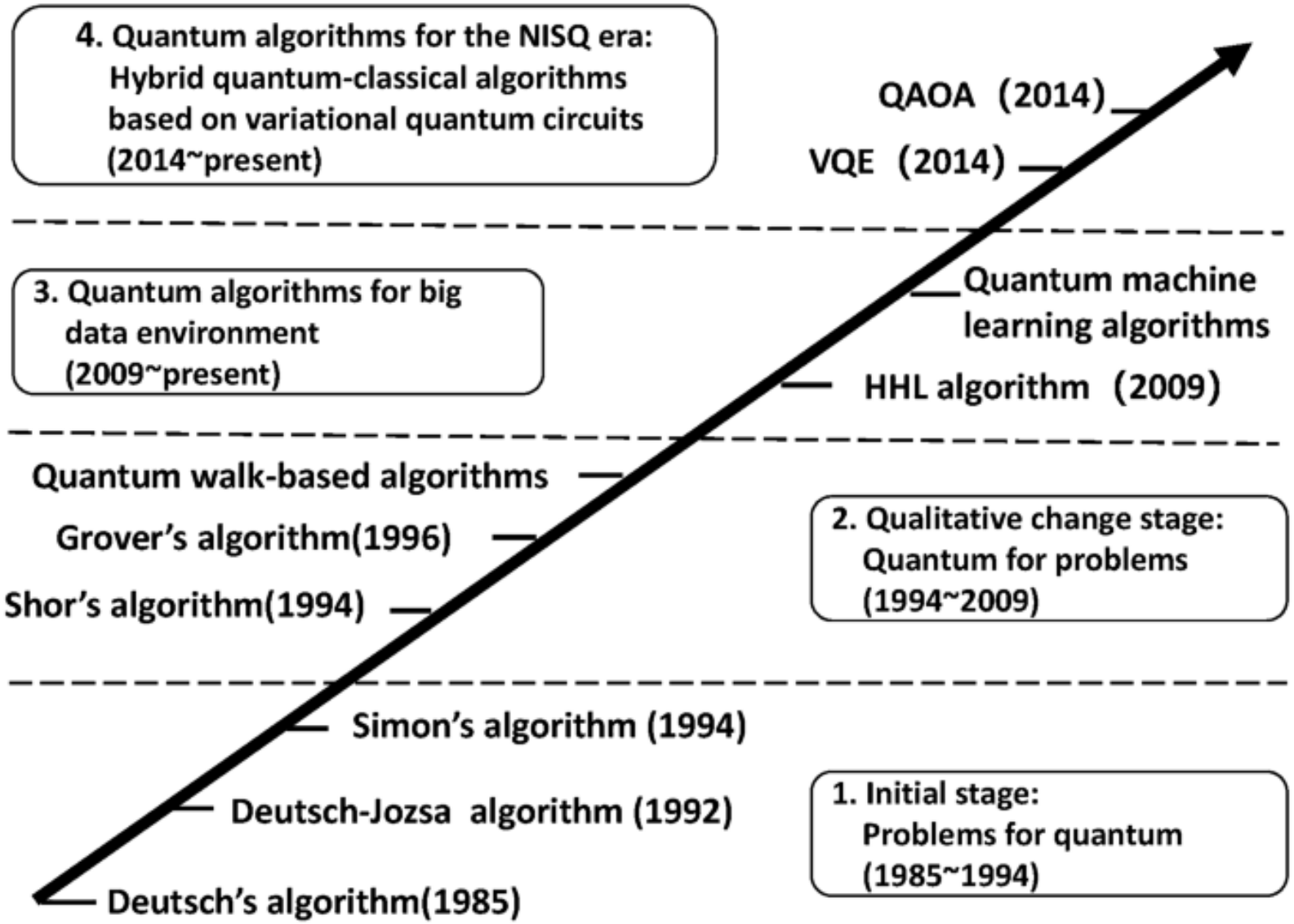
Plan to have 1M qubits in 2026

Quantum annealer has the most qubits.

Superconducting and Ion-trapped QC also increase fast.

From Yole https://www.yolegroup.com/press-release/quantum-technologies-the-market-is-growing/

Development of Quantum Algorithm



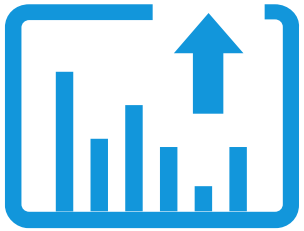
Zhang, S., Li, L. A brief introduction to quantum algorithms. *CCF Trans. HPC* **4**, 2022

Outline of Presentation

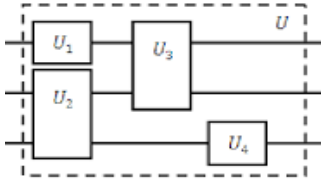
- Background Knowledge
- **Mathematical Model of Quantum Computing**
- Janus (Taiyuan) Quantum Cloud Platform
- Installing JanusQ

Mathematical Model of Quantum Computing

Qubits



Quantum Evolution



Quantum Circuit

Quantum Bit (Qubit)

Single qubit

A **qubit** has two bases $|0\rangle$ and $|1\rangle$. The information stored in its **superposition state** is represented as a **2-dimension state vector** $|\varphi\rangle$.

$$|0\rangle = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$$

$$|1\rangle = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

$$|\varphi\rangle = \alpha|0\rangle + \beta|1\rangle$$

$$|\varphi\rangle = \begin{bmatrix} \alpha \\ \beta \end{bmatrix}$$

subject to $|\alpha|^2 + |\beta|^2 = 1$

Quantum Bit (Qubit)

Single qubit

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$$|\varphi\rangle = \alpha|0\rangle + \beta|1\rangle$$

$$|\varphi\rangle = \begin{bmatrix}\alpha\\\beta\end{bmatrix}$$

subject to $|\alpha|^2 + |\beta|^2 = 1$

Multiple qubits

***N* qubits** has 2^N bases $|00\cdots0\rangle$, $|00\cdots1\rangle\cdots$, $|11\cdots1\rangle$. The information stored in their **superposition state** is represented as a 2^N**-dimension state vector**.

$$|00\cdots0\rangle = \begin{bmatrix}1\\0\\\vdots\\0\end{bmatrix} \quad |00\cdots1\rangle = \begin{bmatrix}0\\1\\\vdots\\0\end{bmatrix} \quad \cdots \quad |11\cdots1\rangle = \begin{bmatrix}0\\0\\\vdots\\1\end{bmatrix}$$

$$|\varphi\rangle = \alpha_0|00\cdots0\rangle + \alpha_1|00\cdots1\rangle + \cdots + \alpha_{2^N}|11\cdots1\rangle$$

$$|\varphi\rangle = \begin{bmatrix}\alpha_0\\\alpha_1\\\vdots\\\alpha_{2^N}\end{bmatrix}$$

subject to $|\alpha_0|^2 + |\alpha_1|^2 + \cdots |\alpha_{2^N}|^2 = 1$

Quantum Evolution

Unitary matrix

A quantum evolution caused by **quantum gates** is represented as a **unitary matrix (unitary),** which is a square matrix whose conjugate transpose is its inverse.

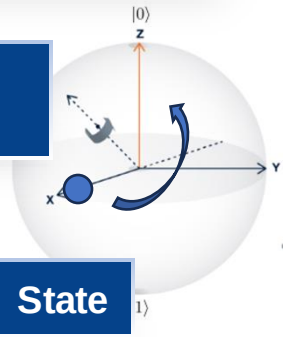
$$UU^{\dagger} = I$$

The evolution of qubit state $|\varphi\rangle$ is represented as:

$$|\varphi'\rangle = U|\varphi\rangle$$

Bloch sphere

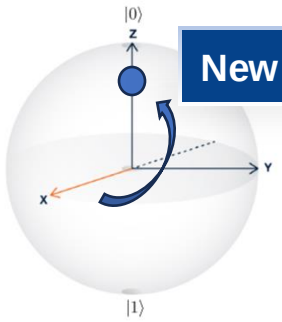
X+Z axes



State

$$H = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$$

π rotation around X+Z axes



New state

Quantum Evolution

Unitary matrix

A quantum evolution caused by **quantum gates** is represented as a **unitary matrix (unitary),** which is a square matrix whose conjugate transpose is its inverse.

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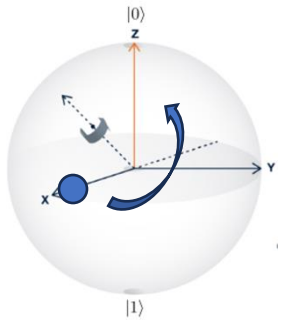
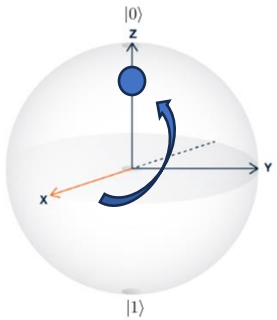
The evolution of qubit state $|\varphi\rangle$ is represented as:

$$|\varphi'\rangle = U|\varphi\rangle$$



$$H = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$$

π rotation around X+Z axis: Exchanges X and Z



Quantum readout

A sampling of a quantum state is a bitstring. Multiple sampling of this state composes a probability distribution of measuring different bitstrings.

Quantum Circuit

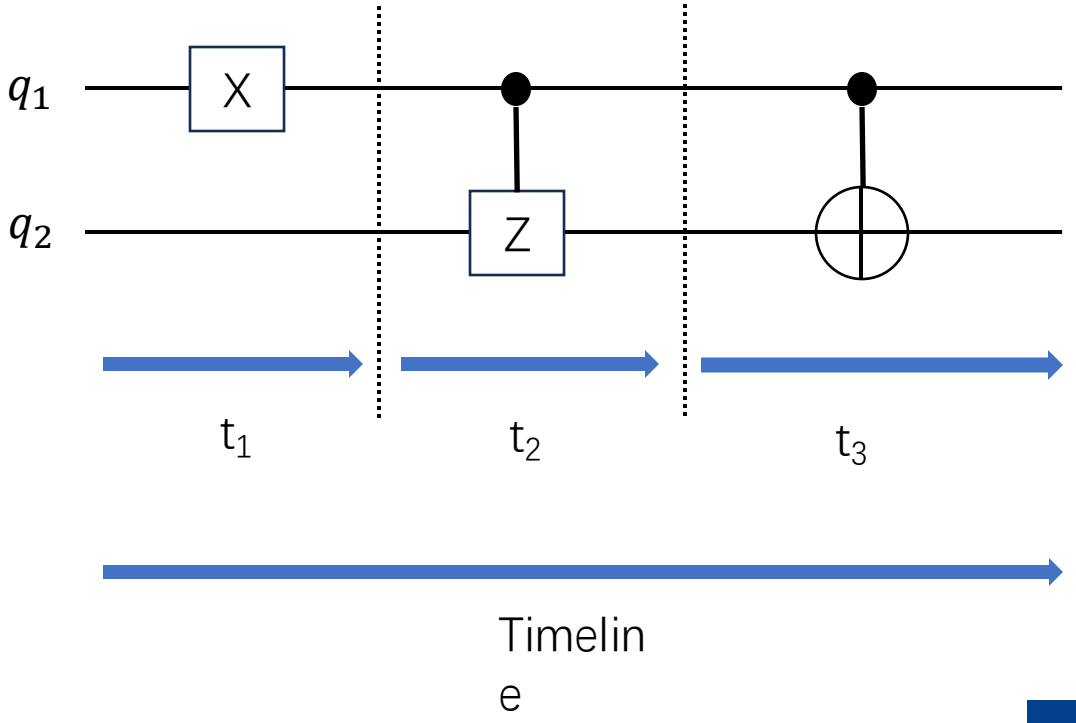
Quantum gates

In the quantum circuit model of computation, a **quantum gate** is a **basic quantum circuit operating** on a small number of qubits.

