ESWeek 2022 Tutorial:

VACSEN: A Visualization Approach for Noise Awareness in Quantum Computing

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VACSEN: A Visualization Approach for Noise Awareness in Quantum Computing

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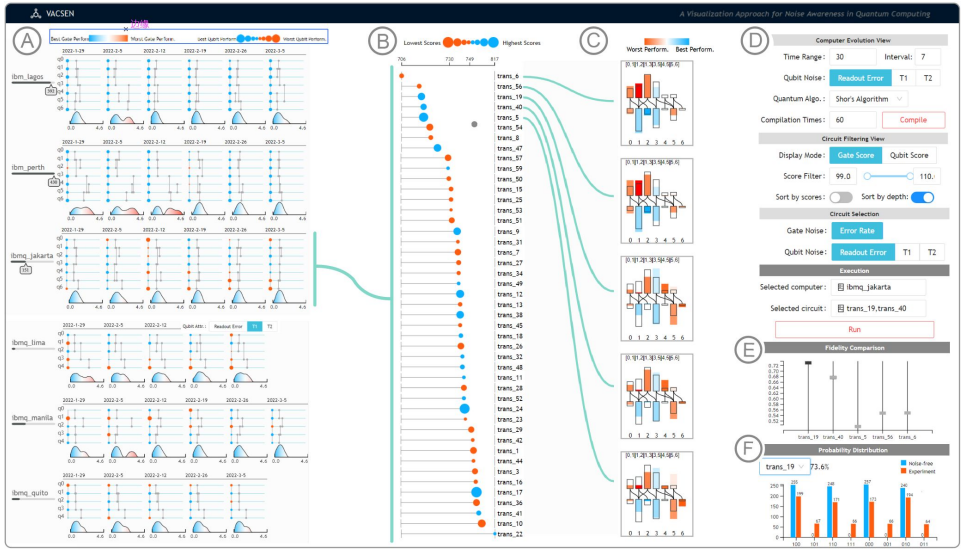
VIS 2022

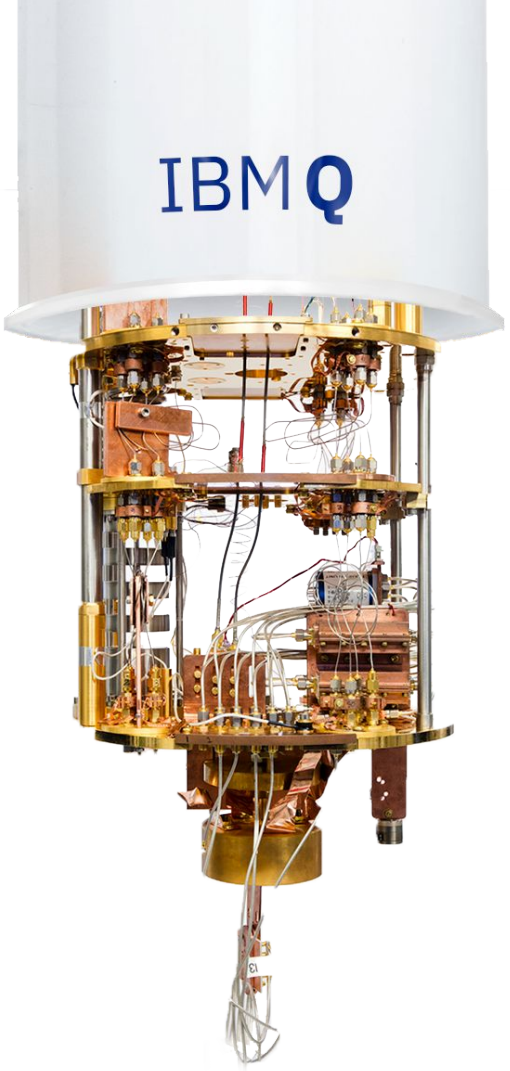
- Background
- Motivation
- Approach
- Hands-on practice
- Evaluation
- Conclusion



Background

Quantum computing

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

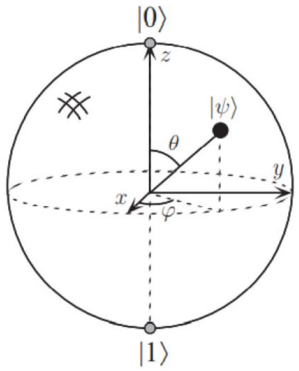


[1] Arute F, Arya K, Babbush R, et al. Quantum supremacy using a programmable superconducting processor[J]. Nature, 2019, 574(7779): 505-510.

