

# VACSEN: A Visualization Approach for Noise Awareness in Quantum Computing



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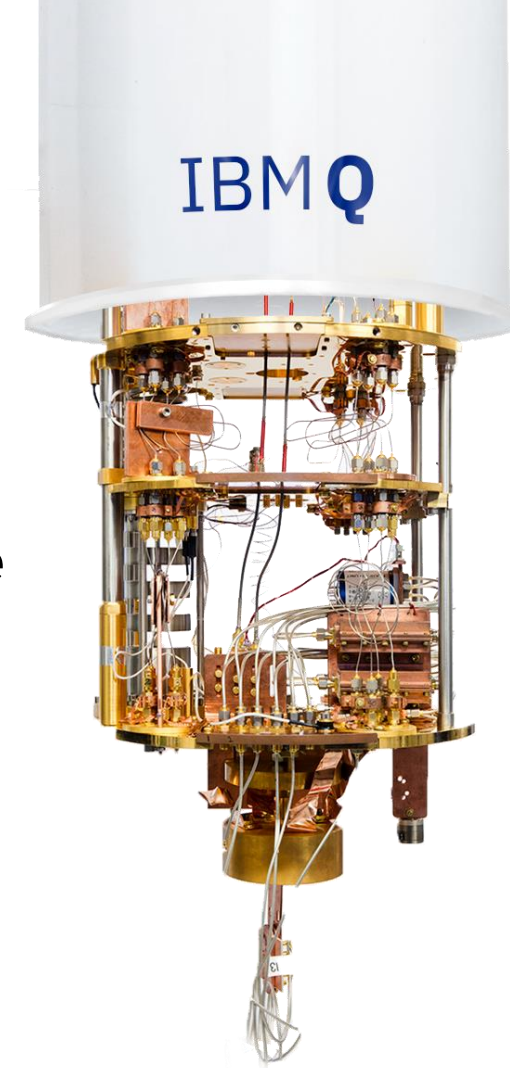
- **Background**
- **Motivation**
- **Approach**
- **Hands-on practice**
- **Evaluation**
- **Conclusion**



# Background

## Quantum computing

- Quantum computers have shown a considerable speedup over classical computers [1]

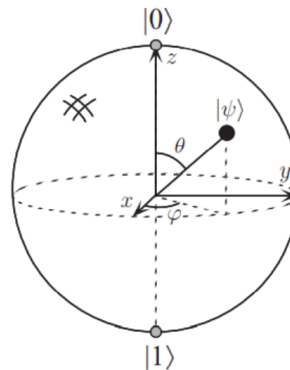


[1] Arute F, Arya K, Babbush R, et al. Quantum supremacy using a programmable superconducting processor[J]. Nature, 2019, 574(7779): 505-510.

# Background

## Quantum computing

- Quantum Bits  $\rightarrow$  Qubits
- *linear combination of states* a.k.a *superposition*:  $|\Psi\rangle = \alpha|0\rangle + \beta|1\rangle$
- Probabilities Summation must be equal to 1,  $|\alpha|^2 + |\beta|^2 = 1$
- Qubit's states is unit vector in two-dimensional complex vector space
- Multiple Qubits :  $|\Psi\rangle = \alpha_{00}|00\rangle + \alpha_{01}|01\rangle + \alpha_{10}|10\rangle + \alpha_{11}|11\rangle$
- Measuring Qubit(s) causes *decoherence* in their state

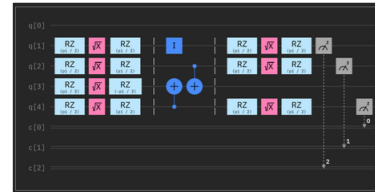


M. A. Nielsen and I. L. Chuang, Quantum Computation and Quantum Information: 10th Anniversary Edition.  
Cambridge University Press, 2010.