Operator	Gate(s)	Matrix
Pauli-X (X)	X	$\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$
Pauli-Y (Y)	Y	$\begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix}$
Controlled Not (CNOT, CX)		$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix}$
Controlled Z (CZ)	Z	$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{bmatrix}$
SWAP		$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$
Toffoli (CCNOT, CCX, TOFF)		$\begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix}$

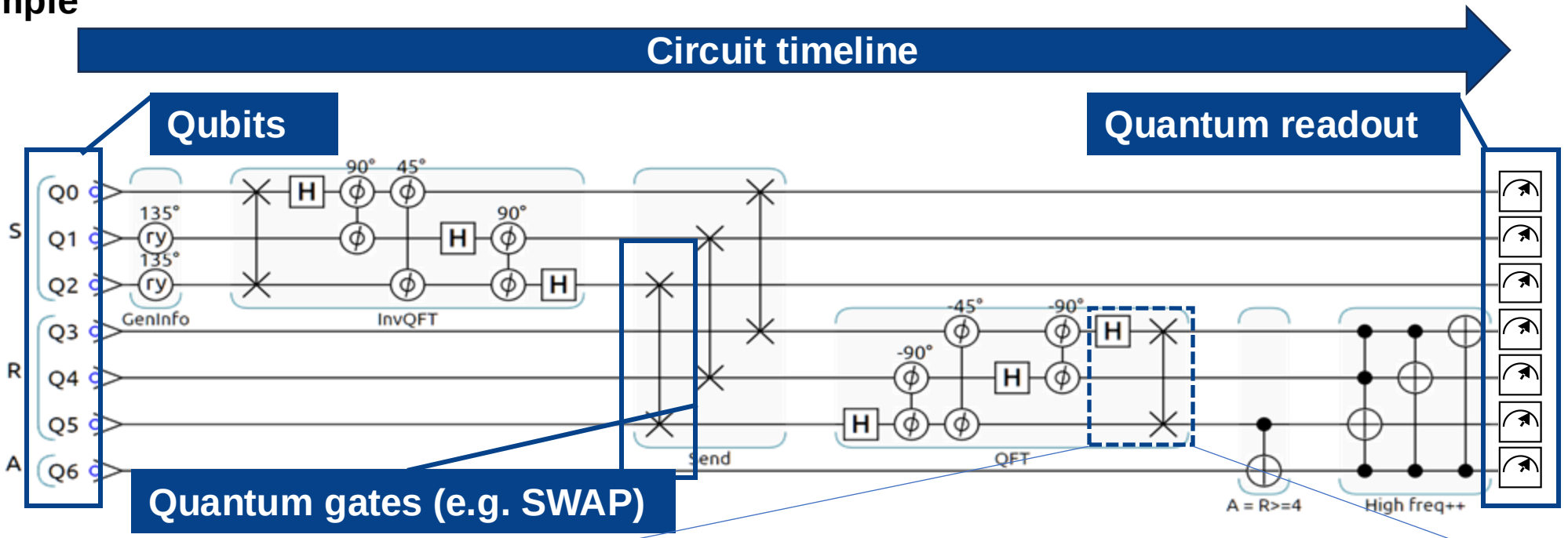
Qubit timeline

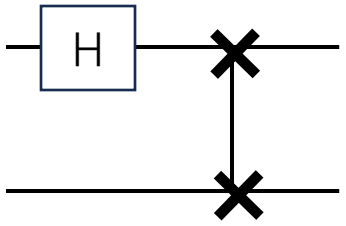
Each line in a quantum circuit represents **a qubit**. The quantum gate in a line is applied on the same qubits **from left to right in time direction.**



Quantum Circuit

For example





$$SWAP \cdot (H \otimes I) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \\ 1 & 0 & -1 & 0 \\ 0 & 1 & 0 & -1 \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 0 & 1 & 0 \\ 1 & 0 & -1 & 0 \\ 0 & 1 & 0 & 1 \\ 0 & 1 & 0 & -1 \end{bmatrix}$$

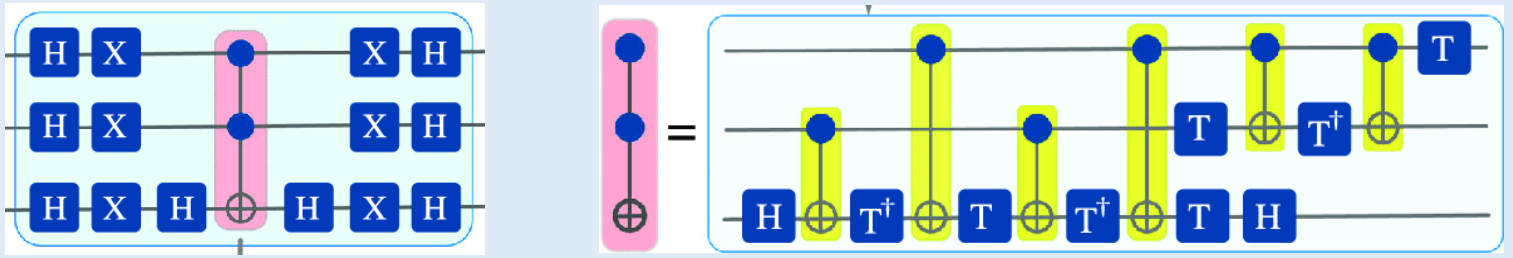
Implementation of Quantum Circuit

On superconducting quantum computer

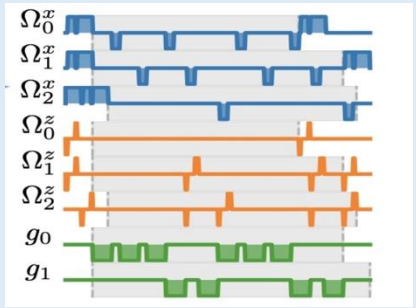
Step 1. Circuit statement

```
OPENQASM 2.0;
qreg qubits[3];
H qubits[1];H qubits[2];
H qubits[3];
X qubits[1];X qubits[2];
X qubits[3];
H qubits[3];
Toffoli qubits[1], qubits[2],
qubits[3];
H qubits[3];
X qubits[1];X qubits[2];
X qubits[3];
H qubits[1];H qubits[2];
H qubits[3];
```

Step 2. Circuit compilation



Step3. Circuit execution



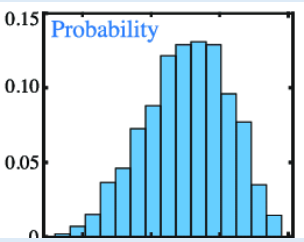
Pulse generation

Quantum device

Step4. Result processing

Error mitigation

Visualization

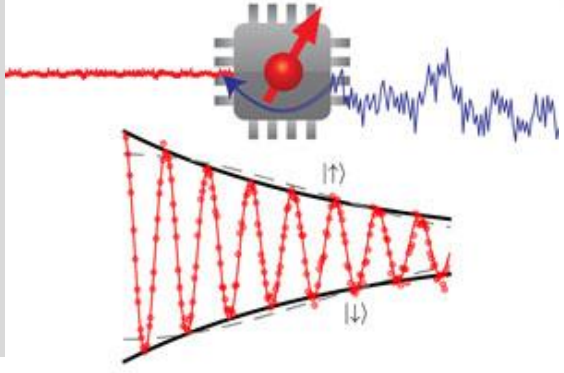


Probability distribution

Challenge in Quantum Computing

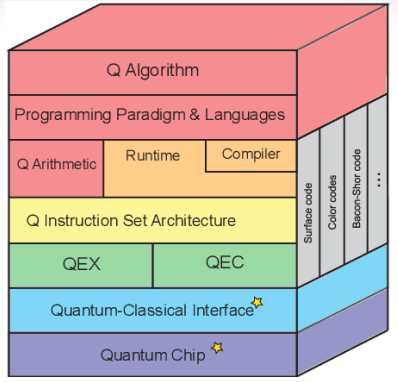
Noise

- Coherence error
- Gate error
- State preparation error
- Readout error
- Crosstalk



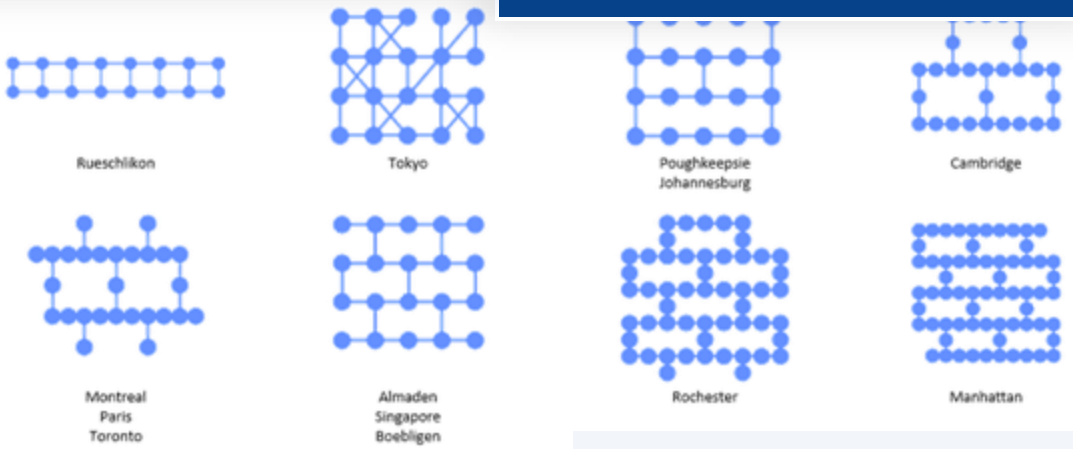
Instructions

- Multi-level compilation
- Micro-architecture instructions
- Quantum-classical communication



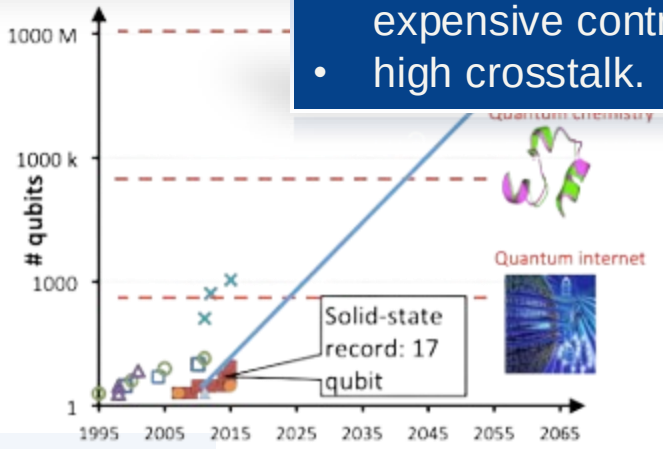
Topology

Locality in communication



Scalability

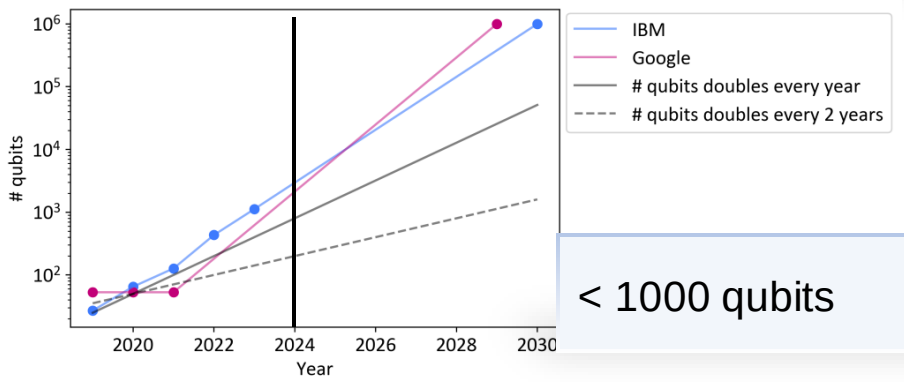
- poor fabrication techniques expensive control systems
- high crosstalk.