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 Topology

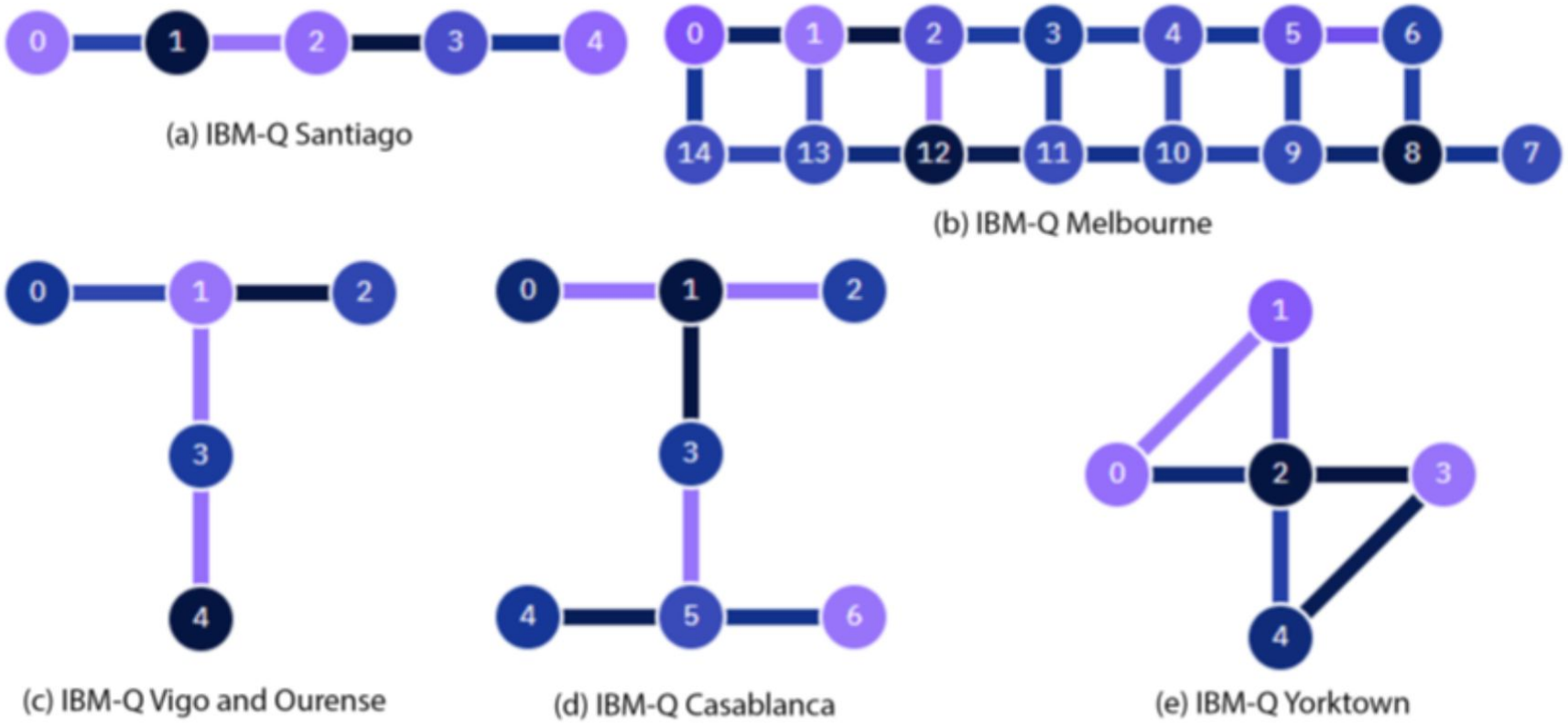
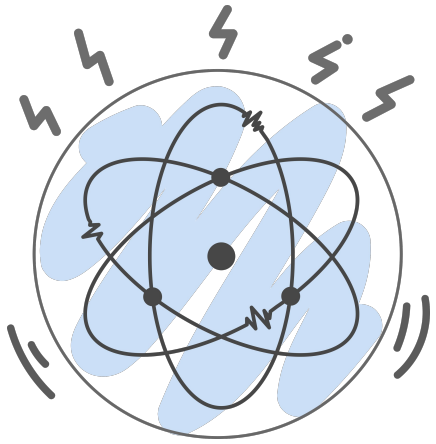


Figure: Geometric presentation of Qubit Connectivity on IBM-Q Machines

Background

Noisy Intermediate-Scale Quantum

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



Noisy

[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.

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

Motivation

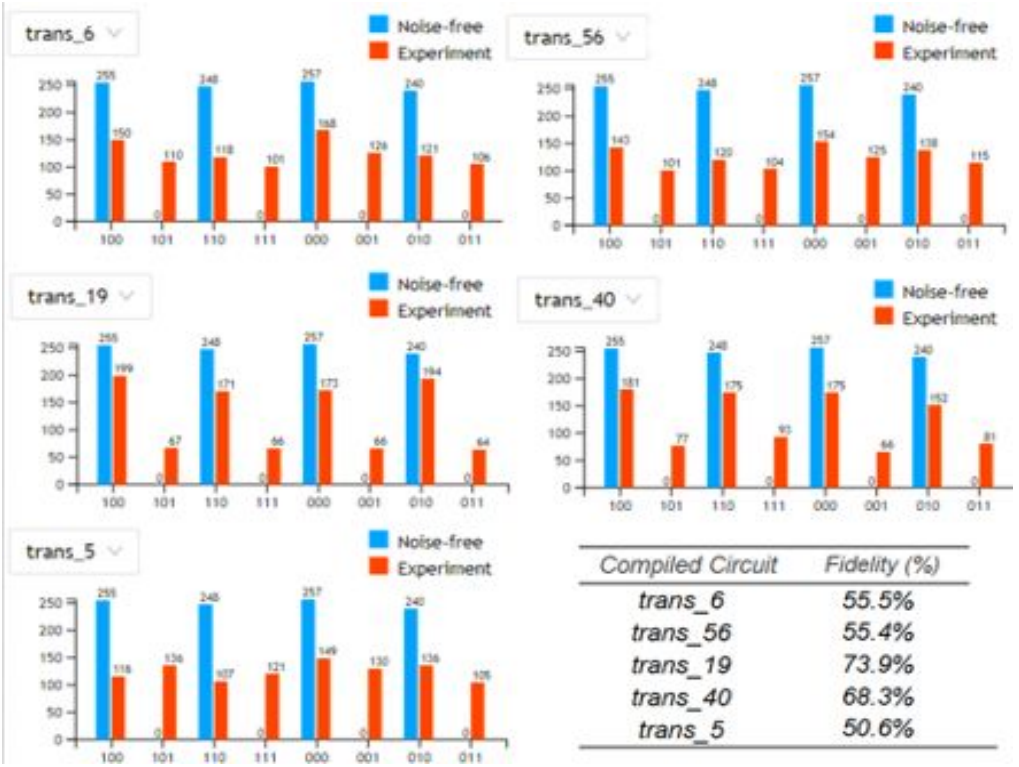
Challenges for Noise Awareness in Quantum Computing

