VACSEN: A Visualization Approach for Noise Awareness in Quantum Computing


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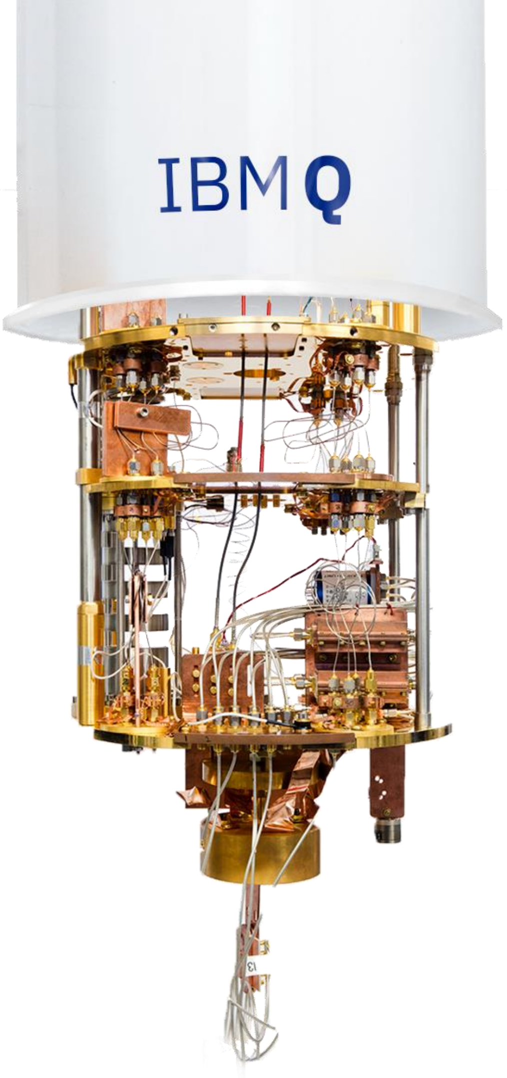
- Background
- Motivation
- Approach
- Hands-on practice
- Evaluation
- Conclusion

IEEE QUANTUM WEEK

Background

Quantum computing

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

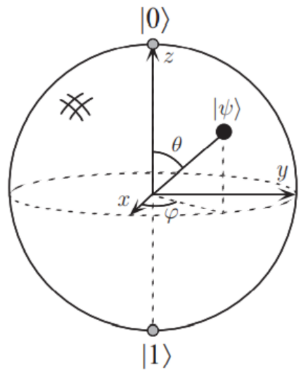


[1] Arute F, Arya K, Babbush R, et al. Quantum supremacy using a programmable superconducting processor[J]. Nature, 2019, 574(7779): 505-510.

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

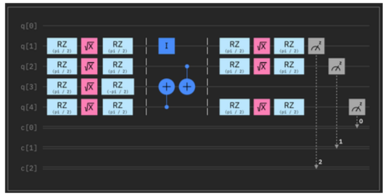


M. A. Nielsen and I. L. Chuang, Quantum Computation and Quantum Information: 10th Anniversary Edition. Cambridge University Press, 2010.

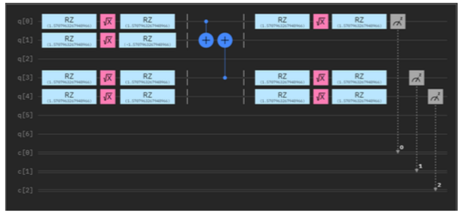
Background

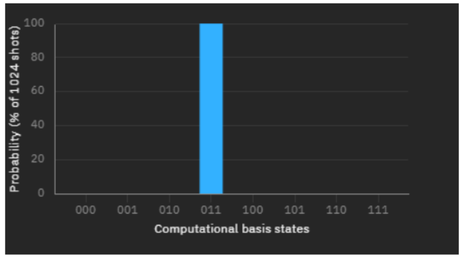
Quantum Computation: Quantum Circuits

- *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	τ_Q	τ_{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 (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]

- τ_Q longest possible quantum operation time
- τ_{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