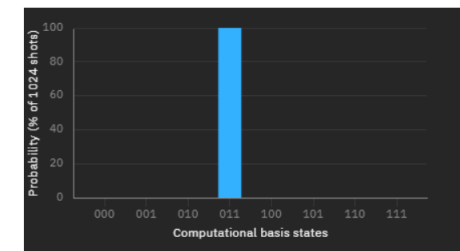
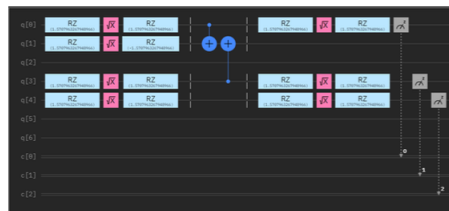
# Background

## Quantum Computation: Quantum Circuits

- *wire* does not necessarily correspond to a physical wire; it may correspond instead to the passage of time or perhaps to a physical particle such as a photon moving from one location to another through space:



- Transpiled, Probabilities: Expected and Reality:



# Background

## Quantum Noise

- *Quantum Noise a.k.a decoherence*

System	$\tau_Q$	$\tau_{op}$	$n_{op} = \lambda^{-1}$
Nuclear spin	$10^{-2} - 10^8$	$10^{-3} - 10^{-6}$	$10^5 - 10^{14}$
Electron spin	$10^{-3}$	$10^{-7}$	$10^4$
Ion trap ( $\text{In}^+$ )	$10^{-1}$	$10^{-14}$	$10^{13}$
Electron – Au	$10^{-8}$	$10^{-14}$	$10^6$
Electron – GaAs	$10^{-10}$	$10^{-13}$	$10^3$
Quantum dot	$10^{-6}$	$10^{-9}$	$10^3$
Optical cavity	$10^{-5}$	$10^{-14}$	$10^9$
Microwave cavity	$10^0$	$10^{-4}$	$10^4$

Figure: Different Qubit Technologies [1]

- $\tau_Q$  longest possible quantum operation time
- $\tau_{op}$  the time for which a system remains quantum-mechanically coherent
- $n_{op}$  the time it takes to perform elementary unitary transformations