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

Motivation

Challenges for Noise Awareness in Quantum Computing

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



Compiled Circuit	Fidelity (%)
trans_6	55.5%
trans_56	55.4%
trans_19	73.9%
trans_40	68.3%
trans_5	50.6%

Background

Quantum Computing Workflow

- Quantum Circuit Implementation
- Quantum Computer Selection
- Qubit Mapping & Execution

Background

Quantum Computing Workflow

- Quantum Circuit Implementation
- Quantum Computer Selection
- Qubit Mapping & Execution

Motivation

Noise in quantum computing

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

Background

Quantum circuit implementation - Step 1

Users need to select a suitable quantum computer for execution.

- It is totally up to users.
- Selecting a quantum computer with the shortest queuing time is the rule-of-thumbs, without the awareness of quantum noise.

Background

Quantum circuit implementation - Step 2

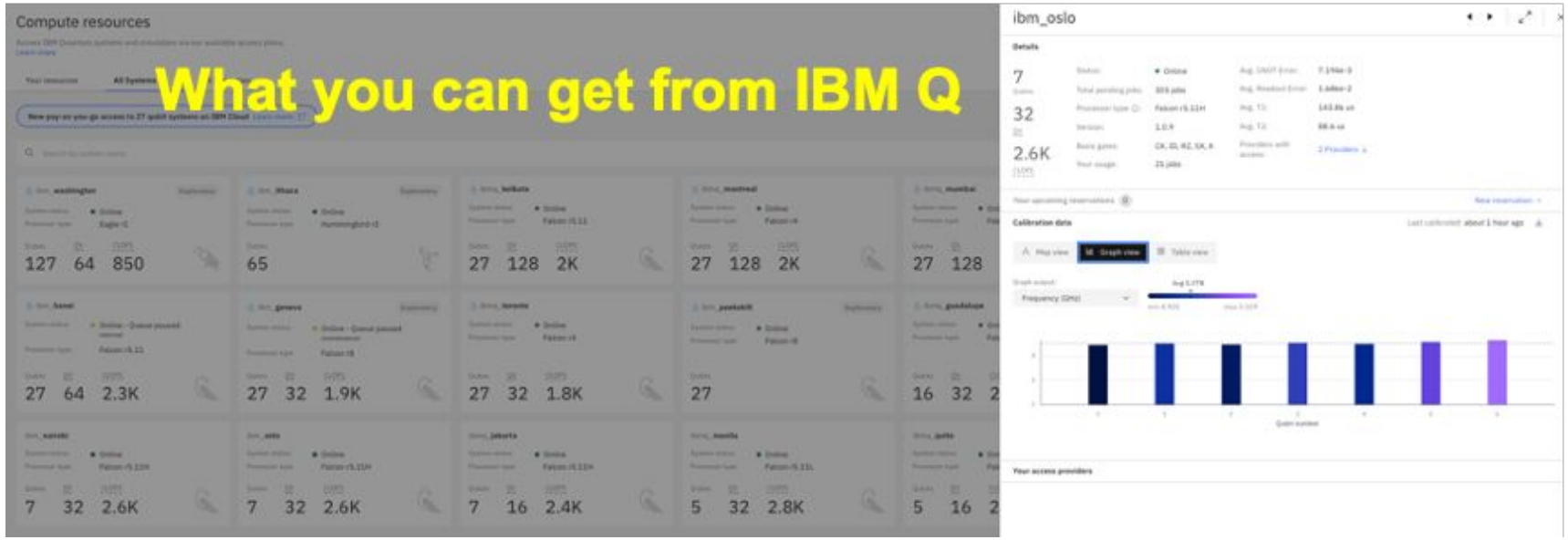
The transpiled quantum circuit will be various

- Transpiled circuits may be even hundreds.
- Different transpiled circuits have different levels of noise.
- Users cannot take the noise levels into account, making the high-fidelity result acquisition a trial-and-error process.

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 T1
- Dephasing time T2
- 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.