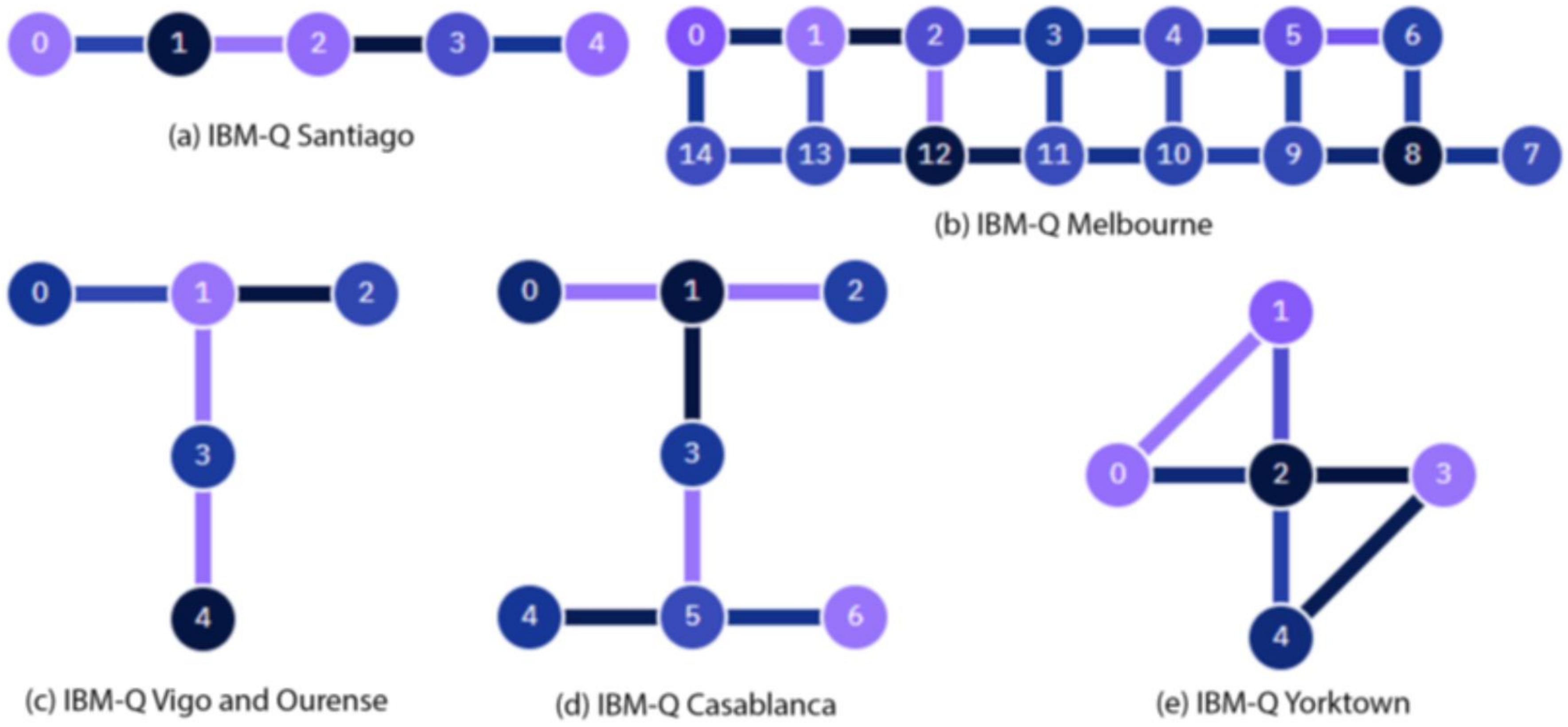
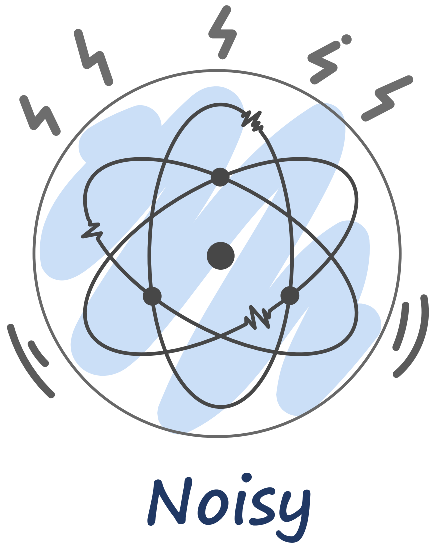


Figure: Geometric presentation of Qubit Connectivity on IBM-Q Machines

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 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.