# Background

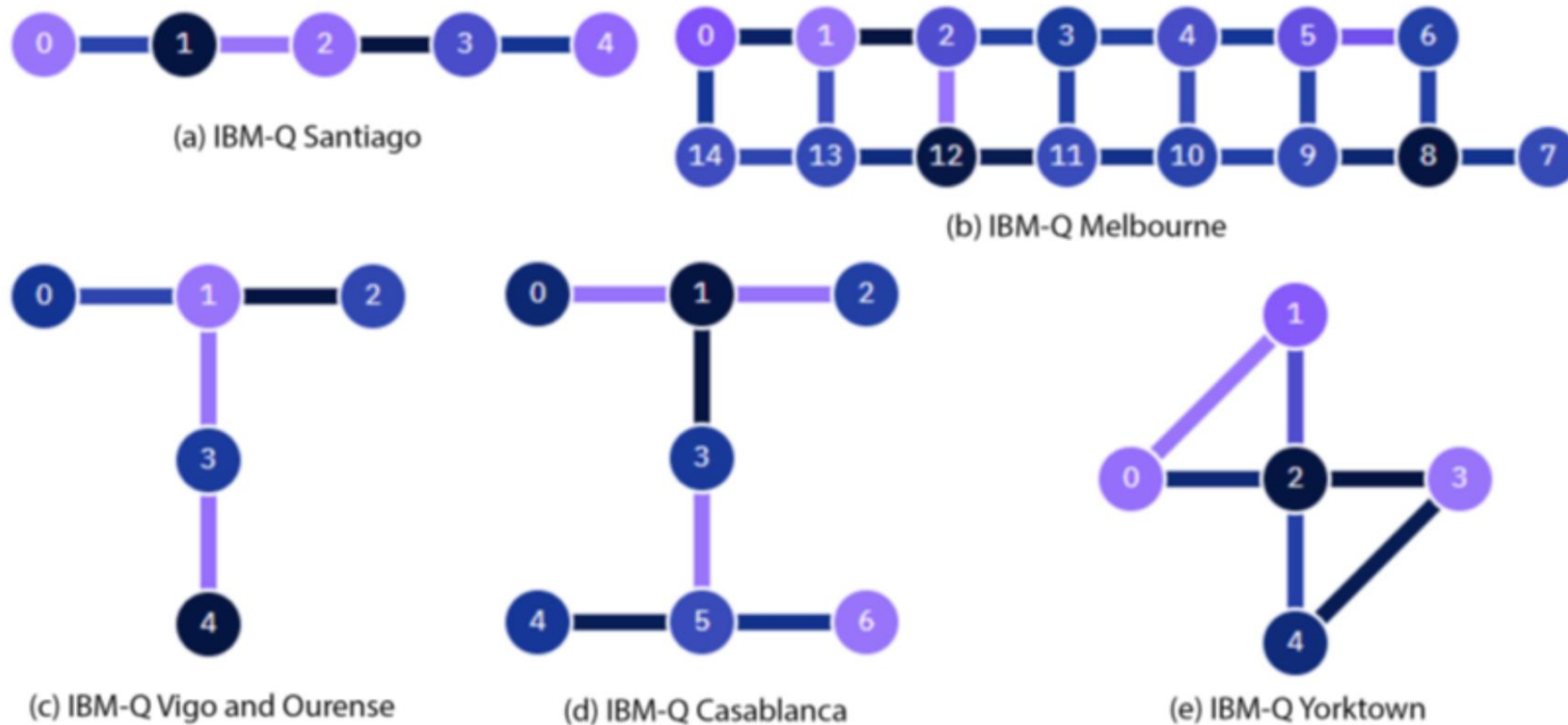
## Superconducting Qubit Properties

- Superconducting Quantum Computers: IBM, Google, IMEC, BBN Technologies, Rigetti, and Intel
- Qubits [5 – 128], QV: [8 – 128], CLOPS (Circuit Layer Operation per Second): [850 – 2.9K]
- Physical Calibration Data
  - 1 T1, T2: errors are the time that qubit holds superposition state and the time qubit is not affected by the environment (other qubits, vibration, radiation, etc.)
  - 2 Readout: a.k.a measurement error, errors affecting qubit state at the final reading phase
  - 3 CNOT: errors between two qubits CNOT operation

Qubit	T1 (us)	T2 (us)	Frequency (GHz)	Readout assignment error	Single-qubit Pauli-X error	CNOT error	Gate time (ns)
Q0	83.13	101.43	5.03	3.08E-02	5.62E-04	0.1:7.992e-3	0.1:305.778
Q1	108.78	127.32	5.128	1.32E-02	3.88E-04	1.0:7.992e-3; 1.3:1.193e-2; 1.2:6.757e-3	1.0:341.333; 1.3:497.778; 1.2:334.222
Q2	130.87	145.74	5.247	2.65E-02	5.80E-04	2.1:6.757e-3	2.1:298.667
Q3	53.2	80.75	5.303	2.52E-02	2.44E-04	3.4:1.733e-2; 3.1:1.193e-2	3.4:519.111; 3.1:462.222
Q4	24.08	24.49	5.092	4.89E-02	6.66E-04	4.3:1.733e-2	4.3:483.556

# Background

## Quantum Topology



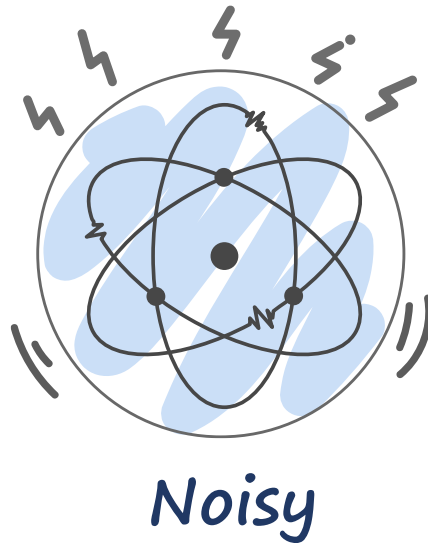
**Figure:** Geometric presentation of Qubit Connectivity on IBM-Q Machines



# Background

## Noisy Intermediate-Scale Quantum

- The noise issues are severe and inevitable in today's quantum computers [2,3]



[2] Bharti K, Cervera-Lierta A, Kyaw T H, et al. Noisy intermediate-scale quantum (NISQ) algorithms[J]. arXiv preprint arXiv:2101.08448, 2021.

[3] Preskill J. Quantum computing in the NISQ era and beyond[J]. Quantum, 2018, 2: 79.

# Motivation

## Noise in quantum computing

- **Noise from fundamental components in a quantum computer**
  - Qubits
  - Quantum gates

# Motivation

## Compiled circuits

**Compiled circuits could be various based on the same logical circuit.**

# Motivation

## Noise in quantum computing

- Thus, the noise may come from various compiled circuits, including:
  - Not deterministic topology
  - A large number of compiled circuits

# Motivation

## Noisy quantum circuit execution

- **No tool** to reflect the hidden noise
- The common practice to obtain less-noisy execution results is still a **trial-and-error** process with **a long queuing time** of up to hours.