Constrained by physical implementation

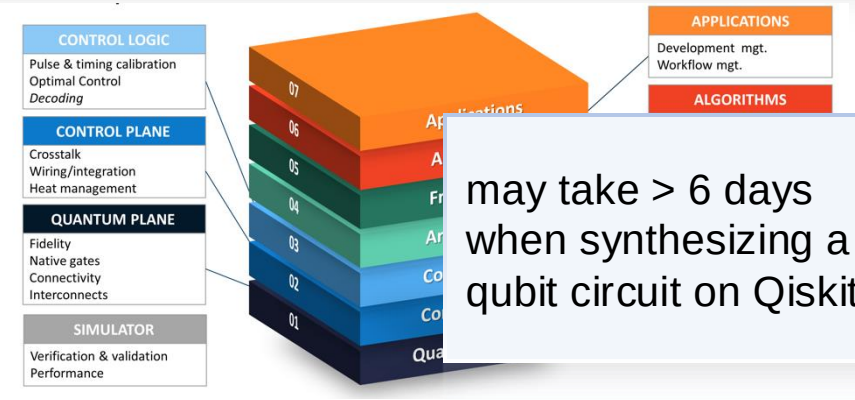
Results of Challenges

Limited Hardware Resource



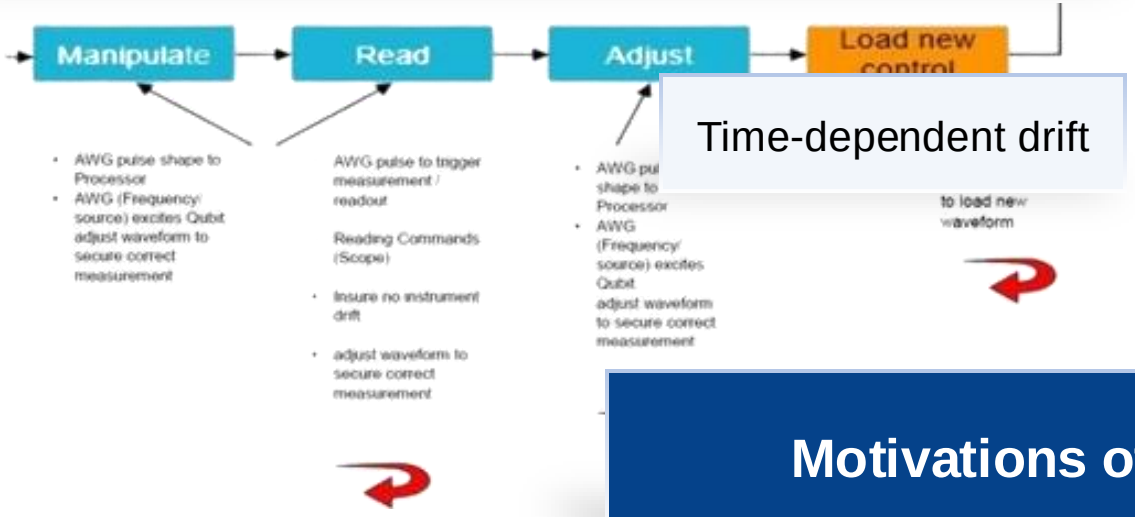
< 1000 qubits

Compilation Complexity



may take > 6 days
when synthesizing a 100-qubit circuit on Qiskit

Difficulty Of Hardware Calibration



Time-dependent drift

Rare quantum advantage

- Limited qubits resources
- High error rate
- Hard to ensure quantum advantage in real applications

Long calibration time
(e.g., readout calibration)

Motivations of JanusQ

Outline of Presentation

- Background Knowledge
- Mathematical Model of Quantum Computing
- **Janus (Taiyuan) Quantum Cloud Platform**
- Installing JanusQ

Janus (Taiyuan) Quantum Cloud Platform

Taiyuan (太元) & Janus

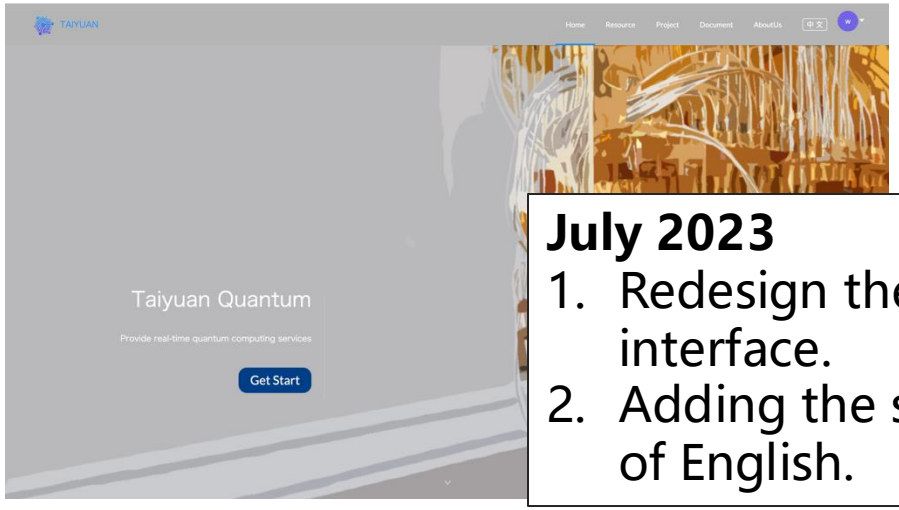
Yin and Yang

Tai Yuan is a Chinese gold who is the wife of Pan Gu (the god that created the world). She was delivered of Yin and Yang, which is entangled like a quantum superposition state

Janus is a two-faced god of the ancient Romans. He is the god of beginning, transition, time, change, dualism, and end. He has two faces simultaneously.