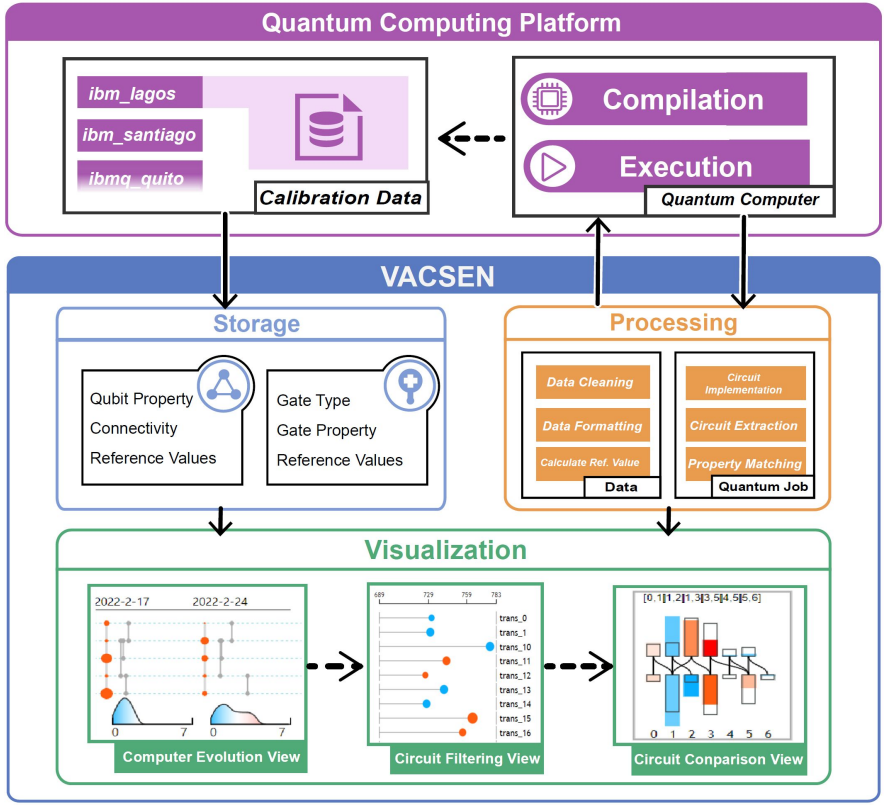
- Compiled circuit selection
  - Provide an overview of all compiled circuits.
  - Enable a detailed comparison of the usages of qubits and gates.
  - Support a real-time compilation and fidelity validation.

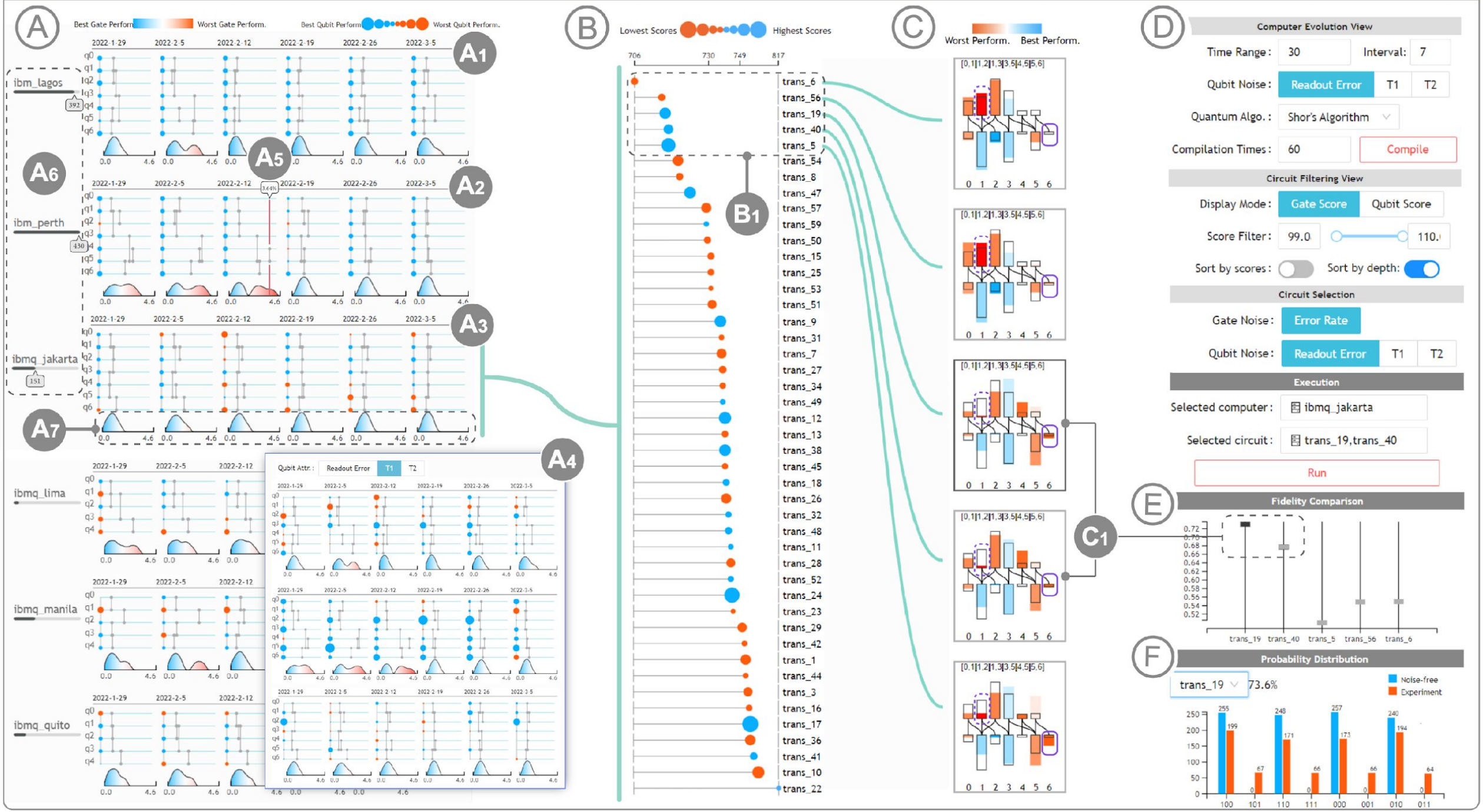
- User Interaction
  - Provide flexible user interactions and intuitive visual designs