# Pilot Study

## Participants

- Five users in quantum computing
  - P1 - researchers in Northwest National Laboratory,
  - P2-4 - experts from three different universities,
  - P5 - Ph.D. student majoring in quantum computing.
- P1-2 - quantum chemistry.
- P3 - quantum machine learning
- P4-5 - quantum hardware analysis

# Datasets

## Calibration data

- Relaxation time  $T_1$
- Dephasing time  $T_2$
- Qubit readout error
- Gate error rate.

# Datasets

compiled physical circuits

- **Real instructions output from the physical circuit**
  - Usage of each qubit and quantum gate



# Approach

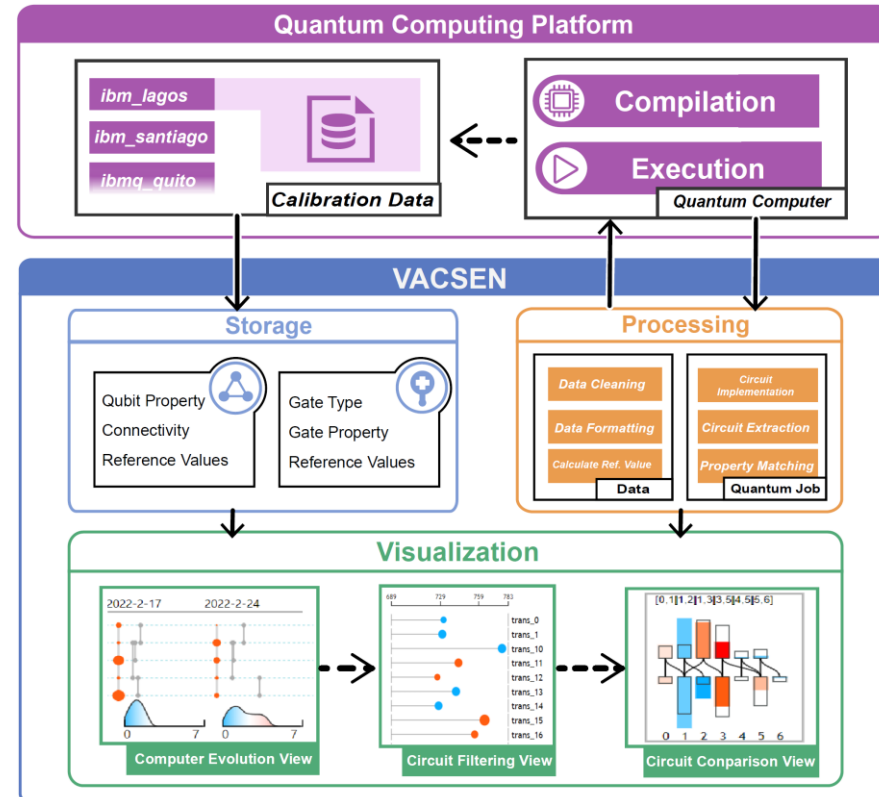
## Design Requirements

- **Quantum computer selection**
  - Facilitate the temporal analysis of various noise.
  - Make users aware of the latest noise.
- **Compiled circuit selection**
  - Provide an overview of all compiled circuits.
  - Enable a detailed comparison of the usages of qubits and gates.
  - Support a real-time compilation and fidelity validation.
- **User Interaction**
  - Provide flexible user interactions and intuitive visual designs

# Approach

## Visualization system

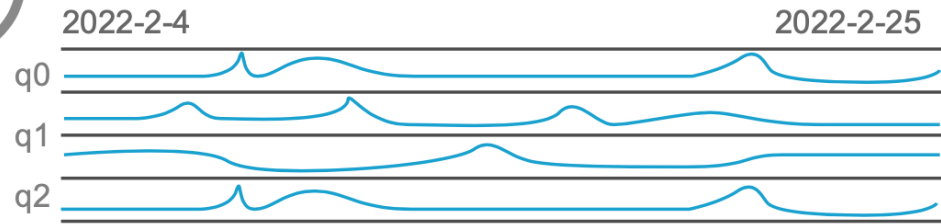
- VACSEN consists three modules: **storage module**, **processing module**, and **visualization module**. The system is connected to an external **cloud quantum computing platform**.