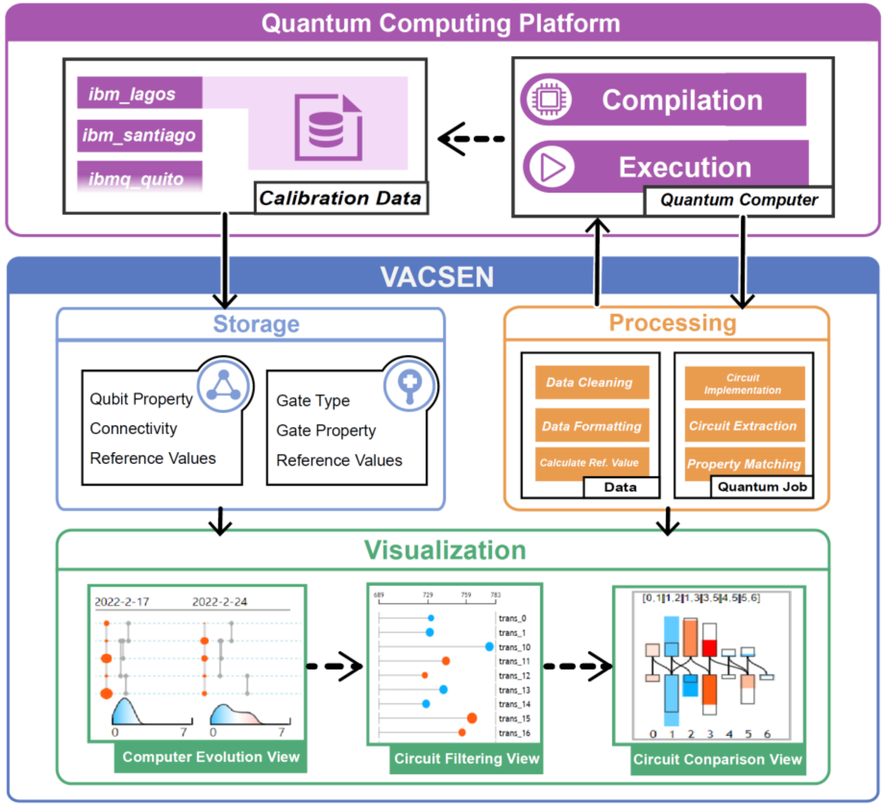
- **Compiled circuit selection**
  - Provide an overview of all compiled circuits.
  - Enable a detailed comparison of the usages of qubits and gates.
  - Support a real-time compilation and fidelity validation.