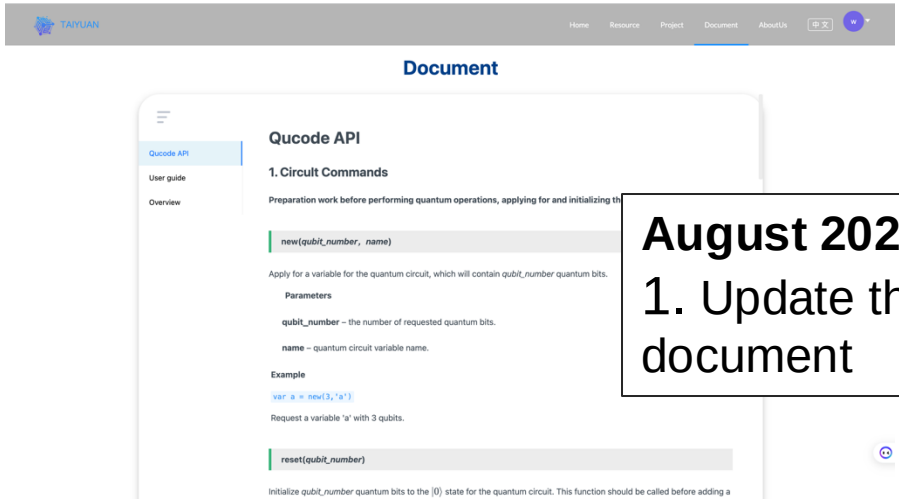
Development History of Janus Cloud

Four updates since July 2023



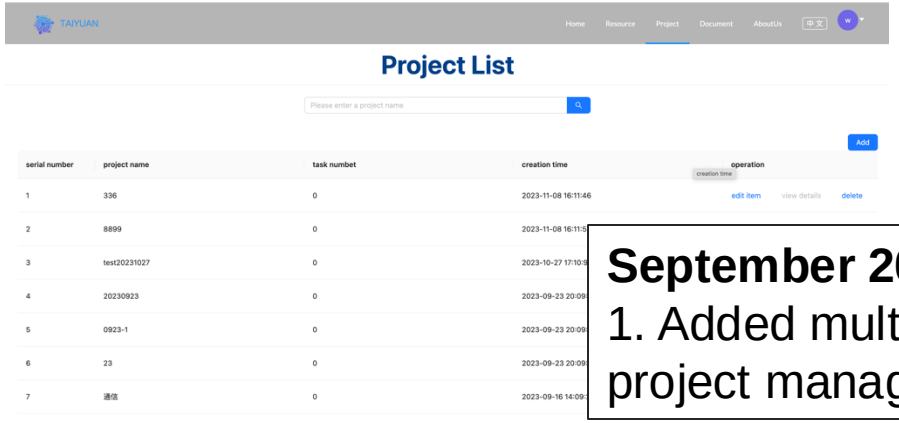
July 2023

1. Redesign the cloud interface.
2. Adding the support of English.



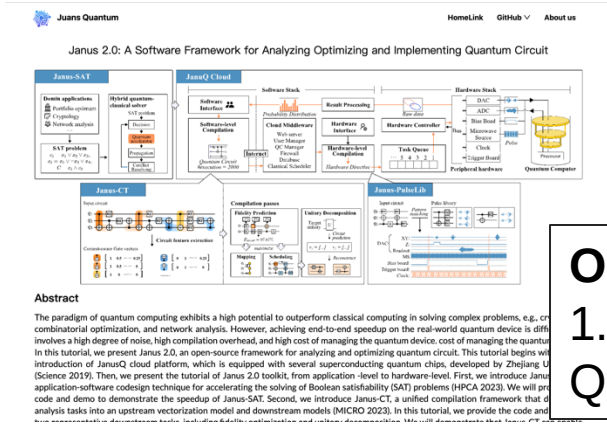
August 2023

1. Update the document



September 2023

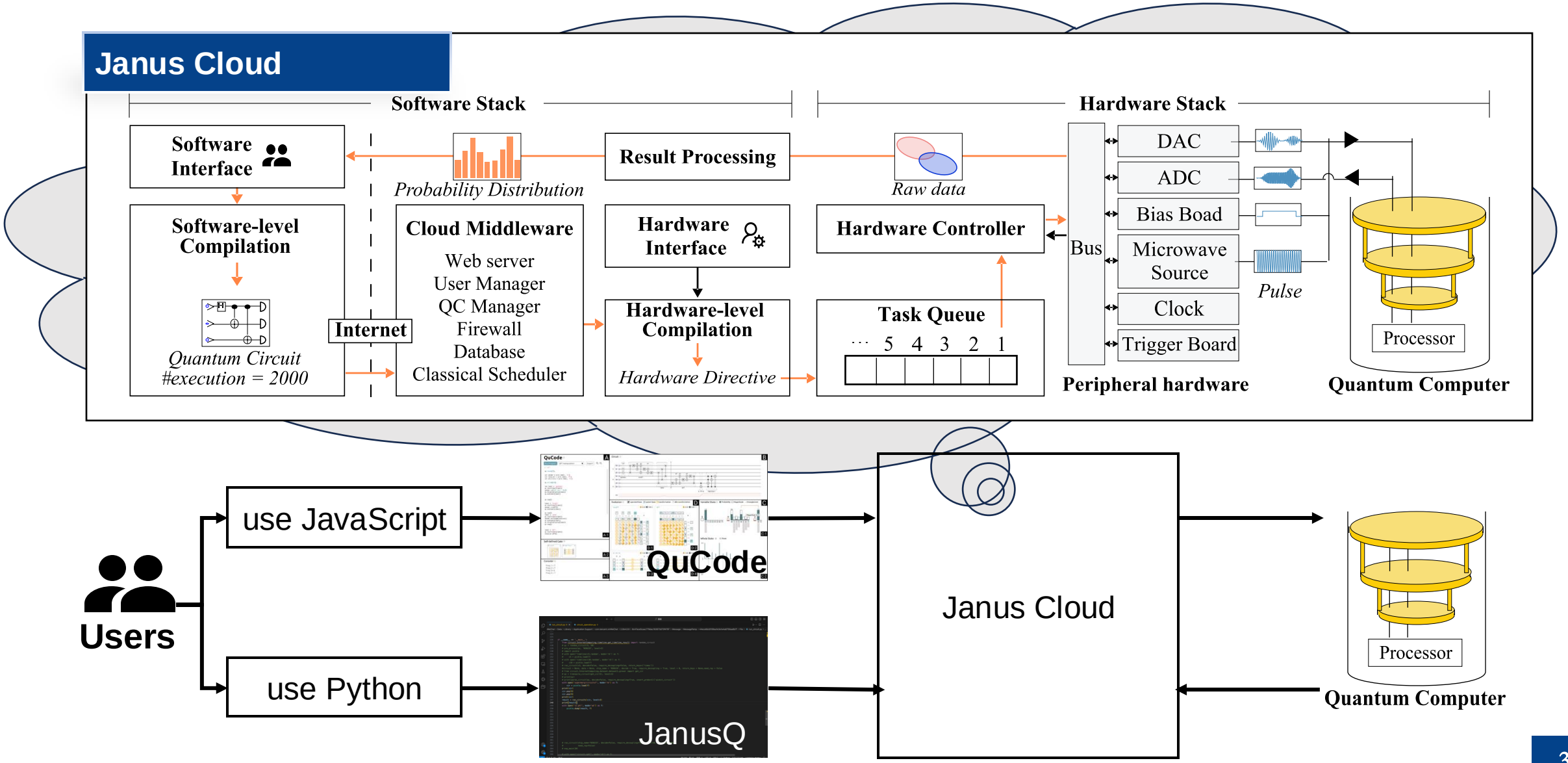
1. Added multi-level project management.