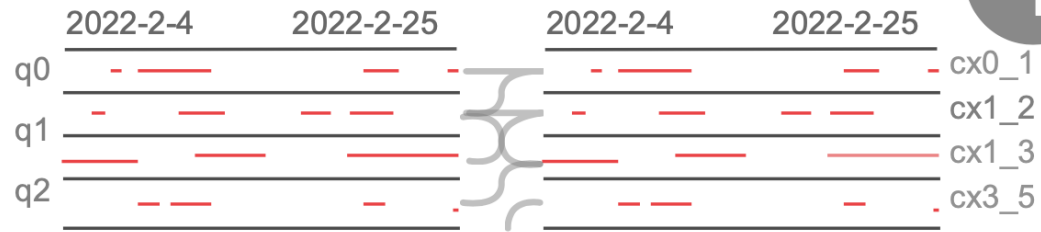
# Approach

## Alternative design

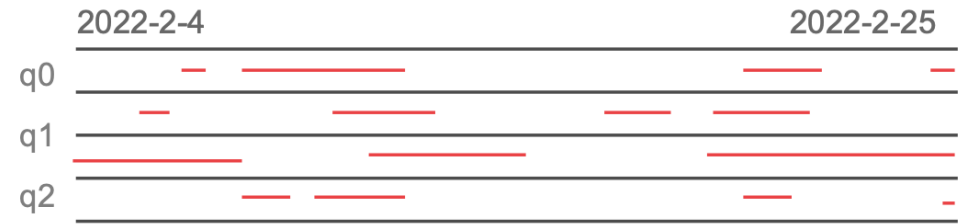
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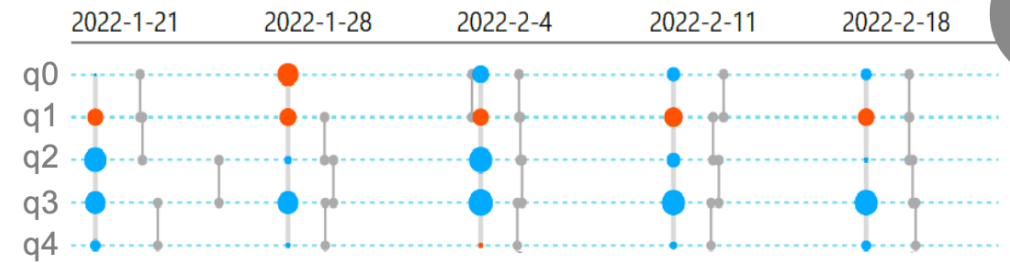
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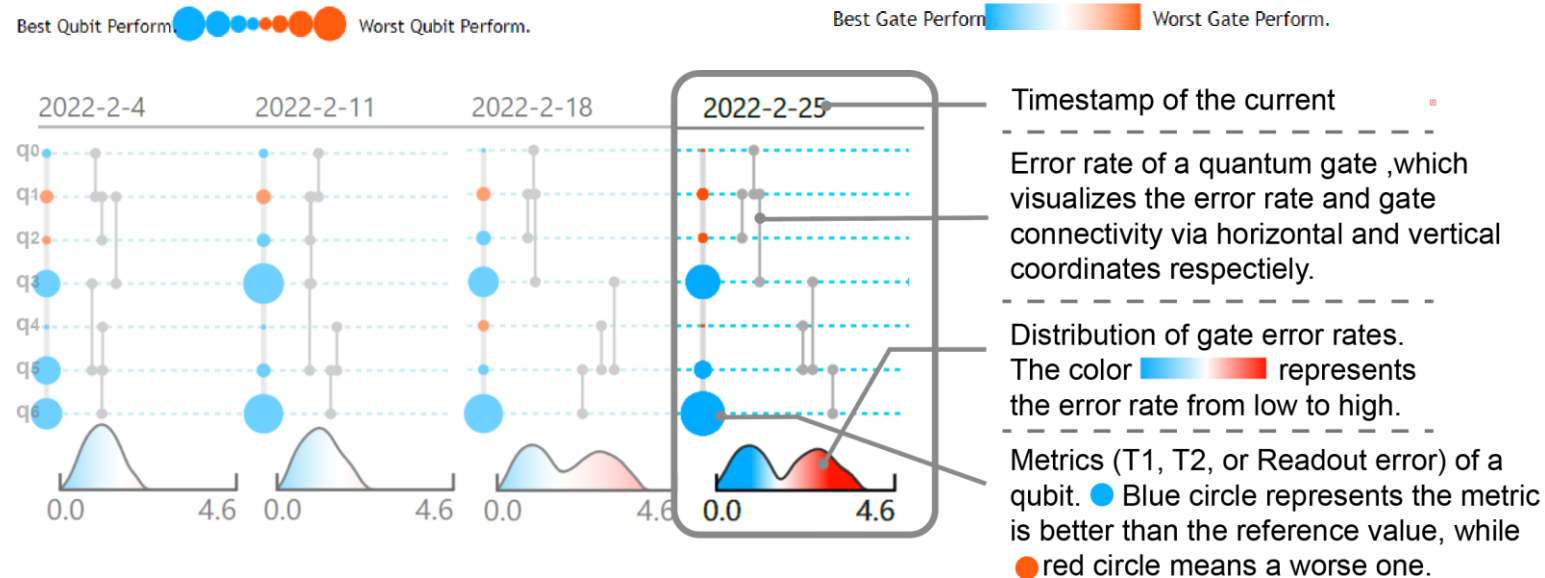