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

Approach

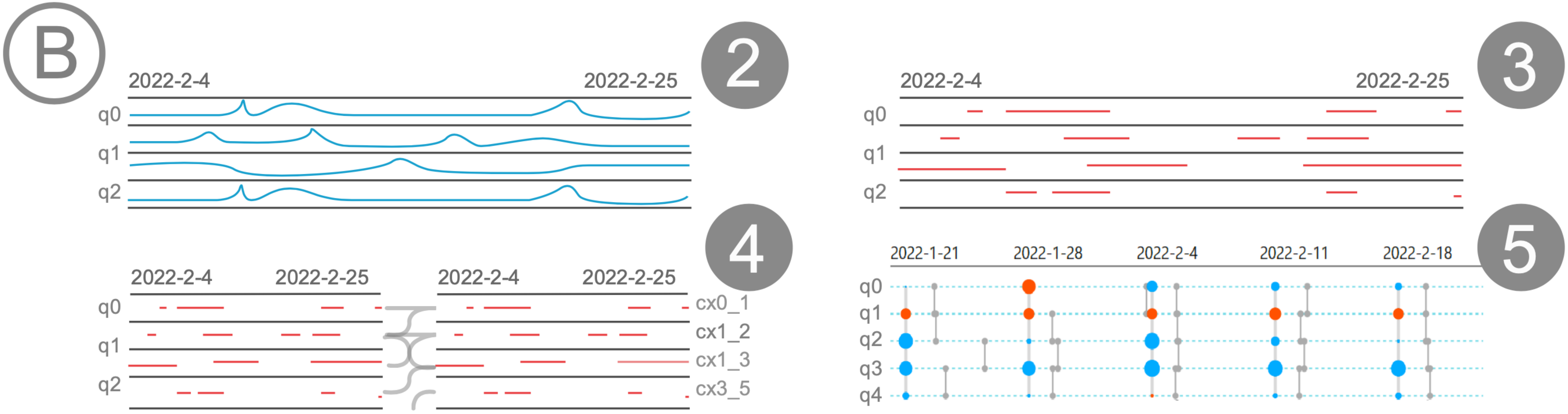
Visualization system

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



Approach

Alternative design

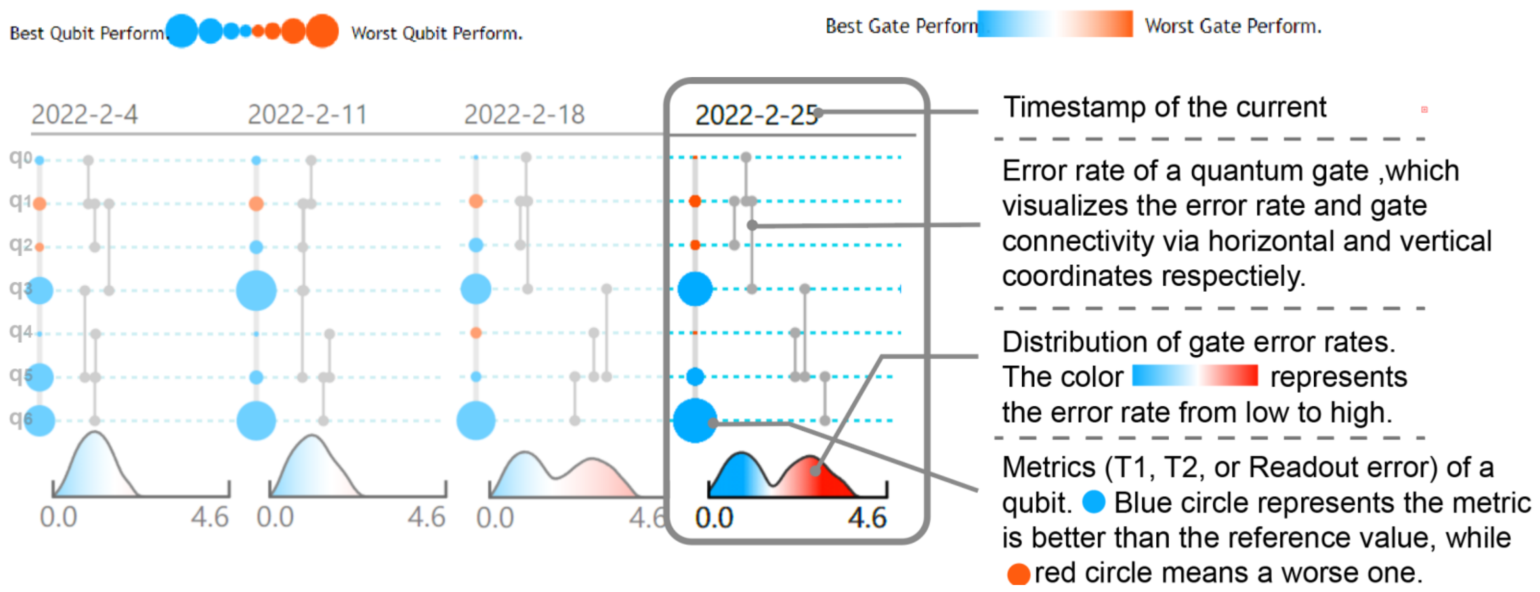


Approach

Circuit-like design