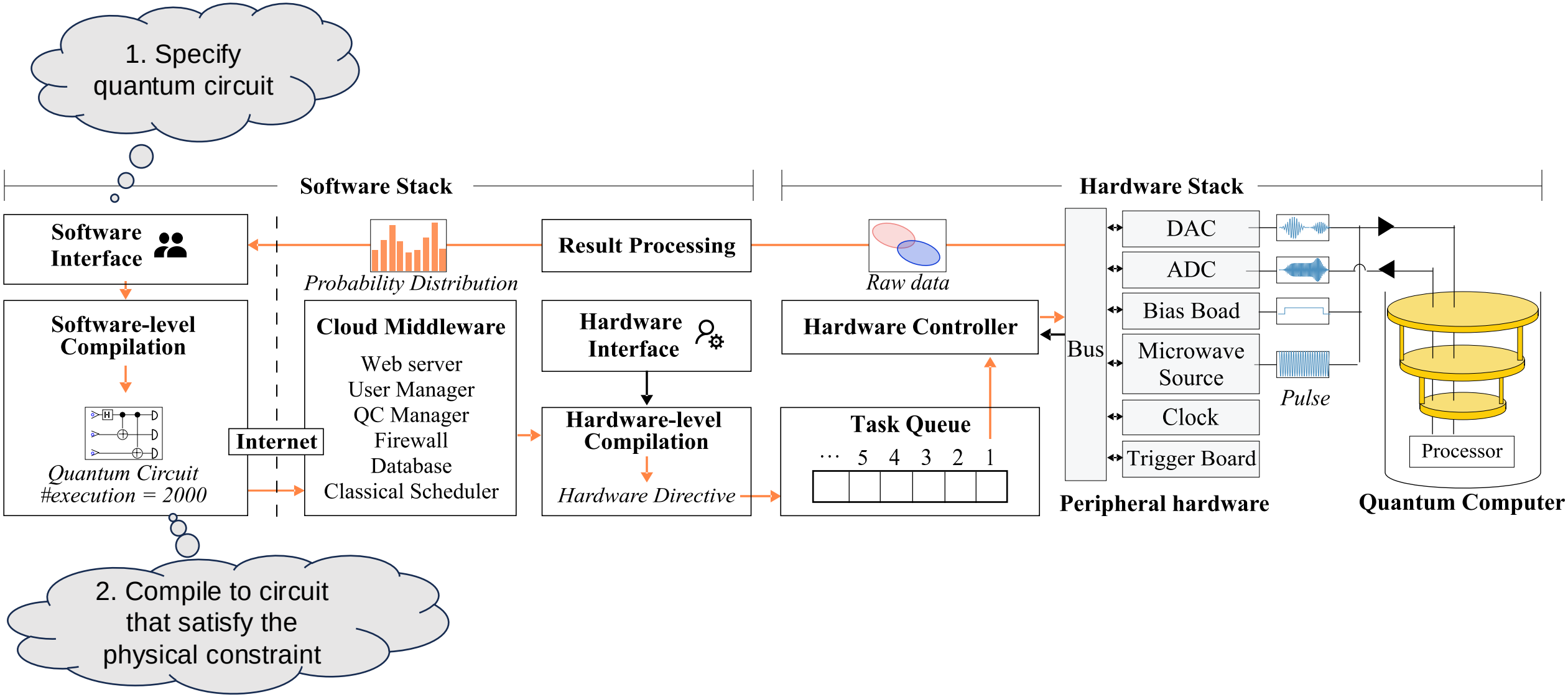
October 2023

1. Enable the online QuCT and HyQSAT

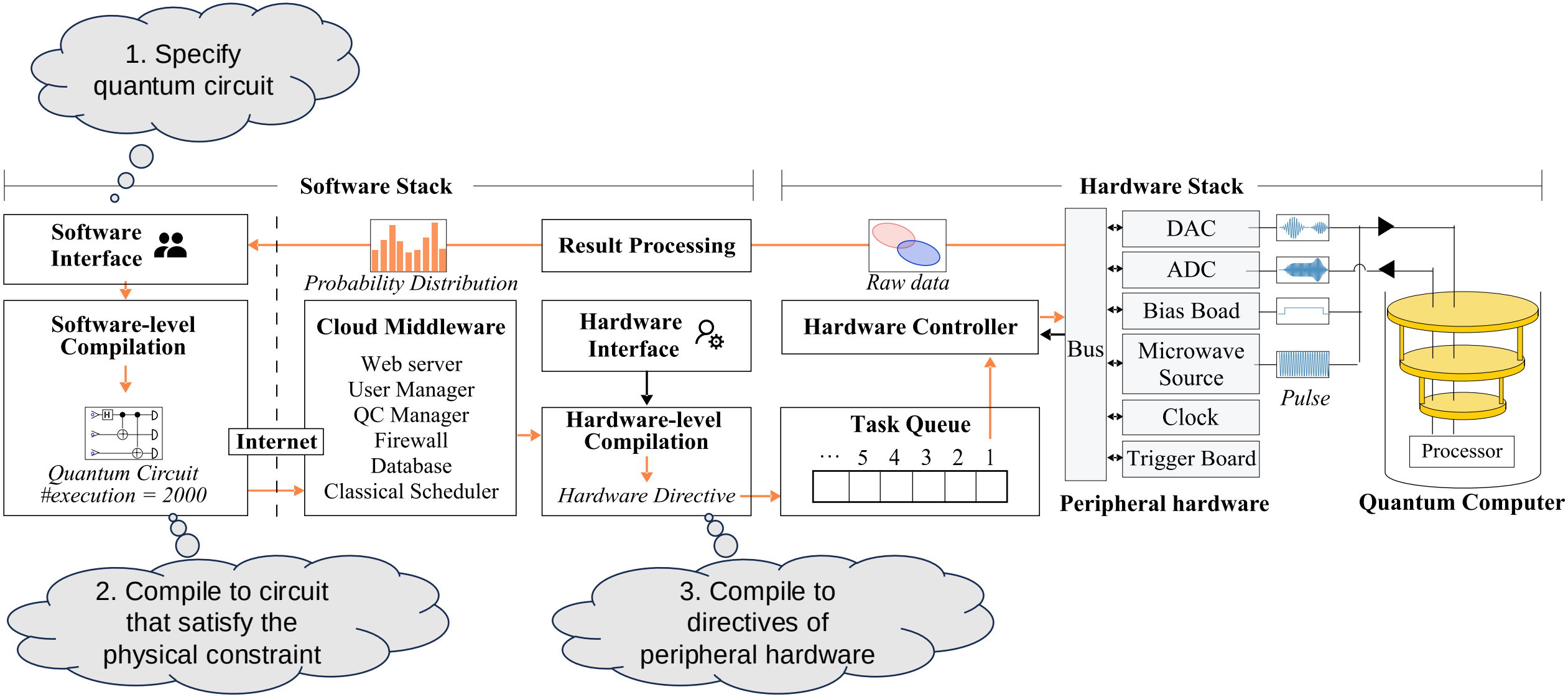
What we can do on Janus Platform



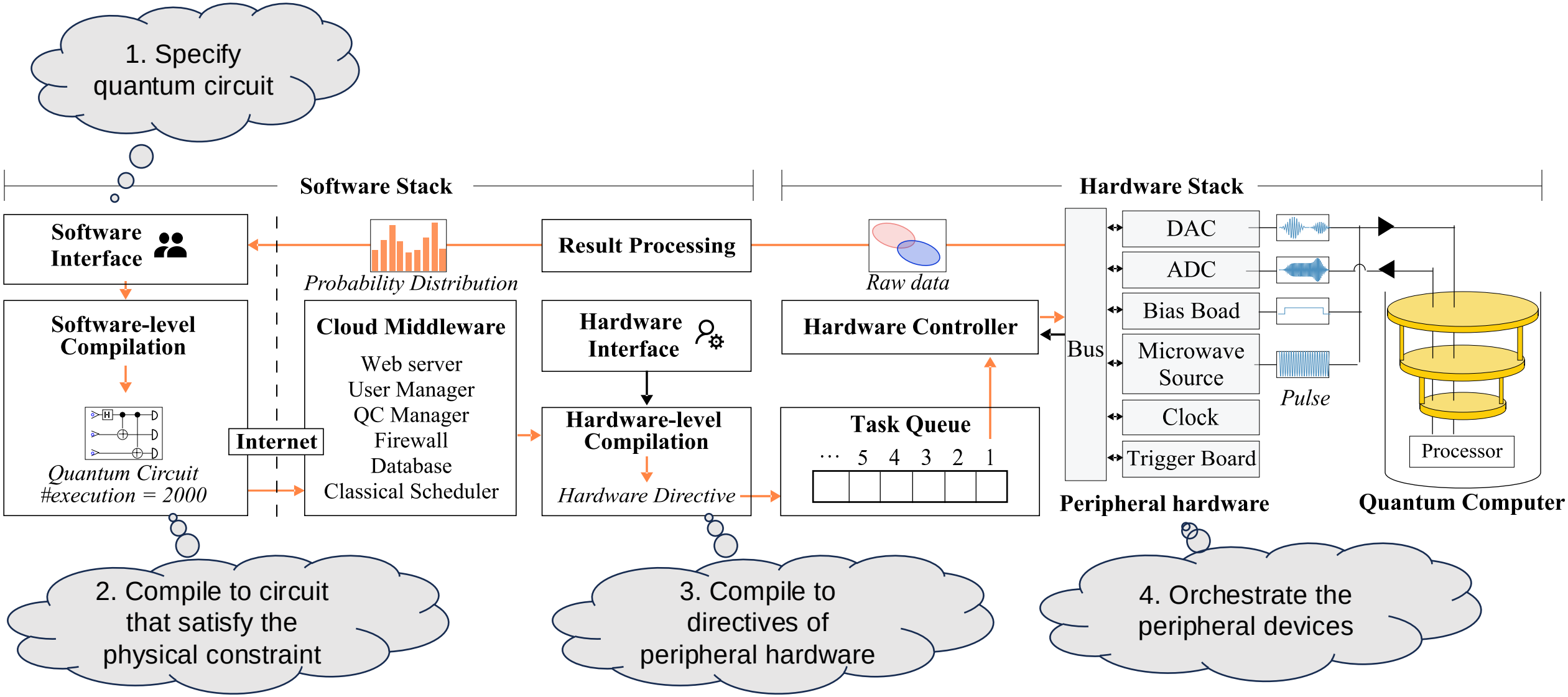
What we can do on Janus Platform



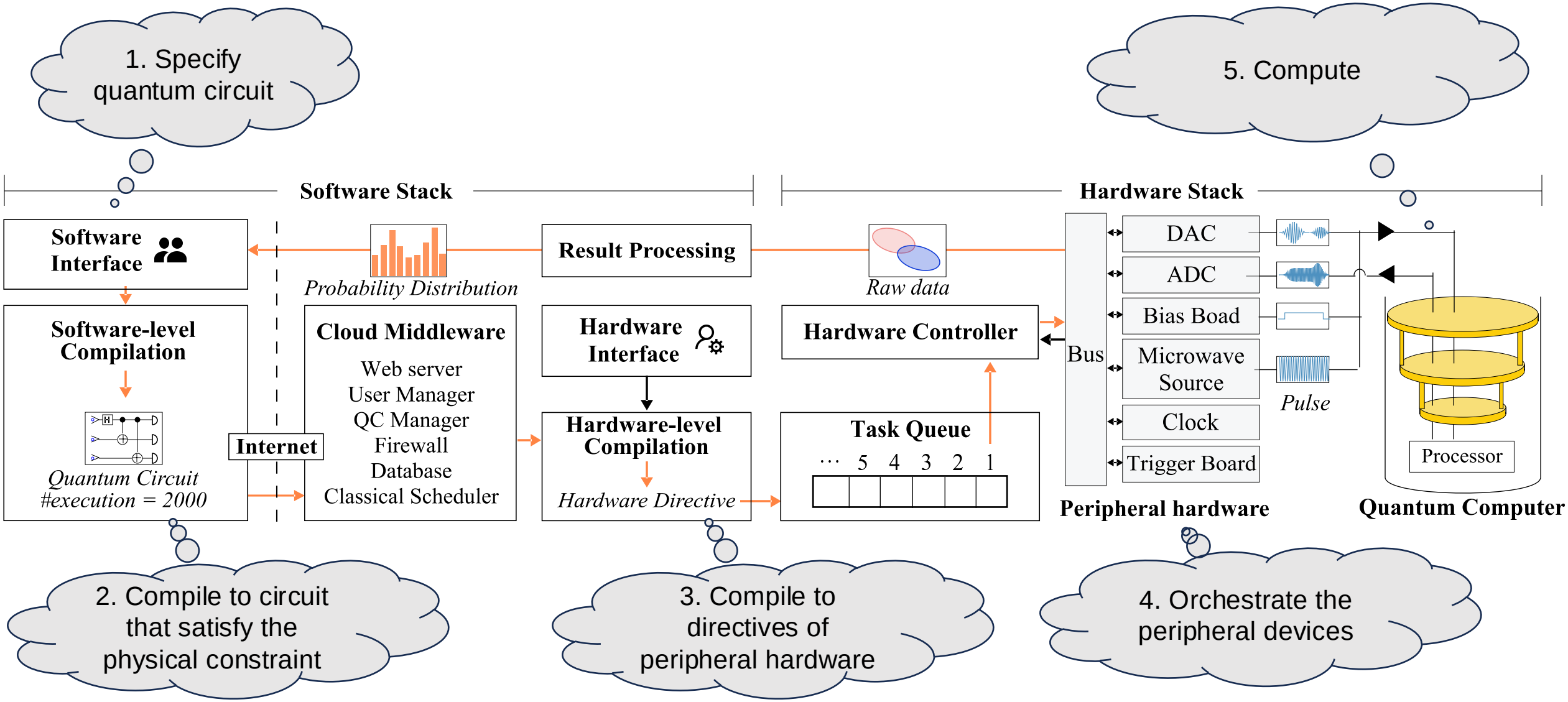
What we can do on Janus Platform



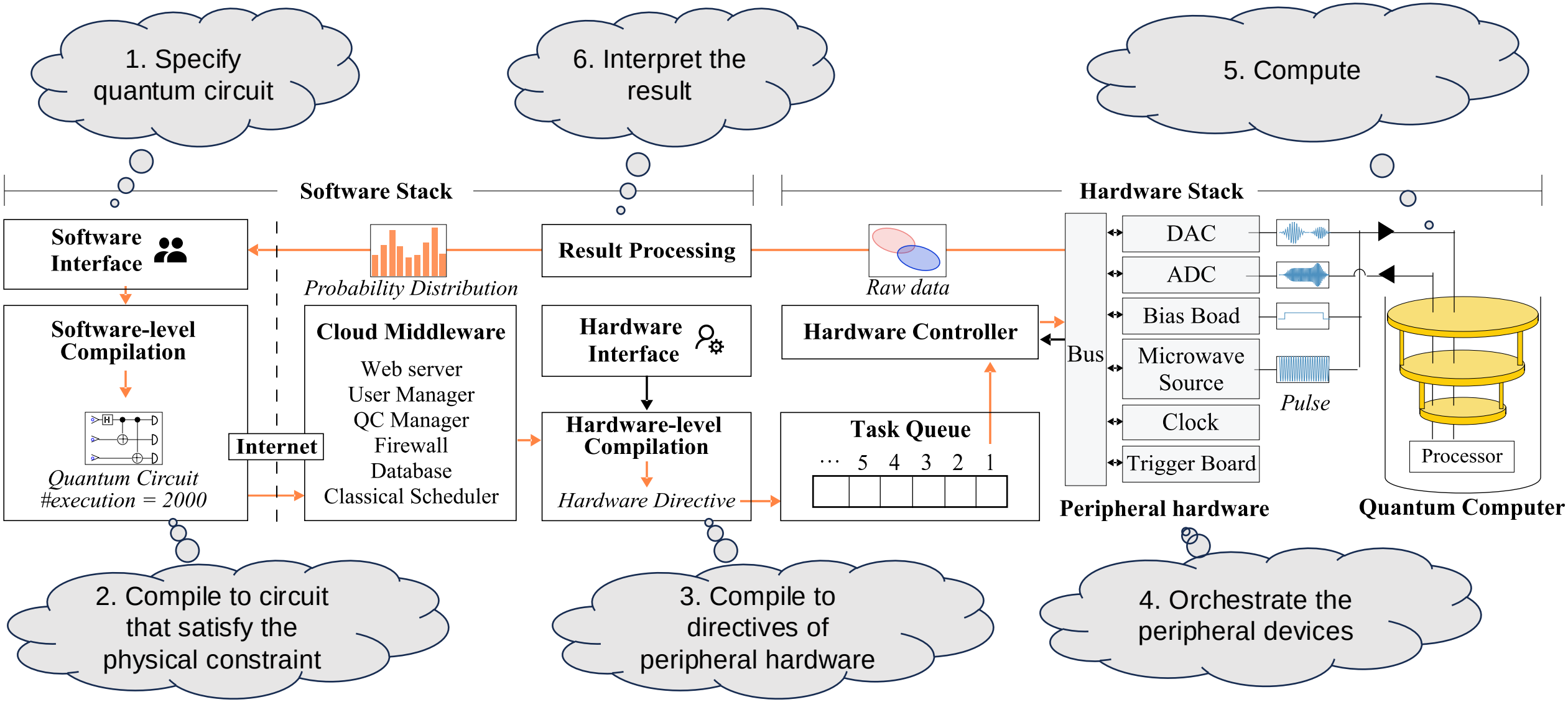
What we can do on Janus Platform



What we can do on Janus Platform



What we can do on Janus Platform



Creating an Account

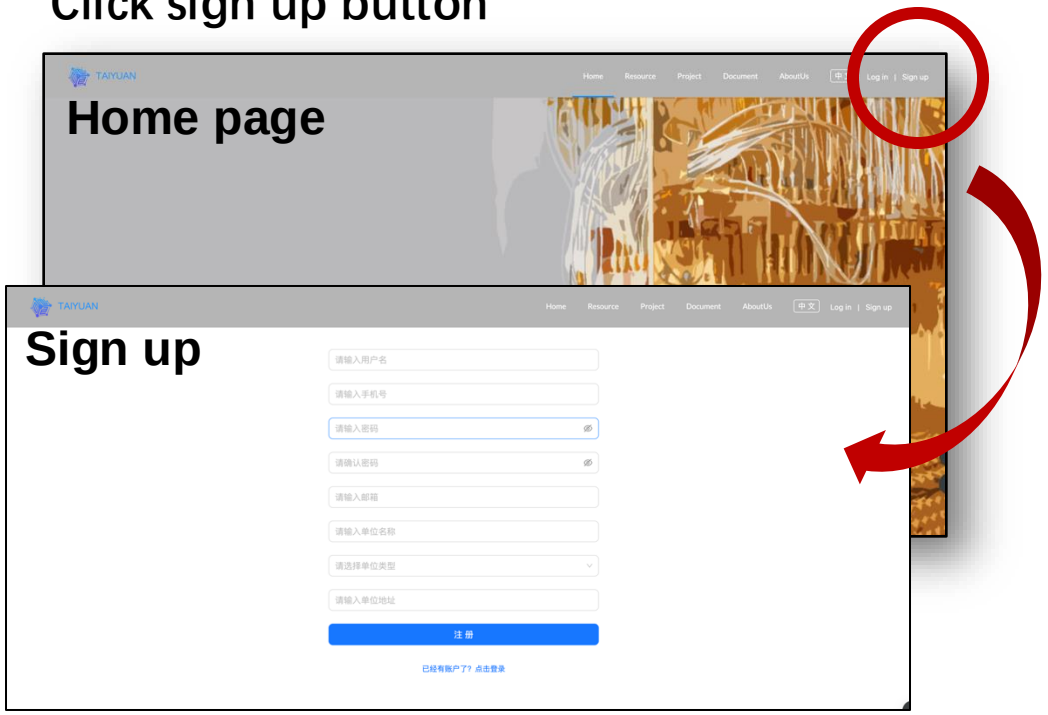
Go to Janus Cloud

Open http://janusq.zju.edu.cn/home

QR code

Sign up

Click sign up button

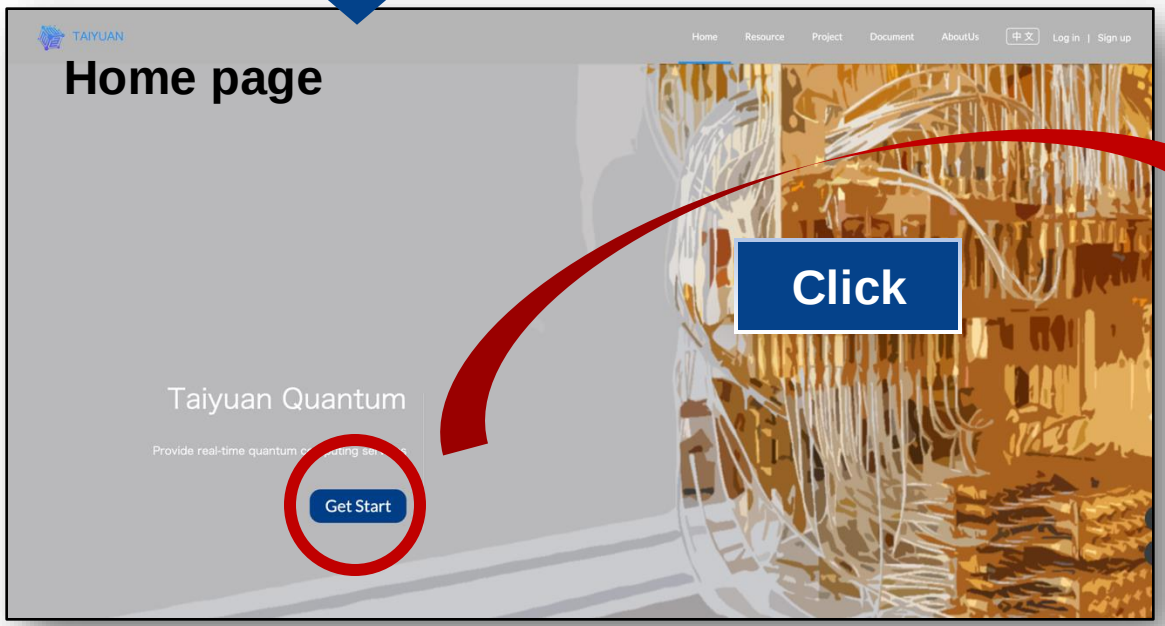


- After signing up, you will get an API key for task submission.
- **The quantum computer can be accessed on the website during the tutorial !!**