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# Approach

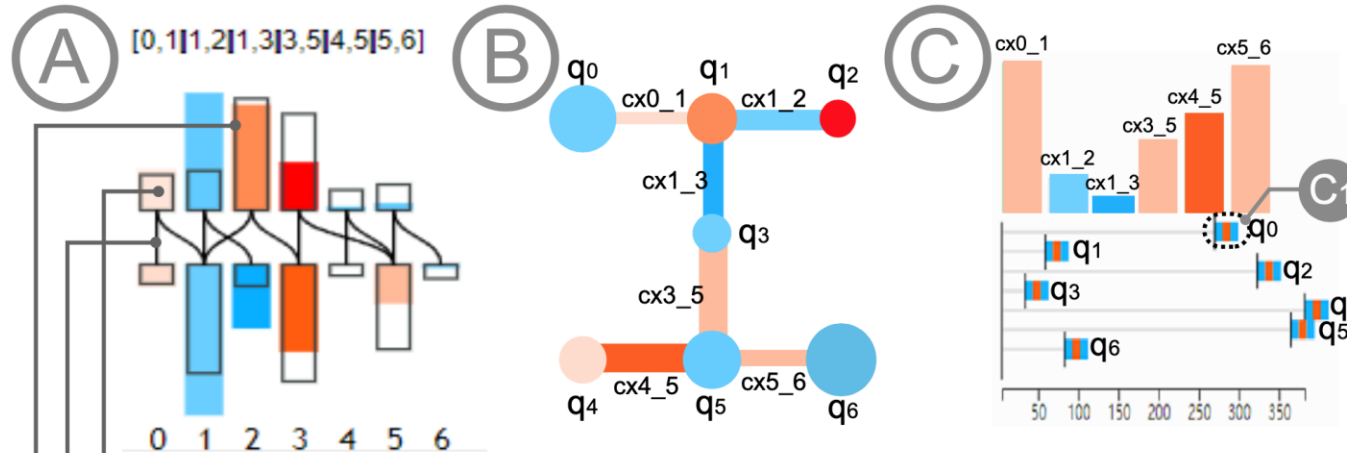
## Circuit-like design


- **Challenge:** It is challenging to temporally visualize the complex noise factors as well as the qubit topological connections along a timeline.
- We propose a **circuit-like design** to portray the quantum computer noise in each time stamp.





# Approach

## Circuit Comparison View



Qubits and quantum gates. Bar height denotes the usage counts, while the color  visualizes the metric values (gate: error rate; qubit: T1, T2, or readout error).


Gate connectivity. Upper endpoint of the curved line is for the gate, while two lower endpoints are for two qubits physically connected with the gate.

Reference values.  indicates the usage count is higher than the reference value, while  depicts a lower usage count.



