Short form:

"For fundamental and pioneering experiments in entangling superconducting qubits and microwave photons, and their application to quantum information processing."

Long form:

2013 Bell prize

The third biennial John Stewart Bell Prize for Research on Fundamental Issues in Quantum Mechanics and Their Applications is awarded to Michel Devoret and Robert Schoelkopf, Professors of Applied Physics at Yale University, USA, for fundamental and pioneering experimental advances in entangling superconducting qubits and microwave photons, and their application to quantum information processing.

John Bell's discovery that entanglement had experimentally testable consequences opened a new experimental field in which the boundaries of validity of quantum mechanics would be explored as far as current technology would permit. One new direction was proposed at the beginning of the 80's by Tony Leggett (recipient of the 2003 Nobel Prize in Physics): test the application of quantum mechanics to collective electrical variables of radio-frequency circuits, like macroscopic currents and voltages. In circuits that are purely linear, like an inductance-capacitance (LC) harmonic oscillator, the difference between classical and quantum behavior is very subtle and is hard to observe if one does not introduce a non-linear element. Leggett suggested that a Josephson junction should be used. According to theory, the Josephson effect provides a non-linear inductance which is non-dissipative when the temperature is reduced well below the superconducting gap.

Pioneering experiments performed at UC Berkeley in 1983-84 in John Clarke's lab by Devoret and John Martinis demonstrated that a Josephson junction can indeed behave as an artificial atom, possessing quantum energy levels which can be excited by microwave light. One can view a Josephson tunnel junction as a sort of one-dimensional atom, with the phase of the junction being the position of the electron and the Josephson "washboard" potential playing the role of the Coulomb potential. The transition frequencies of the Josephson atom are about 100,000 times smaller than a microscopic atom, so instead of falling in the visible or ultra-violet light domain, they lie in the GHz range (microwave radiation). However, the scaling of the quality factor of the transition (ratio of the center frequency to the linewidth) did not appear favorable at first. Even when Yasunobu Nakamura, Yuri Pashkin and Jaw Shen Tsai at NEC Tsukuba in Japan realized the first measurement of the Rabi oscillations associated with the transition between two Josephson levels in the "Cooper pair box" configuration, which had been developed by Devoret, Daniel Esteve and Cristian Urbina and colleagues at Saclay, France, these man-made solid-state systems seemed many orders of magnitude less coherent than their natural counterparts like real atoms. The prospects looked suddenly much more promising when the Saclay team observed Ramsey interference fringes in a new configuration protecting the Josephson junction from the measurement circuit ("quantronium" artificial atom). That experiment showed that the quality factor of superconducting artificial atoms could be improved by more than two orders of magnitude, greatly enhancing the prospects for using these devices as quantum bits (or "qubits") for information processing.

In 2004, Schoelkopf's group and collaborators at Yale, including the theory group of Steve Girvin, further developed the parallels between superconducting circuits and atomic physics by introducing the concepts and techniques known as circuit quantum electrodynamics ("circuit QED"). In this new paradigm, Josephson-junction qubits are coupled to only to microwave photons in a superconducting cavity, and all measurement and control of the circuit is achieved with radio-frequency signals. These techniques allow faster, more precise, and higher signal to noise ratio measurements of superconducting quantum devices. Circuit QED can also go beyond traditional quantum optics and cavity QED with real atoms and photons in some regards. It allows, for instance, vastly stronger couplings between light and matter, and enabled the Yale group to reach a new regime of strong dispersive coupling (previously only possible in Rydberg atom cavity QED), where the presence of a single excitation in either the qubit or the cavity shifts the frequency of its counterpart by many (up to 1,000 or more) linewidths. Using this capability, experimenters today make, measure, and manipulate single microwave photons and generate nonclassical states of light in superconducting circuits. Schoelkopf's group demonstrated the generation of single gigahertz photons on demand in 2007, and the non-demolition measurement of photons in a cavity in 2010. The creation of complex states of light in circuit QED, by superposing many individual photons, was accomplished by the team of Andrew Cleland and John Martinis at UC Santa Barbara in 2008.

The strong coupling of qubits and photons in circuit QED also enables many applications in quantum computation. In 2007 the Yale group used microwave photons, guided by superconducting wires, as a "quantum bus" to connect qubits on opposite sides of a chip. They extended this work in 2009 to realize the first solid-state quantum processor, performing two-qubit (Grover and Deutsch-Josza) quantum algorithms. In parallel with the Martinis group at UCSB, they also announced a violation of Bell's inequalities for superconducting qubits, definitively demonstrating entanglement in these man-made systems. More recently, the Yale team has continued this work to observe three-qubit entanglement (via violation Mermin's extension of the Bell inequalities), and demonstrate the first quantum error correction (QEC) in a solid-state device.

Meanwhile, there have also been huge advances in the capability for quantum measurement with superconducting systems. As with atoms, quantum jumps between energy levels of qubits and photons can be observed with high signal-to-noise ratio using Josephson amplifiers developed in the lab of Devoret (who moved to Yale in 2002) in collaboration with Schoelkopf. The fact that thousands of bits of information can now be extracted from a qubit during its coherence lifetime opens new quantum measurements avenues like the stabilization of states and error correction by continuous feedback, which might be easier than with natural atoms.