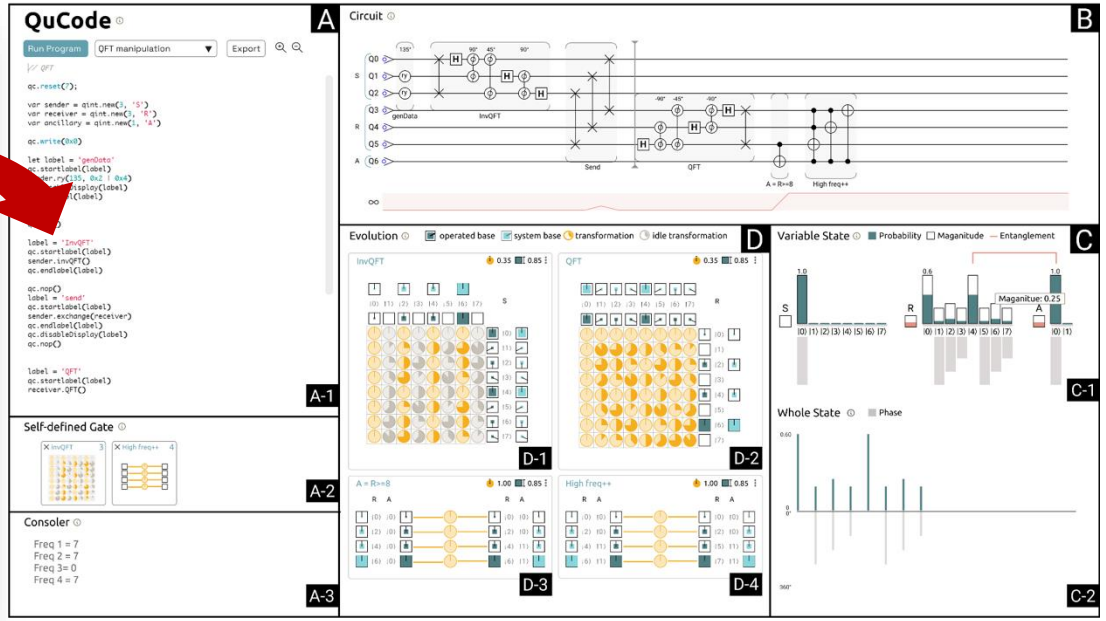
Running Program On the Website

Submitting on website

Open http://janusq.zju.edu.cn/home



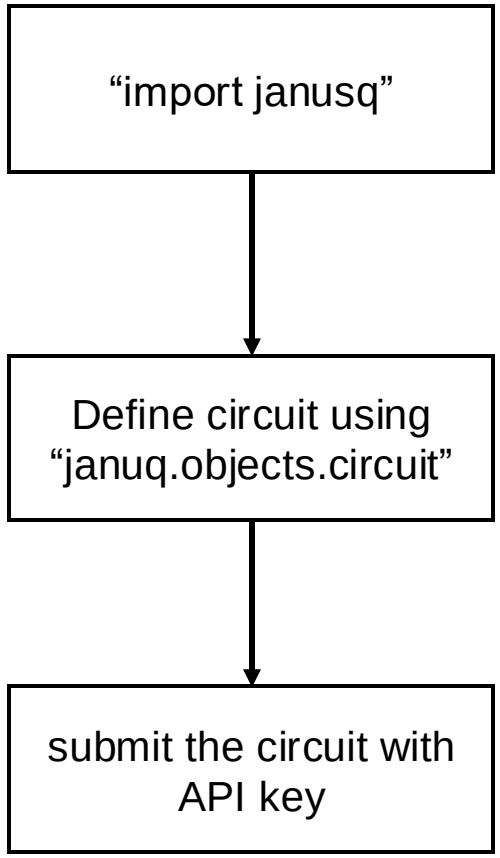
Programming on the Code editor



- **The quantum computer can be accessed on the website during the tutorial !!**

Running Program By Python API

Submitting by Python



Import package

```
import matplotlib.pyplot as plt
from janusq.cloud_interface import submit, get_result
from janusq.objects.circuit import Circuit
```

Define a circuit

```
qc = Circuit([], n_qubits = 4)
qc.h(0, 0)
qc.cx(0, 1, 1)
qc.cx(1, 2, 2)
qc.cx(2, 3, 3)
print(qc)
```

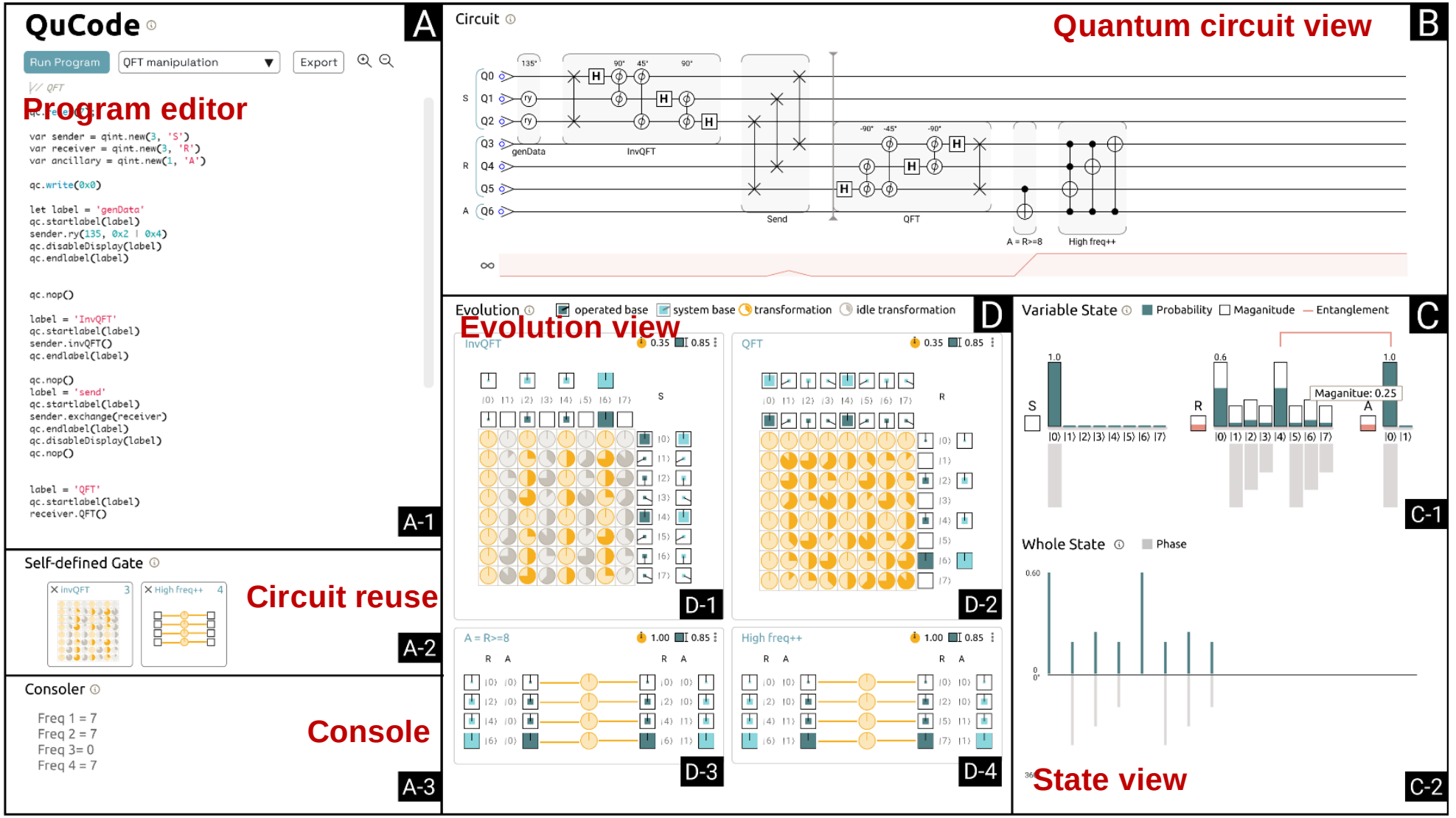
Submit circuit

```
result = submit(circuit=qc, label= 'GHZ', shots= 3000,
run_type='simulator', API_TOKEN='')
```

Get result

```
result = get_result(result['data']['result_id'],
run_type='simulator', result_format='probs')
print(result)
```