# Approach

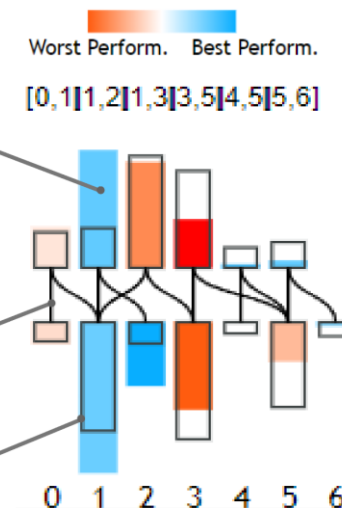
## Coupled bar chart design

- **Challenge:** It is difficult to visually summarize a large number of the compiled circuits regarding the various noises and enable users to select the most appropriate one shortly.
- We proposed **coupled bar chart** to support the in-depth comparison of multiple compiled circuits.

Qubits and quantum gates. Bar height denotes the usage counts, while the color  visualizes the metric values (gate: error rate; qubit: T1, T2, or readout error).

Gate connectivity. Upper endpoint of the curved line is for the gate, while two lower endpoints are for two qubits physically

Reference values.  indicates the usage count is higher than the reference value, while  depicts a lower usage count.



# Hands-on (20 mins)

Platform

- **Demo showcase**

# Hands-on (20 mins)

## Platform

- Online interface:
  - <https://vacsensystem.github.io/>



# Hands-on (20 mins)

## Tasks - for Quantum Computer Selection

- Find the best-quality quantum computer regarding qubit's relaxation time  $T_1$ .
- Find the best-quality quantum computer regarding qubits' dephasing time  $T_2$ .
- Find the best-quality quantum computer regarding qubits' readout error.
- Find the best-quality quantum computer regarding gates' error rate.
- According to the tasks above, find the most suitable computer for the further execution.

# Hands-on (20 mins)

## Tasks – for Compiled Circuit Selection

- Find the circuits of interest regarding the quality of building blocks.
- Find the circuits of interest regarding the quality of building blocks.
- Compare and highlight the compiled circuits with good gate-quality for the final execution.
- Compare and highlight the compiled circuits with good qubit-quality for the final execution.

**Hands-on (20 mins)**

***Let's start!***

# Evaluation

## Case study

- **Quantum circuits:**
  - Two-qubit circuit
  - Shor's algorithm
- **Participants:**
  - Two domain experts from universities
- **Tasks:**
  - Perform quantum circuit execution with noise awareness provided by VACSEN

# Evaluation

## User interview

- **Participants:**
  - 12 domain experts

- **Tasks:**

T1	Find the best-quality quantum computer regarding qubit's relaxation time $T1$ .
T2	Find the best-quality quantum computer regarding qubits' dephasing time $T2$ .
T3	Find the best-quality quantum computer regarding qubits' readout error.
T4	Find the best-quality quantum computer regarding gates' error rate.
T5	According to the tasks above, find the most suitable computer for the further execution.
T6	Find the circuits of interest regarding the quality of building blocks.
T7	Find the circuits of interest regarding the circuit depth.
T8	Compare and highlight the compiled circuits with good gate-quality for the final execution.
T9	Compare and highlight the compiled circuits with good qubit-quality for the final execution.