Approach

Visualization system

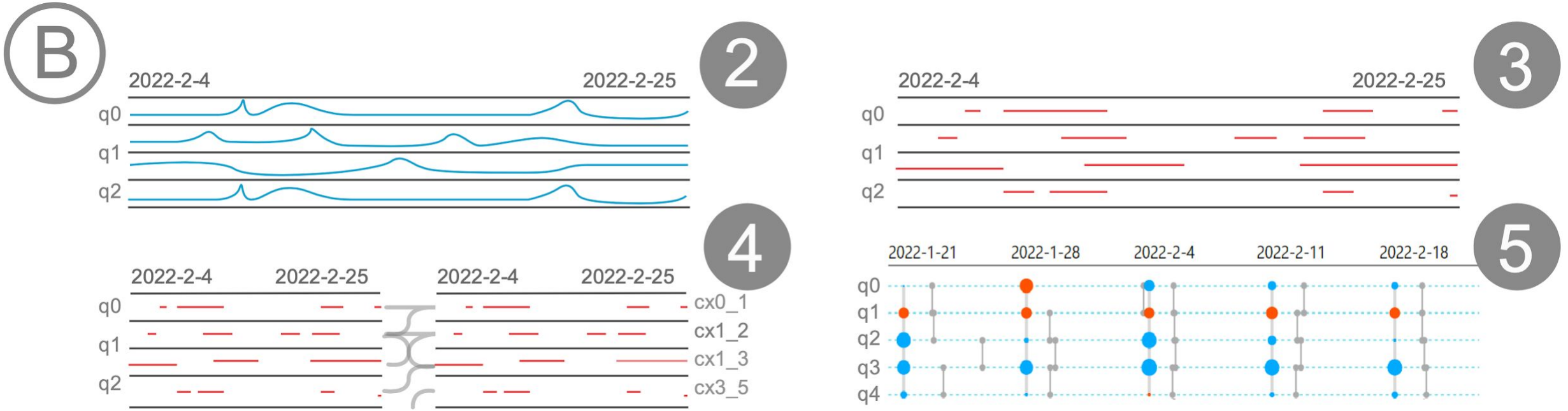
- VACSEN consists three modules: storage module, processing module, and visualization module. The system is connected to an external cloud quantum computing platform.




A
Best Gate Perform.
Worst Gate Perform.
Best Qubit Perform.
Worst Qubit Perform.
A1
A2
A3
A4
A5
A6
A7
ibm_lagos
ibm_perth
ibmq_jakarta
ibmq_lima
ibmq_manila
ibmq_quito
Qubit Attr.:
Readout Error
T1
T2
B
Lowest Scores
Highest Scores
B1
trans_6
trans_56
trans_19
trans_40
trans_5
C
Worst Perform.
Best Perform.
C1
D
Computer Evolution View
Time Range: 30
Interval: 7
Qubit Noise: Readout Error T1 T2
Quantum Algo.: Shor's Algorithm
Compilation Times: 60
Compile
Circuit Filtering View
Display Mode: Gate Score Qubit Score
Score Filter: 99.0 110.
Sort by scores:
Sort by depth:
Circuit Selection
Gate Noise: Error Rate
Qubit Noise: Readout Error T1 T2
Execution
Selected computer: ibmq_jakarta
Selected circuit: trans_19,trans_40
Run
E
Fidelity Comparison
F
Probability Distribution
trans_19
73.6%
Noise-free
Experiment

Approach

Computer Evolution View -- Alternative Designs

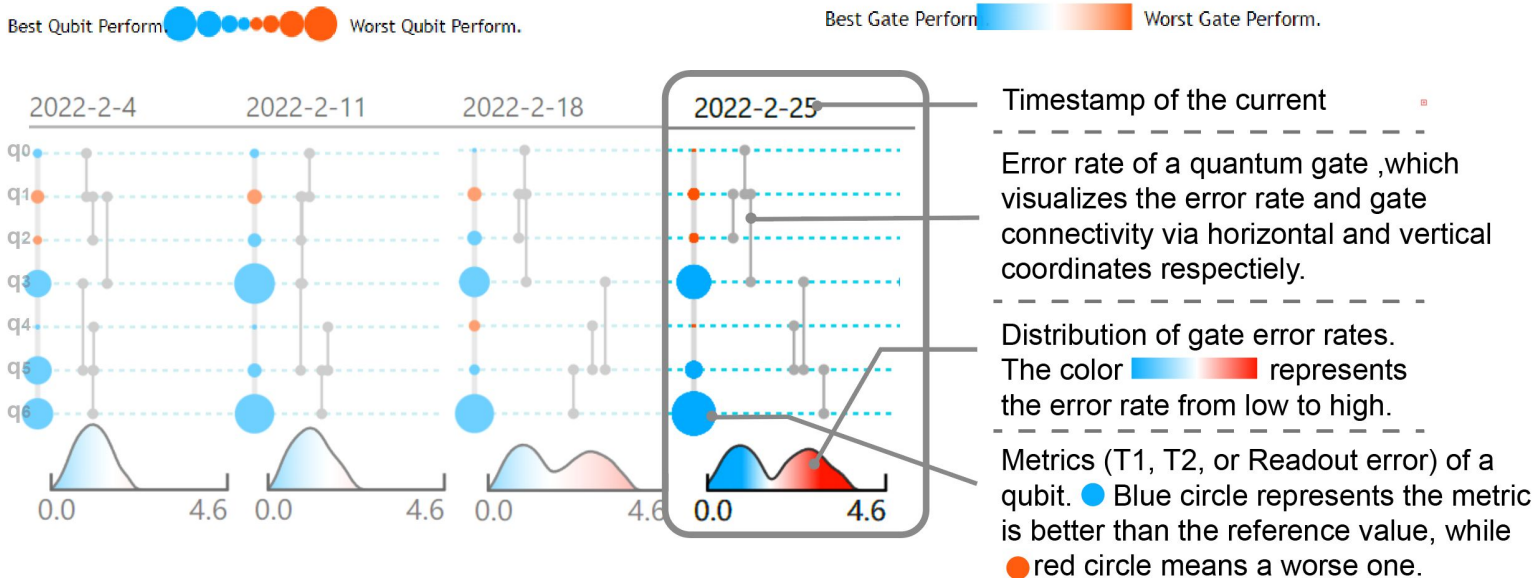


Approach

Computer Evolution View -- 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.