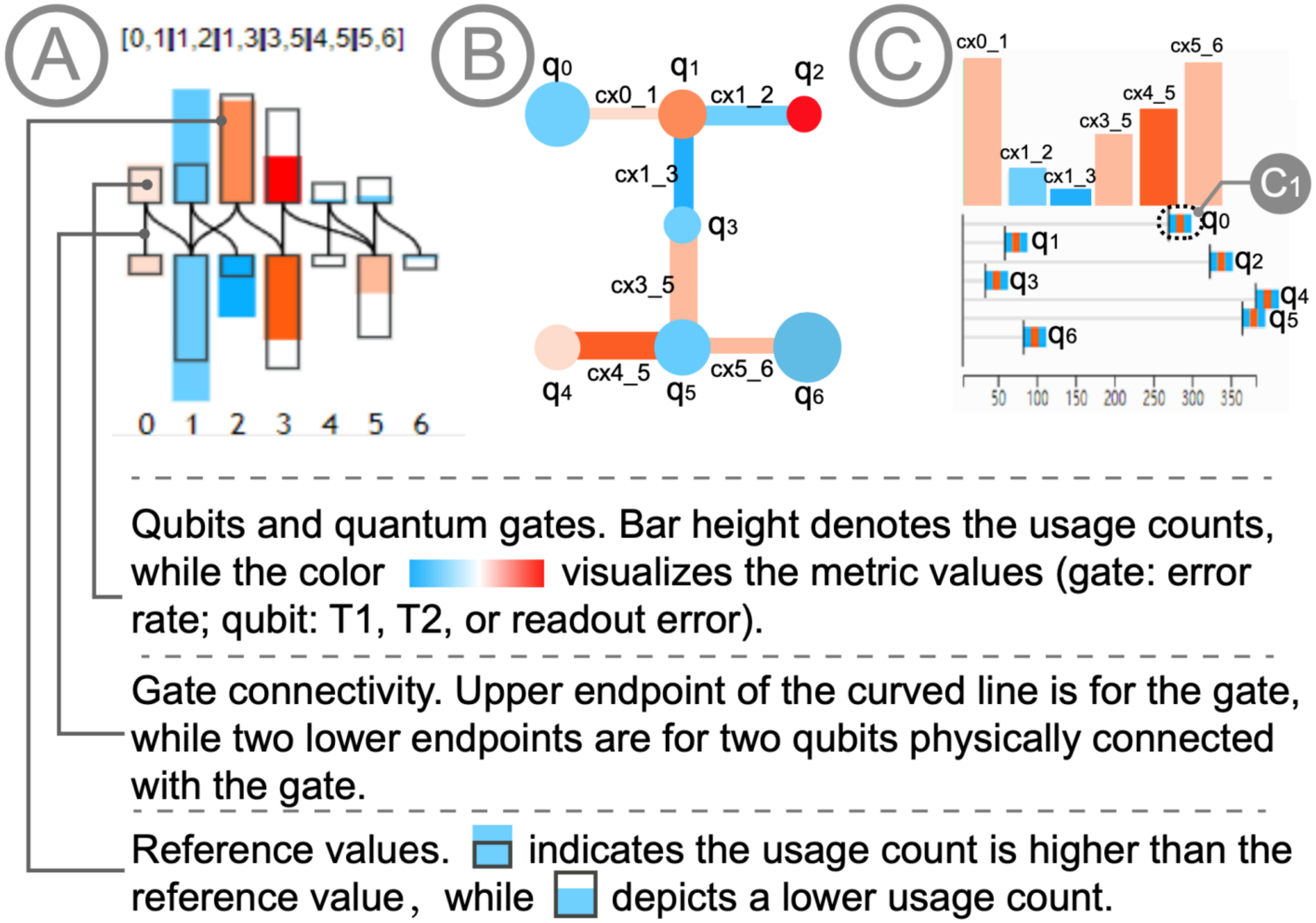
- **Challenge**: It is challenging to temporally visualize the complex noise factors as well as the qubit topological connections along a timeline.

- We propose a **circuit-like design** to portray the quantum computer noise in each time stamp.