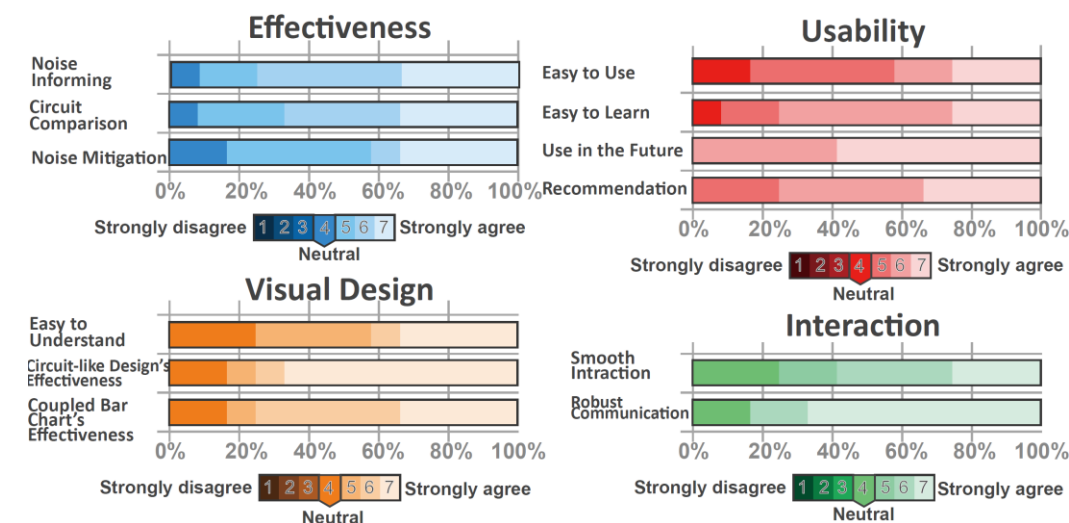
- **Methods**

- Rating for VACSEN
- Feedback

# Evaluation

## Results for the user interview

- Likert-scale rating:



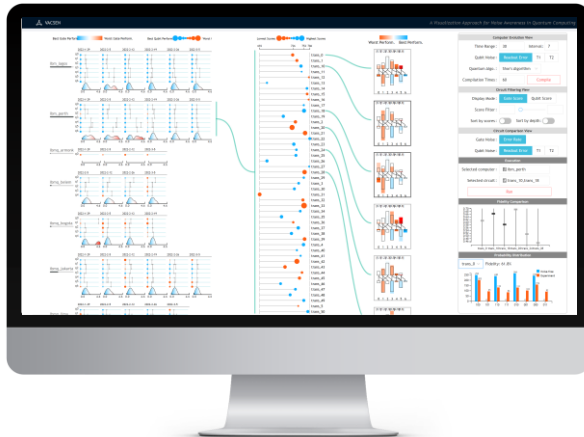
- Feedback:

*"I believe VACSEN will be helpful for our current research topic of quantum network routing. We can utilize VACSEN to host our different routing algorithm and get more accurate results as it can reflect various noises in real-time."*

# Conclusion



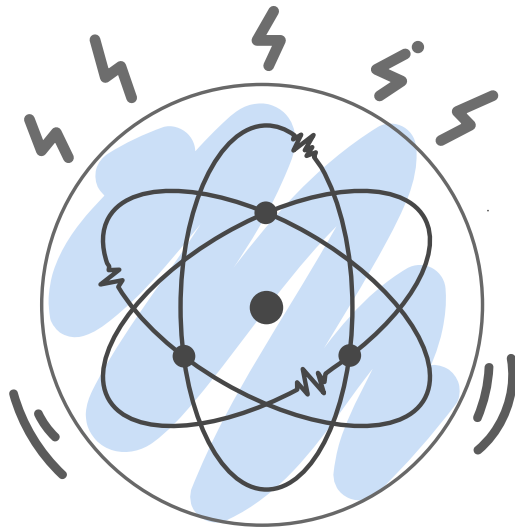
# Conclusion



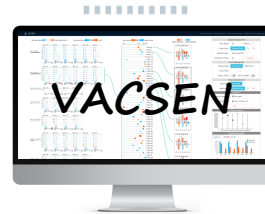
**VACSEN** supports a real-time noise awareness of quantum computers and compiled circuits, leading to a better circuit execution with higher fidelity



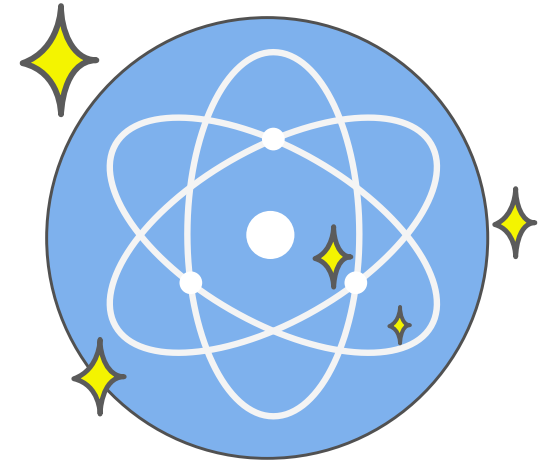
# Conclusion



*Noisy*



*Inform users of the quantum noise*



*Reliable*

# Thank you for your attention!

Q&A

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Online demo: <https://vacsen.github.io/>  
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My homepage: <https://shaolun-ruan.com/>