Over the last decade or so, the Yale collaboration of Devoret and Schoelkopf has been a leader in the development of new superconducting qubit designs, and in the improving lifetimes of quantum states and quantum information in these systems. During this time frame, the field has seen coherence times improve about a factor of ten every three years, undergoing a remarkable "Moore's law" type of growth by almost six orders of magnitude. Today coherence times are approaching the so-called error correction threshold, implying that workable quantum error correction and scalable quantum computing may soon be possible.

The achievements of the new field of superconducting quantum circuits, fostered by the Yale collaboration, and now practiced in many labs around the world, have opened a new platform for experiments in quantum physics. In a way that is similar to how conventional electronic circuits are built from individual components, one can now construct novel, complex quantum systems built from modular parts. These systems can perform signal processing functions at the level of individual quanta, and perhaps one day allow quantum computing to become a practical reality.

Main references to the work for which the prize is awarded:

1) 'Strong Coupling of a Single Photon to a Superconducting Qubit Using Circuit Quantum Electrodynamics,' A. Wallraff, D.I. Schuster, A. Blais, L. Frunzio, R.S. Huang, J. Majer, S. Kumar, S.M. Girvin, and R.J. Schoelkopf, Nature 431, pp. 162-167 (2004).
2) 'Resolving Photon Number States in a Superconducting Circuit,' D.I. Schuster, A.A. Houck, J.A. Schreier, A. Wallraff, J. Gambetta, A. Blais, L. Frunzio, B. Johnson, M.H. Devoret, S.M. Girvin, and R.J. Schoelkopf, Nature 445, pp. 515-518 (2007).
3) 'Demonstration of Two-Qubit Algorithms with a Superconducting Quantum Processor,' L. DiCarlo, J. M. Chow, J. M. Gambetta, Lev S. Bishop, D. I. Schuster, J. Majer, A. Blais, L. Frunzio, S. M. Girvin, and R. J. Schoelkopf, Nature 460, pp. 240-244 (2009).
4) 'Phase-preserving amplification near the quantum limit with a Josephson ring modulator,' N. Bergeal, F. Schackert, M. Metcalfe, R. Vijay, V. E. Manucharyan, L. Frunzio, D. E. Prober, R. J. Schoelkopf, S. M. Girvin, M. H. Devoret, Nature 465, pp. 64-68 (2010).
5) 'Observation of High Coherence in Josephson Junction Qubits Measured in a Three-Dimensional Circuit QED Architecture,' H. Paik, D.I. Schuster, L.S. Bishop, G. Kirchmair, G. Catelani, A.P. Sears, B.R. Johnson, M.J. Reagor, L. Frunzio, L.I. Glazman, M.H.Devoret, and R.J. Schoelkopf, Physical Review Letters 107, 240501 (2011).
6) 'Quantum Back-Action of an Individual Variable-Strength Measurement,' M. Hatridge, S. Shankar, M. Mirrahimi, F. Schackert, K. Geerlings, T. Brecht, K.M. Sliwa, B. Abdo, L. Frunzio, S.M. Girvin, R.J. Schoelkopf, and M.H. Devoret, Science 339, pp. 178-181 (2013).

Further related reading:

<u>Review articles on superconducting qubits</u>

1) 'Quantum Mechanics of a Macroscopic Variable: the Phase Difference of a Josephson Junction,' J. Clarke, A.N. Cleland, M.H. Devoret, D. Esteve, J.M. Martinis, Science 239, pp. 992-997 (1988).

2) ‘Superconducting Quantum Bits,’ John Clarke and Frank K. Wilhelm, Nature 453, pp. 1031-1042 (2008).
3) ‘Superconducting Circuits for Quantum Information: An Outlook,’ M.H. Devoret and R.J. Schoelkopf, Science 339, pp. 1169-1174 (2013).

On cavity QED and circuit QED
4) ‘Exploring the Quantum: Atoms, Cavities, and Photons,’ by S. Haroche and J.M. Raimond, (Oxford Univ. Press, 2006).
5) ‘Wiring Up Quantum Systems,’ R.J. Schoelkopf and S.M. Girvin, Nature 451, pp. 664-669 (2007).

On amplifiers and quantum measurement
6) see for example the 2012 Nobel lectures by S. Haroche and D. Wineland at http://www.nobelprize.org/nobel_prizes/physics/laureates/2012/
7) ‘Introduction to Quantum Noise, Measurement, and Amplification,’ A.A. Clerk, M.H. Devoret, S.M. Girvin, F. Marquardt, and R.J. Schoelkopf, Reviews of Modern Physics 82, pp. 1155-1208 (2010).
8) ‘Non-Degenerate, Three-Wave Mixing with the Josephson Ring Modulator,’ B. Abdo, A. Kamal, and M.H. Devoret, Physical Review B 87, 014508 (2013).