Approach

Circuit Comparison View

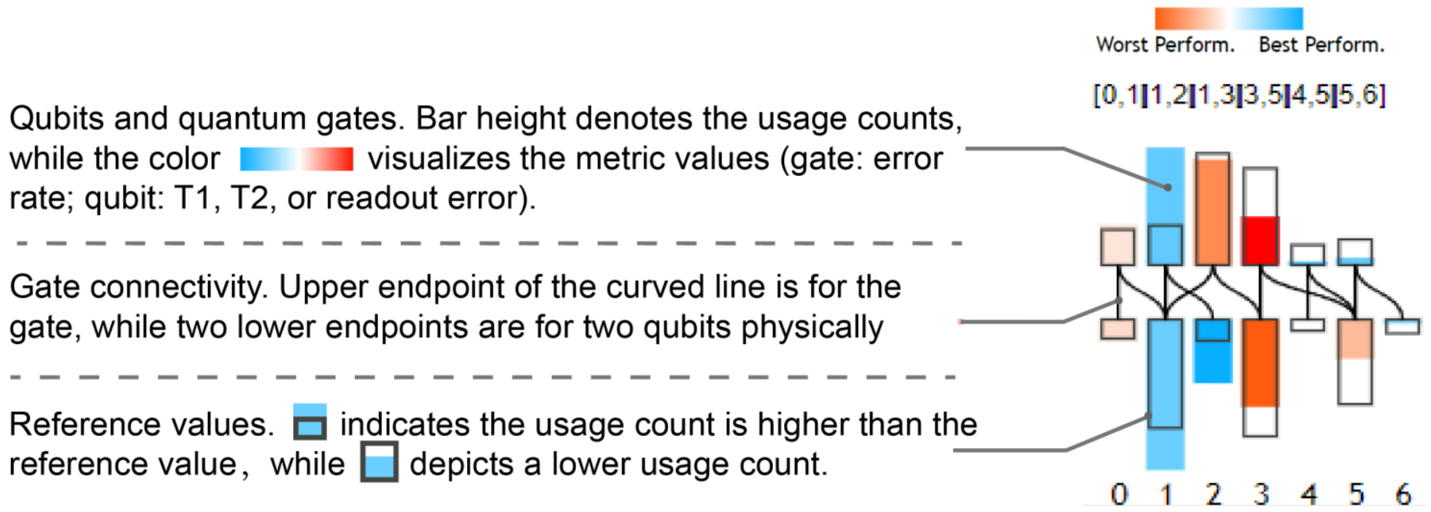


Approach

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.



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 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 (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:**

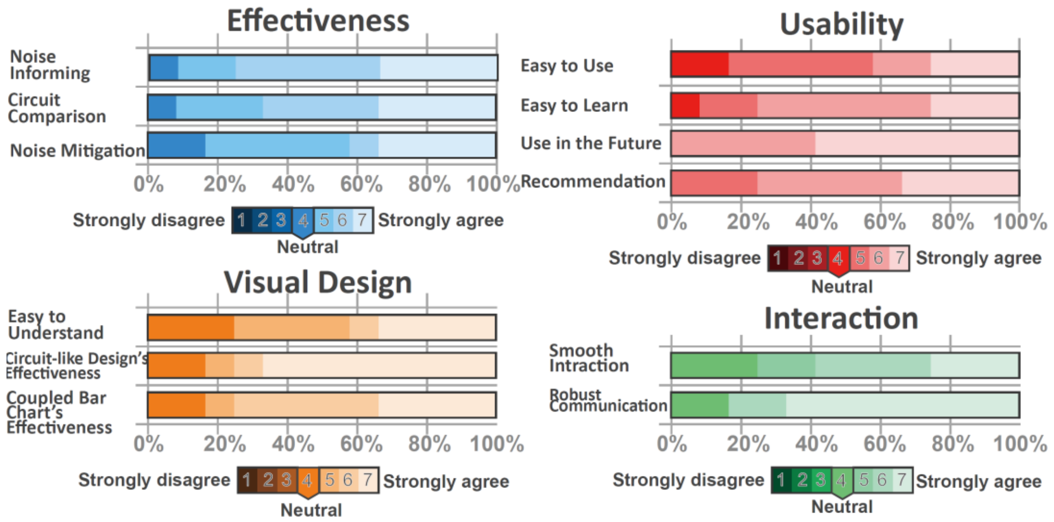
T1	Find the best-quality quantum computer regarding qubit's relaxation time *T1*.
T2	Find the best-quality quantum computer regarding qubits' dephasing time *T2*.
T3	Find the best-quality quantum computer regarding qubits' readout error.
T4	Find the best-quality quantum computer regarding gates' error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