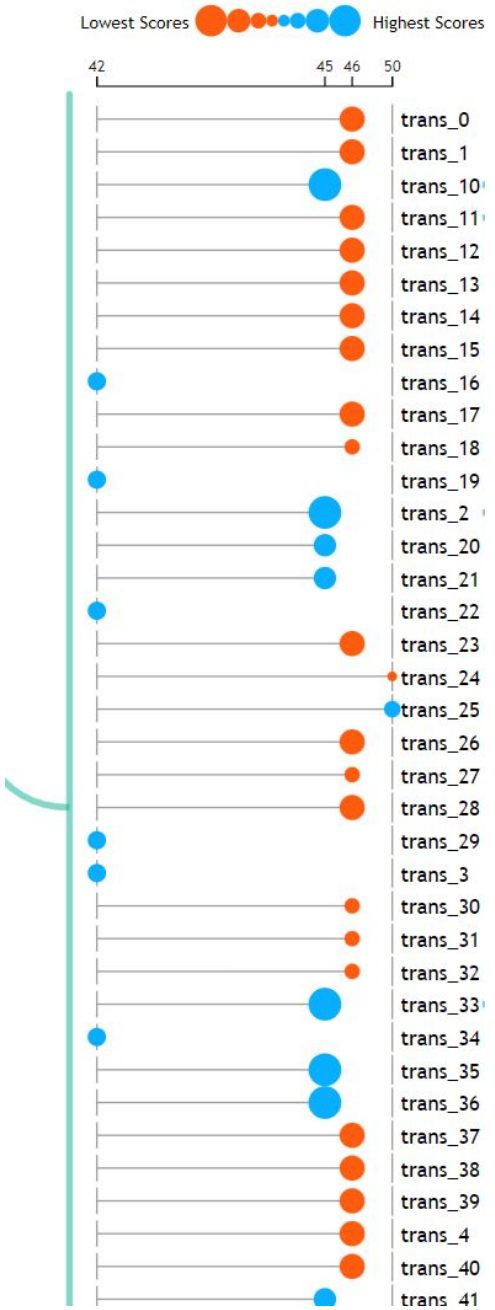


Approach

Circuit Filtering View

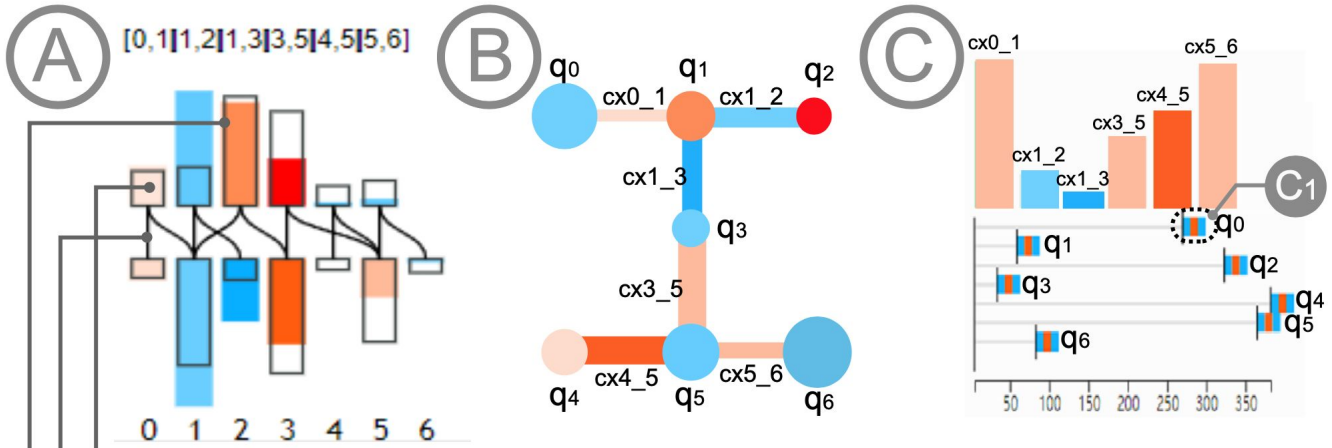
- Challenge: It is difficult to filter even hundreds of compiled circuit regarding their corresponding quality.

We design a circuit filtering view, which can enable users to select the optimal compiled circuit shortly. The area of the circle represents the qubit/gate scores for measuring the general noise of the qubit or gate. The horizontal axis of each circle indicates the depth of the compiled circuit.



Approach

Circuit Comparison View -- Alternative Designs



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.

