Japan Academy Prize to:

Yasunobu NAKAMURA Director, RIKEN Center for Quantum Computing Professor, Department of Applied Physics, Graduate School of Engineering, The University of Tokyo	and	Jaw-Shen TSAI Team Leader, Superconducting Quantum Simulation Research Team, RIKEN Center for Quantum Computing Professor, Graduate School of Science, Tokyo University of Science Professor, Research Institute for Science and Technology, Tokyo University of Science

for "Pioneering Research on Superconducting Qubits and Their Quantum Control" (Joint Research)

Outline of the work:

Drs. Yasunobu Nakamura and Jaw-Shen Tsai were the first to achieve quantum-bit (qubit) operation on superconducting circuits and demonstrated the controllability of quantum states in superconducting qubit devices, contributing significantly to the development of superconducting quantum computers. Further, they have played pivotal roles in elucidating the fundamental physics of superconducting qubits and also in leading exploratory research on microwave quantum optics and hybrid quantum systems based on superconducting qubits.

In quantum information science, particularly in quantum computing, the fundamental principles of quantum mechanics are applied not only to elucidate the physics of advanced electronic devices for improving their performance but also to disclose the potential of quantum information processing schemes that would enable extremely efficient computation, not achievable by conventional technology. Unlike traditional computers where "bits" can only take values 0 or 1 as the basic unit of information, quantum computers use qubits that can represent any superposition of 0 and 1. By controlling the qubits with high precision and taking the advantage of various unique characteristics of the quantum world, such as superposition, quantum entanglement, and projective measurement, computations can be performed based on algorithms unique to quantum computers.

As shown by the pioneering work on quantum entanglement, to which the Nobel Prize in Physics was awarded in 2022, fundamental ideas in quantum information science emerged during the second half of the 20th century. They paved the way for the invention of prime factorization algorithms and quantum error correction protocols in the mid-1990s. Consequently, interest in quantum computation grew, triggering an intensive search for physical systems that would enable quantum computing.

Various approaches were taken in the early phases of exploration to realize quantum bits, such as the use of the states of light, including its polarization, path, and the number of photons, the nuclear spins of organic molecules in solutions, and ions trapped in vacuum; some of these approaches have been continuously investigated since then. However, Drs. Nakamura and Tsai focused on the tunneling process of the Cooper pair, an electron pair that can tunnel through a superconducting junction (the Josephson junction) without energy dissipation. By combining this tunneling process with the single-electron charging effect, they successfully controlled charge quantum states in the circuit called the Cooper pair box, where a single Cooper pair tunnels in and out of a small superconducting island; this work done in 1999 was the first realization of the superconducting charge qubit. Later, they demonstrated a two-bit gate-controlled operation between superconducting qubits. Moreover, Dr. Nakamura, together with collaborators from the Delft University of Technology, realized the first superconducting magnetic flux qubit in 2003. Drs. Nakamura and Tsai investigated also the decoherence processes of qubits and improved qubit readout, contributing significantly to the research and development of superconducting quantum computers.

Recently, worldwide efforts to develop quantum computers have taken place, including the intensive developments of superconducting computers by corporate giants such as IBM and Google. Furthermore, research activities utilizing neutral or ionized atoms trapped in vacuum and semiconductor quantum dots have been actively promoted and have driven progress in quantum information science. Consequently, superconducting quantum computers with a scale of over 100 qubits have been realized. Although the non-negligible error rate in these systems remains an issue, various schemes are in development to mitigate this problem, including the hybrid usage of quantum and classical computers on a small scale. Additionally, active studies are being carried out to develop large-scale fault-tolerant quantum computers by adopting advanced quantum error correction techniques. Humankind is now approaching the dawn of a new age of science and technology where the full potential of multi-qubit large-scale physical systems can be utilized by controlling their quantum states at will.