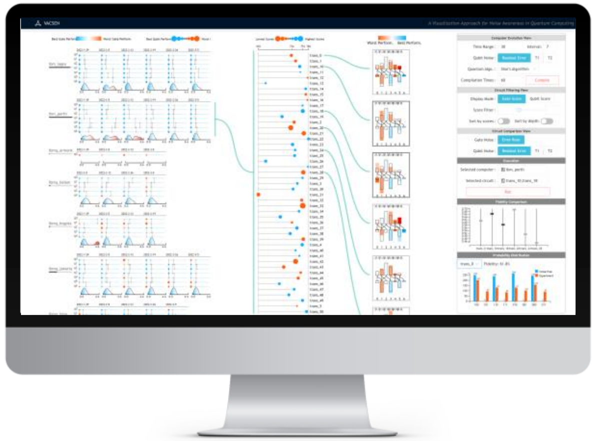


- **Feedback:**

"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."

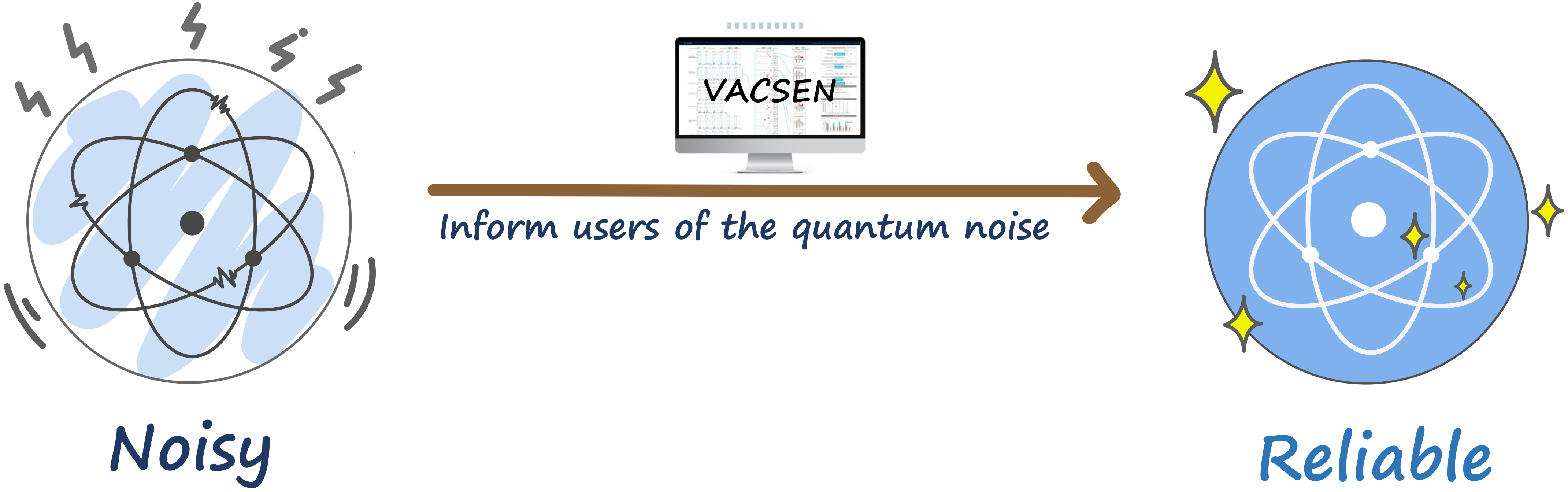
Conclusion

Conclusion



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

Conclusion



Thank you for your attention!

Q&A

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