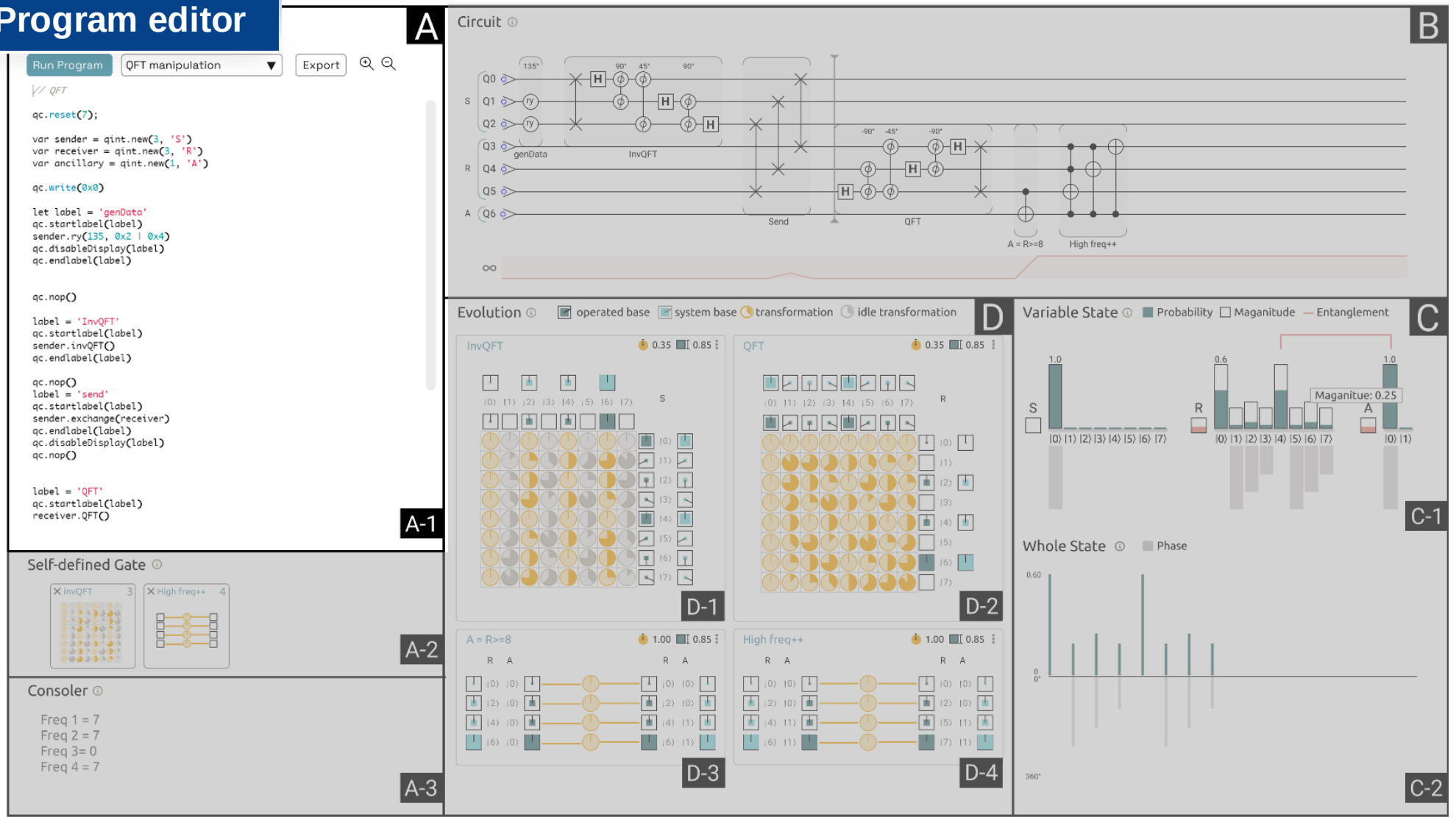
QuCode: Online Quantum Program Editor



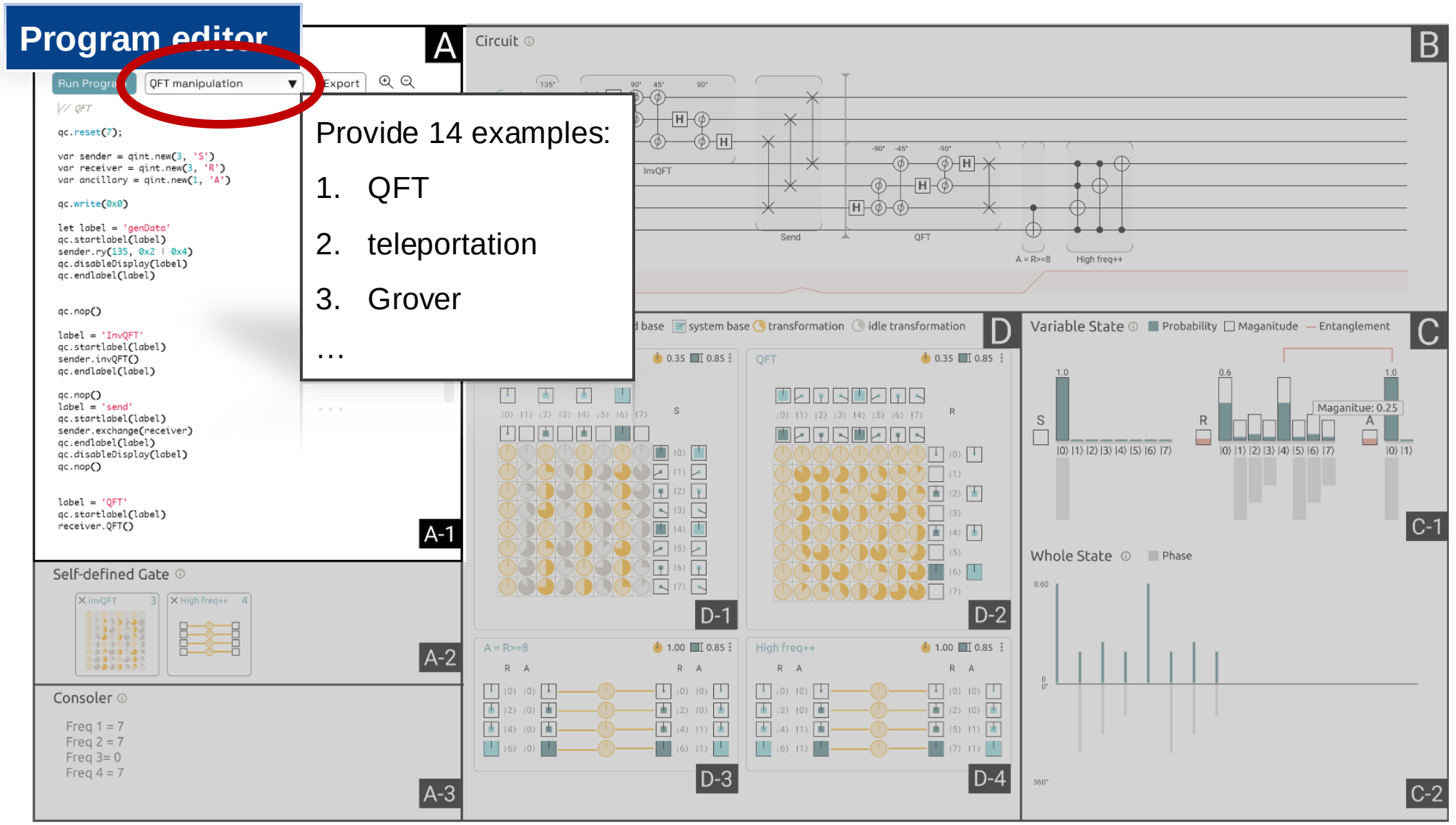
QuCode: Online Quantum Program Editor

ZHEJIANG UNIVERSITY

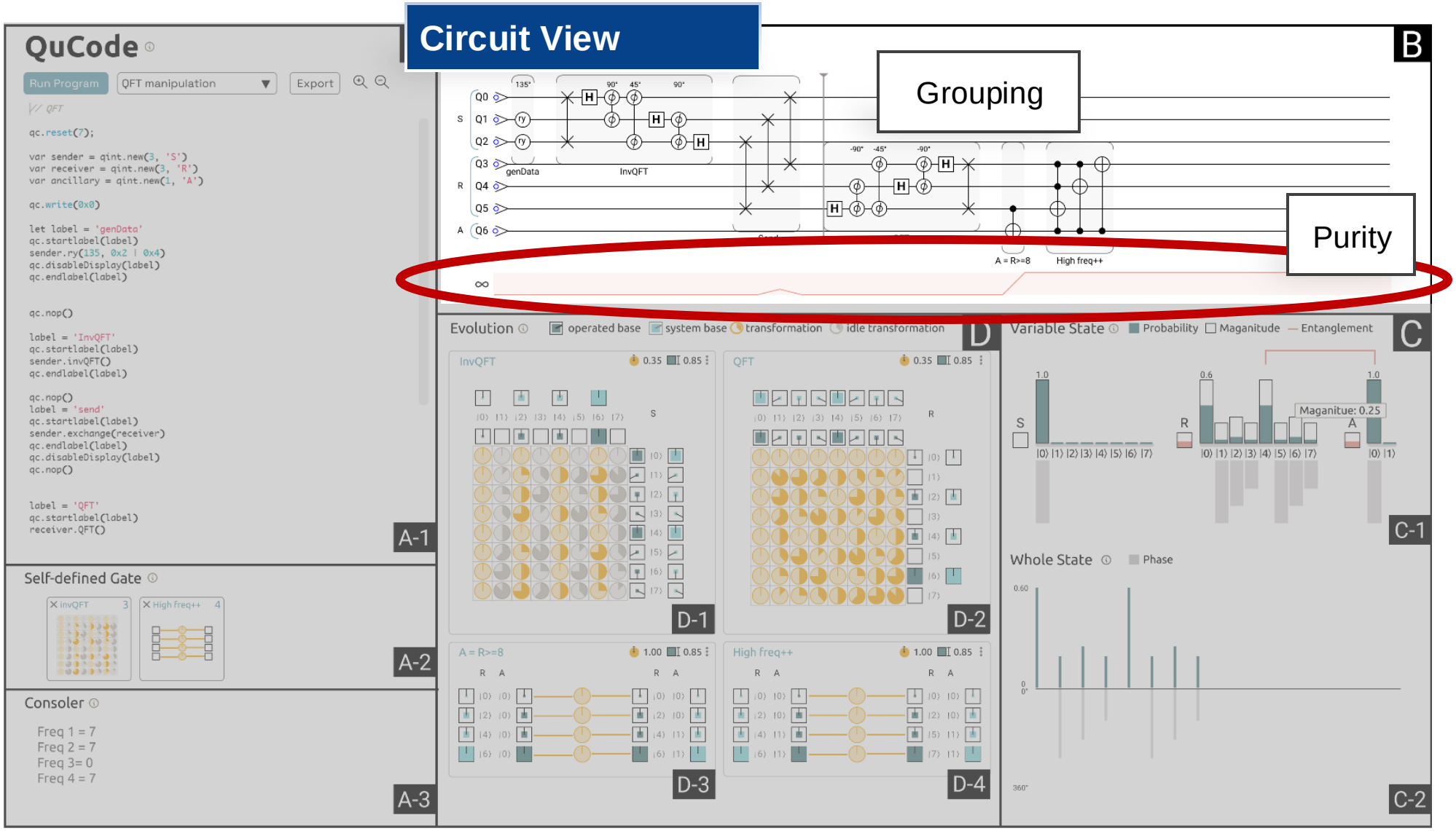
Program editor



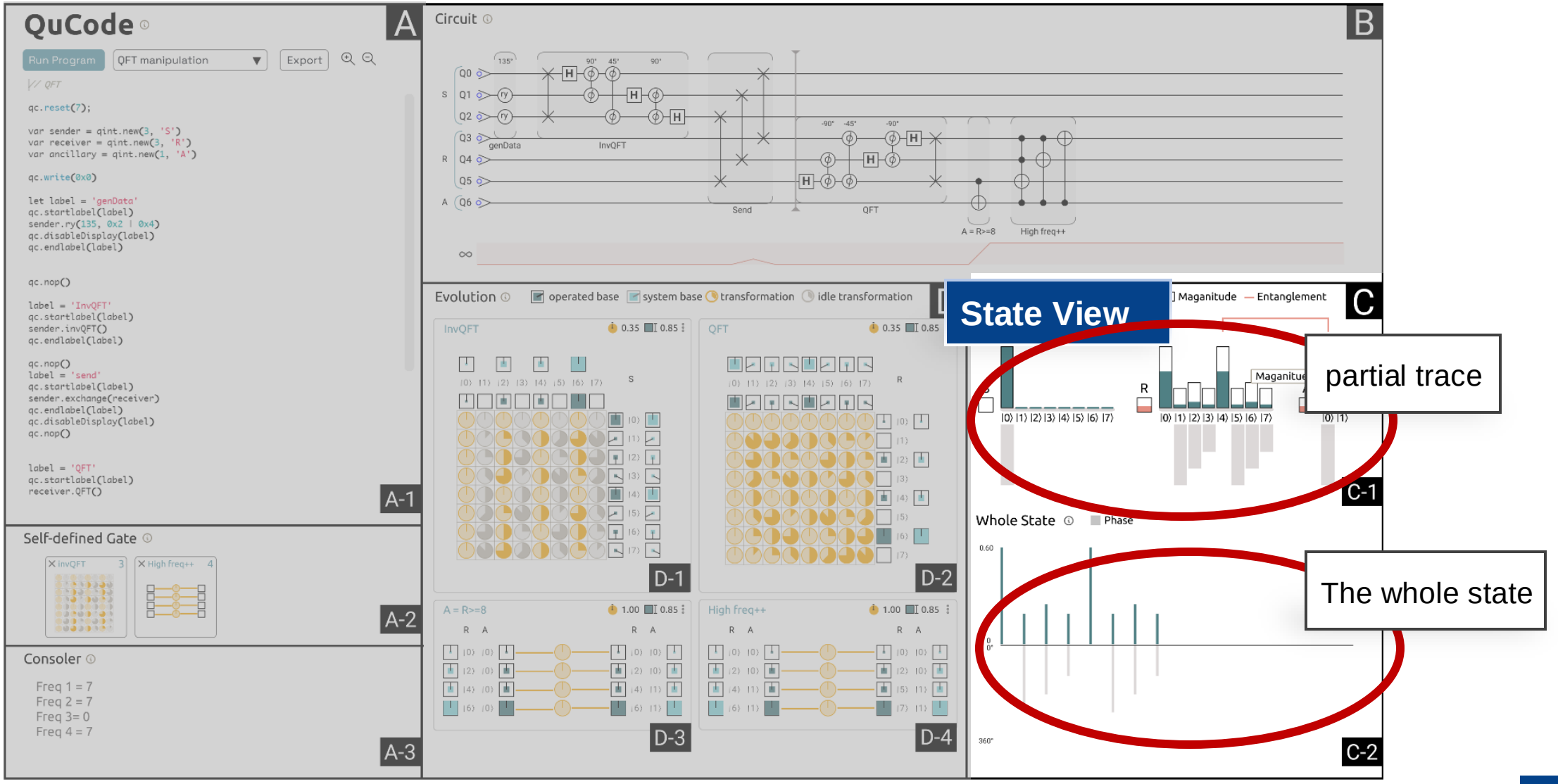
QuCode: Online Quantum Program Editor



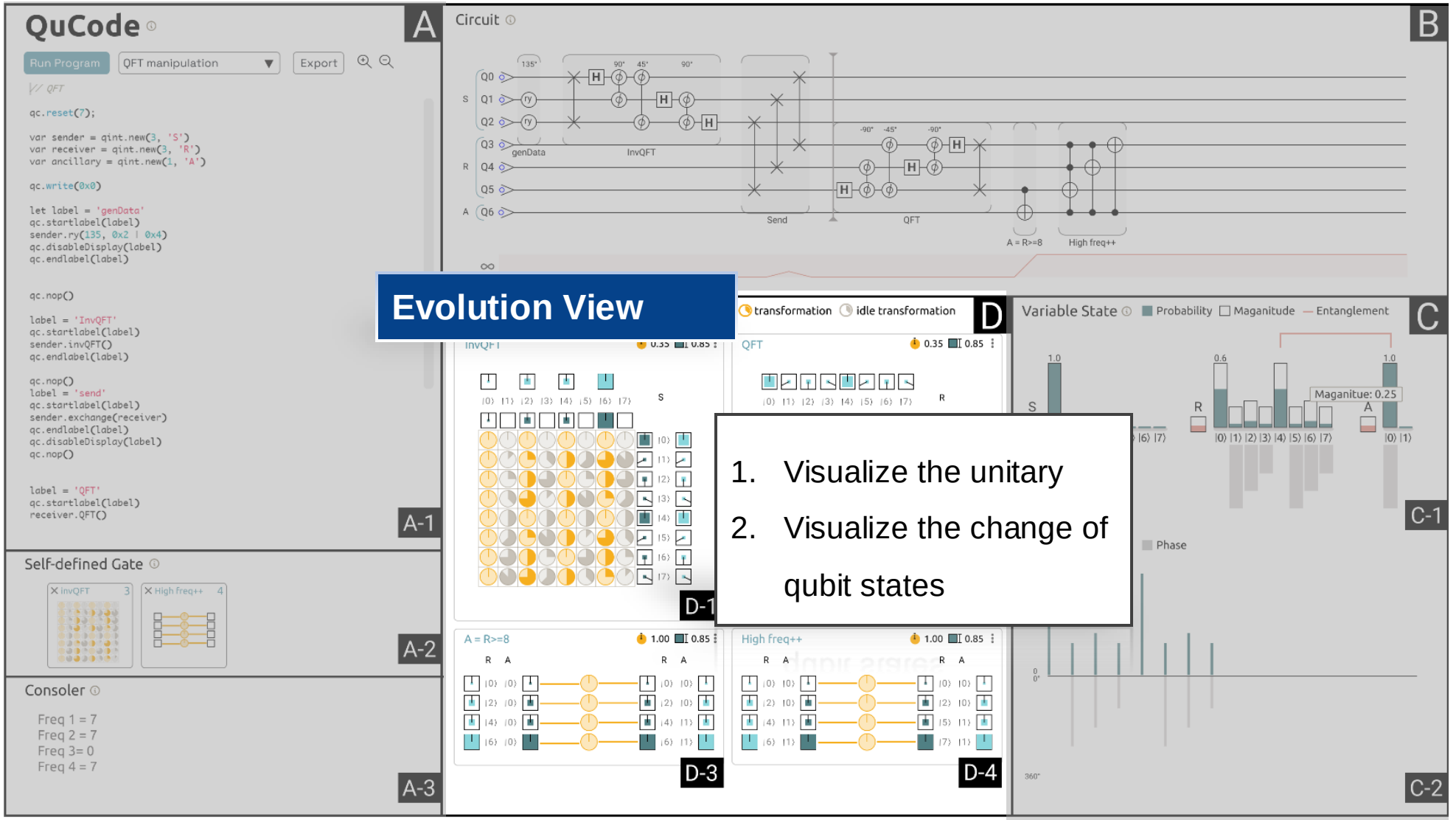
QuCode: Online Quantum Program Editor



QuCode: Online Quantum Program Editor



QuCode: Online Quantum Program Editor



Outline of Presentation

- Background Knowledge
- Mathematical Model of Quantum Computing
- Janus (Taiyuan) Quantum Cloud Platform
- **Installing JanusQ**

Installing JanusQ

https://github.com/JanusQ/JanusQ

Installing Methods

Language: Python 3, C++

Available platforms: Linux, Mac, Windows

HyQSAT has not been tested on Windows.

Hardware requirements:

- Classical computer: ≥ 16 GB Memory, Intel i5 10 Gen

Hardware used in the experiment

- A server with two AMD EPYC 2.25GHz 64-core CPUs and 1.6TB DDR 5 memory is preferable.
- Superconducting, ion-trapped quantum computer and D-Wave quantum annealer.

Data collected from the quantum hardware are put into the framework.

Installation:

From Docker (recommend)

From Source code

Wheel is provided in https://github.com/JanusQ/JanusQ/tree/main/dist. But HyQSAT is disabled.

Install from Docker (Preferred)

Step 1. download docker-desktop

https://www.docker.com/products/docker-desktop/

Windows Subsystem for Linux (WSL) are required for windows.

Step 2. pull JanusQ image

```
docker pull janusq3
```

Step 3. start image

```
docker run -itd -p 8888:22 -p 9999:23 --name tutorial janusq3
```

Step 4. Use SSH/VSCode/PyCharm to connect the docker

```
ssh root@localhost -p 8888
```

Step 5. Or use Jupyter Lab to connect the docker

```
http://localhost:9999/lab
```

Docker page of JanusQ:
https://hub.docker.com/r/janusq3

The password of the docker is “” (empty).

Install from Source Code

Step 1. clone the source code

```
git clone git@github.com:JanusQ/JanusQ.git
```

Step 2. install requirements (virtual environment is preferred)

```
cd ./JanusQ
conda create -n janusq python=3.10
conda activate janusq
pip install -r requirements.txt
```

Step 3. compile HyQSAT

```
cd ./janusq/application/hyqsat/solver
cmake .
make install
```

Step 3. install requirements for Choco-Q (Linux with CPU)

```
cd ./janusq/application/chocoq
conda env create -f environment_linux_cpu.yml
```

Page of github:
https://github.com/JanusQ/JanusQ

implemented based on C++.

Testing JanusQ