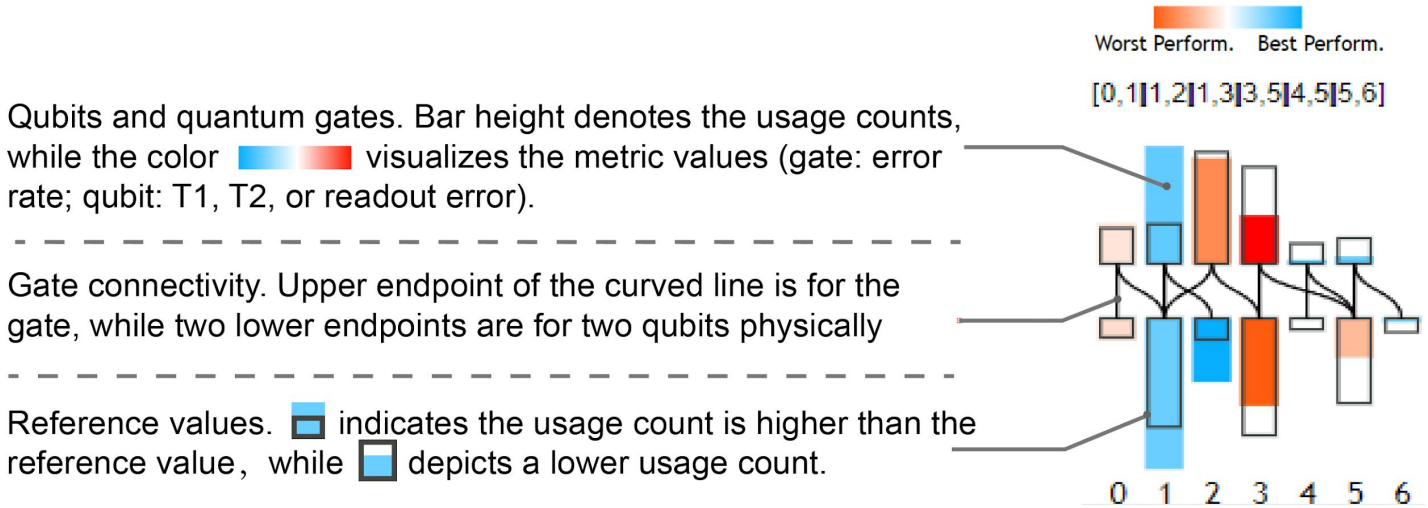
Reference values. indicates the usage count is higher than the reference value, while depicts a lower usage count.

Approach

Circuit Comparison View -- Coupled Bar Chart Design

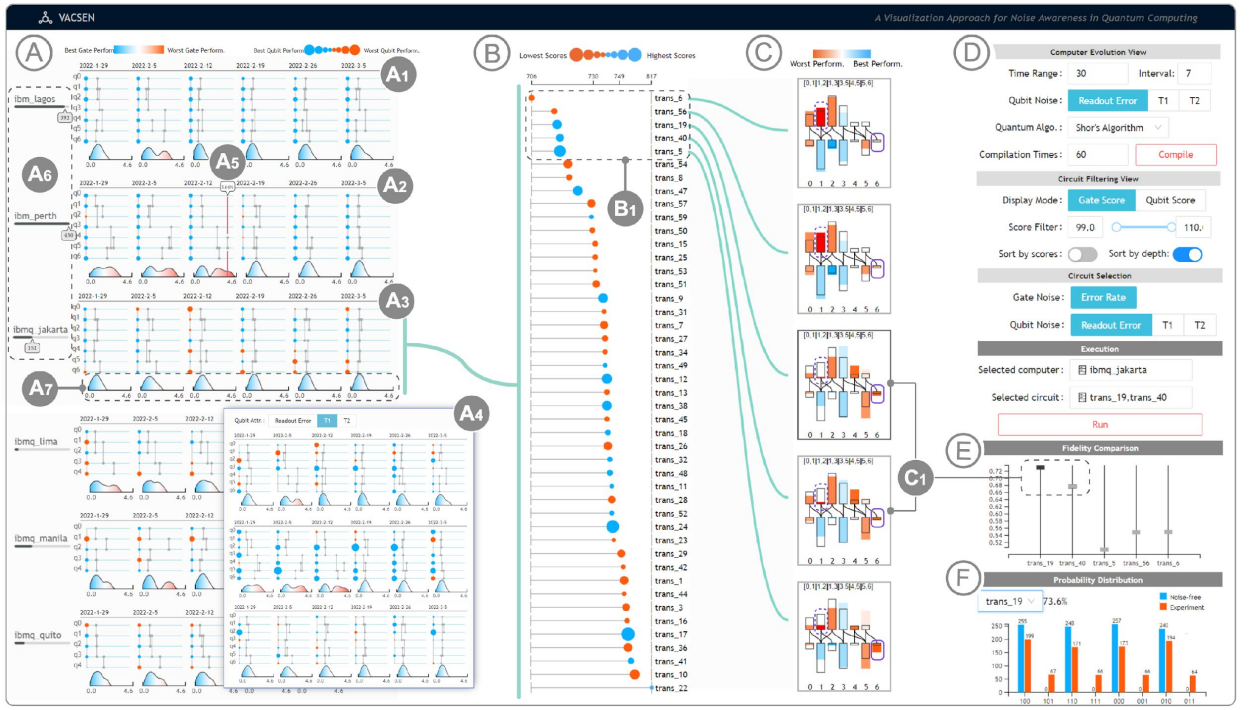
- Challenge: It is difficult to visually summarize a large number of the compiled circuits regarding the various noises and enable users to select the most appropriate one shortly.

- We proposed coupled bar chart to support the in-depth comparison of multiple compiled circuits.