While superconducting qubits play key roles in quantum computers, these qubits have emerged also as a state-of-the-art resource for quantum control and measurement in the microwave frequency range because of their excellent characteristics. Circuits combining low-loss superconducting resonators and waveguides have contributed significantly to the emergence of the “microwave quantum optics” field, in which the control of the quantum state of microwave modes is achieved at the level of a single photon. From the very beginning of the field, Drs. Nakamura and Tsai played leading roles in elucidating coherent interactions between superconducting qubits and microwave photons in a resonator, opening a field of “circuit quantum electrodynamics”. Further, they pioneered the field of “waveguide quantum electrodynamics” where interactions between qubits and microwave photons propagating on waveguides are studied. They succeeded also in the generation and detection of a single microwave photon using a superconducting qubit as well as in the generation and detection of squeezed vacuum states using the Josephson parametric amplifiers. These results have been applied to the control and measurement of elementary excitations in physical systems, such as magnons (the quanta of collective excitations of spins in magnetic materials), phonons (the quanta of mechanical vibrations in nanomechanical devices) and other “hybrid quantum systems.”

As described earlier, Drs. Nakamura and Tsai pioneered superconducting qubits by realizing a quantum two-level system on an artificial and macroscopic electric circuit and significantly contributed to the progress of superconducting quantum computers. They have also greatly contributed to the advancement of fundamental physics of superconducting qubits, making them deserving awardees of the Japan Academy Prize.

List of Main Publications

1. “Fast readout and reset of a superconducting qubit coupled to a resonator with an intrinsic Purcell filter”, Y. Sunada, S. Kono, J. Ilves, S. Tamate, T. Sugiyama, Y. Tabuchi, and Y. Nakamura, Phys. Rev. Appl. **17**, 044016 (2022).
2. “Autonomous quantum error correction in a four-photon Kerr parametric oscillator”, S. Kwon, S. Watabe, and J. S. Tsai. npj Quantum Inf. **8**, 40 (2022).
3. “Quantum circuits for exact unitary *t*-designs and applications to higher-order randomized benchmarking”, Y. Nakata, D. Zhao, T. Okuda, E. Bannai, Y. Suzuki, S. Tamiya, K. Heya, Z. Yan, K. Zuo, S. Tamate, Y. Tabuchi, and Y. Nakamura, PRX Quantum **2**, 030339 (2021).
4. “Fast parametric two-qubit gates with suppressed residual interaction using a parity-violated superconducting qubit”, A. Noguchi, A. Osada, S. Masuda, S. Kono, K. Heya, S. P. Wolski, H. Takahashi, T. Sugiyama, D. Lachance-Quirion, and Y. Nakamura, Phys. Rev. A **102**, 062408 (2020).
5. “Programmable directional emitter and receiver of itinerant microwave photons in a waveguide”, N. Gheeraert, S. Kono, and Y. Nakamura, Phys. Rev. A **102**, 053720 (2020).
6. “Single-photon quantum regime of artificial radiation pressure on a surface acoustic wave resonator”, A. Noguchi, R. Yamazaki, Y. Tabuchi, and Y. Nakamura, Nat. Commun. **11**, 1183 (2020).
7. “Entanglement-based single-shot detection of a single magnon with a superconducting qubit”, D. Lachance-Quirion, S. P. Wolski, Y. Tabuchi, S. Kono, K. Usami, and Y. Nakamura, Science **367**, 425–428 (2020).
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10. “Pseudo-2D superconducting quantum coupling circuit for the surfacecode: proposal and preliminary tests”, H. Mukai, K. Sakata, S. J. Devitt, R. Wang, Y. Zhou, Y. Nakajima, and J. S. Tsai, New J. Phys. **22**, 043013 (2020).
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12. “Hybrid quantum systems with circuit quantum electrodynamics”, A. A. Clerk, K. W. Lehnert, P. Bertet, J. R. Petta, and Y. Nakamura, Nat. Phys. **16**, 257–267 (2020).
13. “Hybrid quantum systems based on magnonics”, D. Lachance-Quirion, Y. Tabuchi, A. Gloppe, K. Usami, and Y. Nakamura, Appl. Phys. Express **12**, 070101 (2019).
14. “On-demand generation of traveling cat states using a parametric oscillator”, H. Goto, Z. R. Lin, T. Yamamoto, and Y. Nakamura, Phys. Rev. A **99**, 023838 (2019).
15. “Information-to-work conversion by Maxwell’s demon in a superconducting circuit quantum electrodynamical system”, Y. Masuyama, K. Funo, Y. Murashita, A. Noguchi, S. Kono, Y. Tabuchi, R. Yamazaki, M. Ueda, and Y. Nakamura, Nat. Commun. **9**, 1291 (2018).
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