On “./JanusQ/examples/ipynb/1_1_install_janusq.ipynb”

Test QuCT

```
from janusq.analysis.vectorization import *

vec_model = RandomwalkModel()
vec_model.train()
```

Test QuFEM

```
from janusq.calibration.readout_mitigation.qufem
import EnumeratedProtocol

protocol = EnumeratedProtocol(4)
```

Test MorphQPV

```
from janusq.verification.morphqpv import
MorphQC,Config

myconfig = Config()
myconfig.solver = 'sgd'
with MorphQC(config=myconfig) as morphQC:
    morphQC.add_tracepoint(0,1)
    morphQC.assume(0,IsPure())
    …
```

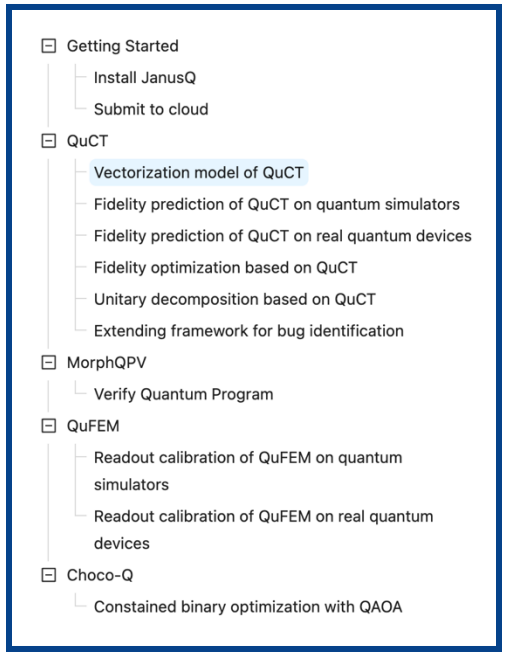
Test Choco-Q

```
from janusq.application.chocoq.chocoq.model import
LinearConstrainedBinaryOptimization as LcboModel

m = LcboModel()
x = m.addVars(5, name="x")
m.setObjective((x[0] + x[1])* x[3] + x[2], "max")
m.addConstr(x[0] + x[1] - x[2] == 0)
m.addConstr(x[2] + x[3] - x[4] == 1)
optimize = m.optimize()
```

Document and Example

On: **JanusQ/examples** or **https://janusq.github.io/HPCA_2025_Tutorial/demo**



Include 12 examples

Vectorization Model of QuCT

Author: Siwei Tan

Date: 7/4/2024

Based on paper "QuCT: A Framework for Analyzing Quantum Circuit by Extracting Contextual and Topological Features" (MICRO 2023)

In the current Noisy Intermediate-Scale Quantum era, quantum circuit analysis is an essential technique for designing high-performance quantum programs. Current analysis methods exhibit either accuracy limitations or high computational complexity for obtaining precise results. To reduce this tradeoff, we propose QuCT, a unified framework for extracting, analyzing, and optimizing quantum circuits. The main innovation of QuCT is to vectorize each gate with each element, quantitatively describing the degree of the interaction with neighboring gates. Extending from the vectorization model, we can develope multiple downstream models for fidelity prediction and unitary decomposition, etc. In this tutorial, we introduce the APIs of the vectorization model in QuCT.

In [1]:

```
%matplotlib inline

import os
os.chdir("../..")
import logging
logging.basicConfig(level=logging.WARN)

import random
import numpy as np

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

Vectorization Flow

Below is the workflow to vectorize a gate in the quantum circuit. The gate is vectorized by two steps. The first step runs random walks to extract circuit features in the neighbor of the gates. the second step use a table comparison to generate the gate vector.

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Thanks for listening!