Demo

- Online System:
  - https://vacsensystem.github.io/



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:

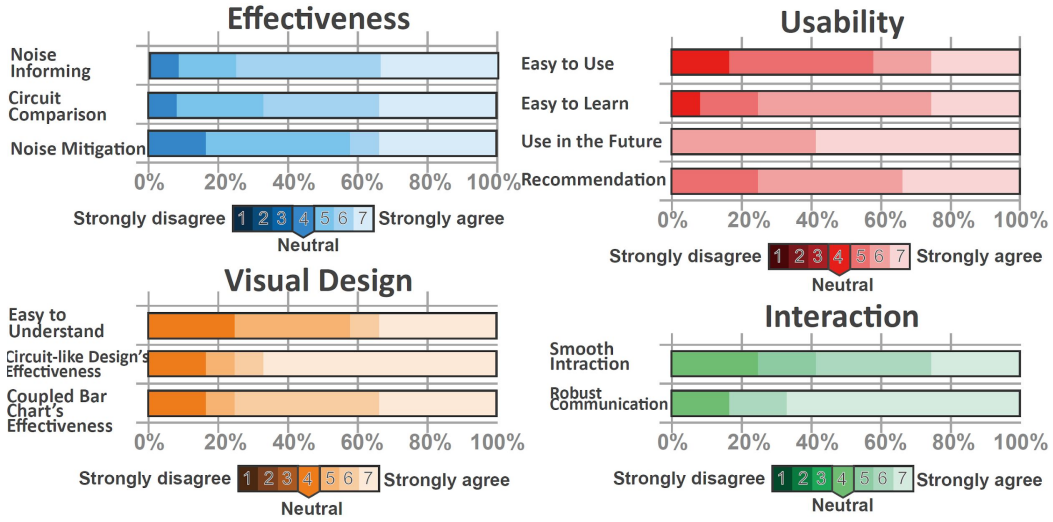
T1	Find the best-quality quantum computer regarding qubit's relaxation time *T1*.
T2	Find the best-quality quantum computer regarding qubits' dephasing time *T2*.
T3	Find the best-quality quantum computer regarding qubits' readout error.
T4	Find the best-quality quantum computer regarding gates' error 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."

Hands-on (10 mins)

Task 1 – Quantum Computer Selection

- Find the best-quality quantum computer regarding qubit's relaxation time T1.
- Find the best-quality quantum computer regarding qubits' dephasing time T2.
- 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 (10 mins)

Task 2 – Compiled Circuit Selection

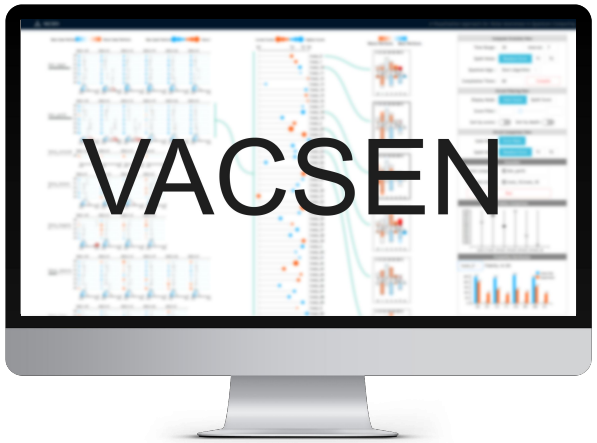
- Find the circuits of interest regarding the quality of building blocks.
- Find the circuits of interest regarding the quality of building blocks.
- Compare and highlight the compiled circuits with good gate-quality for the final execution.
- Compare and highlight the compiled circuits with good qubit-quality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

Hands-on (10 mins)

- Online System:
  - https://vacsensystem.github.io/

Let's start!

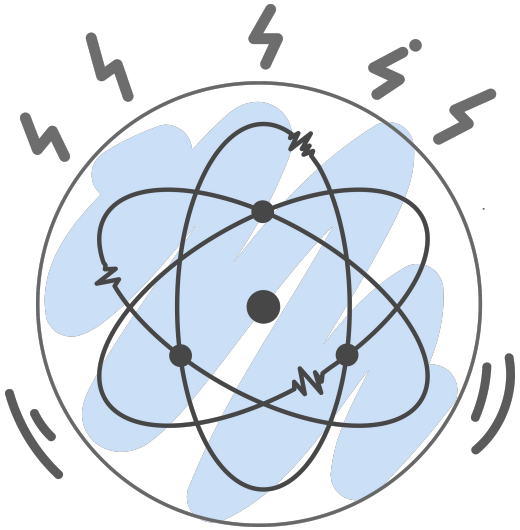
Conclusion



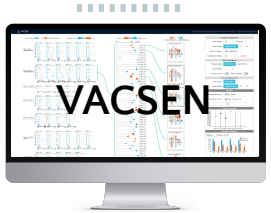
Conclusion

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

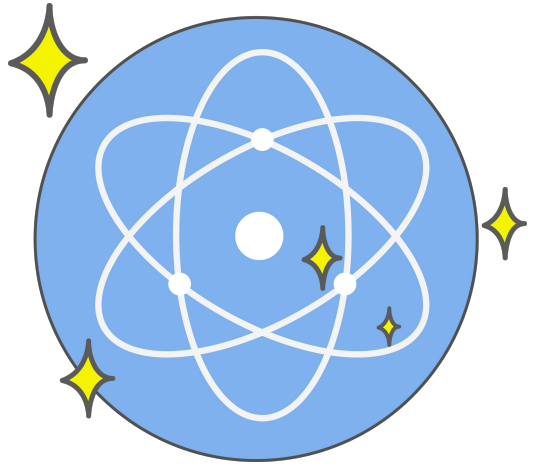
Conclusion



Noisy



Inform users of the quantum noise



Reliable

Thank you for your attention!

Q&A

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