

Achievements of 2026 C&C Prize Recipients

Group A

■Recipient

Dr. Hidetoshi Katori

Professor, Department of Applied Physics, Graduate School of Engineering, The University of Tokyo

Team Director, Spacetime Engineering Research Team, RIKEN Center for Advanced Photonics

■Citation

Pioneering Contributions to the Realization of the Optical Lattice Clock

■Achievements

Precise time measurement is a fundamental technology that underpins modern information and communications technology (ICT) society, including information and communications networks, global navigation satellite systems (GNSS), electronic transactions, and scientific measurements. The current definition of the “second” is based on the cesium atomic clock, which uses the frequency of microwaves absorbed and emitted by cesium-133 atoms as its standard. On the other hand, by utilizing optical transitions in atoms—which have frequencies approximately 100,000 times higher than those of microwaves—time can be divided into finer intervals, offering the potential to significantly improve the accuracy of clocks. Against this backdrop, research and development of optical atomic clocks has been advancing. Dr. Hidetoshi Katori proposed the concept of the optical lattice clock and, by actually realizing it, established an ultra-high-precision time standard that far surpasses conventional atomic clocks. Furthermore, he extended these results to relativistic geodesy and spacetime sensing, paving the way for applications in next-generation information and communications, quantum technology, and precision positioning.

In conventional optical atomic clocks using a single ion, it was difficult to achieve both high precision and short-duration measurements. To improve statistical precision, repeated measurements were necessary, requiring a single charged atom—cooled to near absolute zero—to be trapped between electrodes and measured multiple times. To overcome this limitation, Dr. Katori proposed the concept of the optical lattice clock in 2001 and successfully conducted fundamental experiments in 2003. In an optical lattice clock, a large number of strontium atoms are trapped within an optical lattice—a periodic structure formed by standing waves of light created by the interference of opposing laser beams. The optical lattice suppresses the Doppler effect caused by the thermal motion of the atoms and allows for the simultaneous observation of a large number of atoms. However, optical atomic clocks faced the challenge that the laser light used to trap the atoms could alter the frequency of the clock transition. Dr. Katori proposed and demonstrated that this effect could be counteracted by forming the optical lattice at a specific wavelength—the “magic wavelength”—at which the electric polarizabilities of the ground state and excited state are equal. Furthermore, by observing a large number of atoms simultaneously using this method, he established a technique to reduce quantum noise. In 2015, he reported in *Nature Photonics* the achievement of 10^{-18} -level precision in optical lattice clocks, approximately three orders of

magnitude better than the 10^{-15} -level precision of conventional cesium atomic clocks. This level of precision corresponds to a timing error of only about one second over more than 10 billion years. These achievements made it possible to simultaneously achieve high precision and short-time measurements in atomic clocks, laying the foundation for the advancement of optical lattice clock research and development around the world. Optical lattice clocks have been established as a new time standard technology in the fields of atomic physics and quantum metrology. Furthermore, in 2006, the International Committee for Weights and Measures (CIPM) adopted the optical transition of the strontium-87 atom as one of the secondary representations of the “second,” and the strontium optical lattice clock has become one of the leading candidates for the redefinition of the “second,” which is currently under international discussion for a possible redefinition of the second around 2030.

Dr. Katori has developed optical lattice clocks not merely as time standards, but as a new measurement technology. According to the general theory of relativity, clocks run at different rates in locations with different gravitational potentials. Optical lattice clocks with 10^{-18} -level precision can detect these extremely small differences. Dr. Katori and his team installed two optical lattice clocks—one on the ground floor of Tokyo Skytree and the other at the observation deck, approximately 450 meters above ground—and compared their clock frequencies. They demonstrated that the clock at the observation deck ran slightly faster than the one on the ground and published their findings in 2020. This achievement marked a significant step toward the practical application of relativistic geodesy, which measures differences in altitude and gravitational potential based on variations in clock frequency. It also demonstrated that optical lattice clocks can serve as high-performance sensors for measuring height differences and gravitational potential differences, paving the way for spacetime sensing to monitor crustal movements and volcanic activity.

Furthermore, Dr. Katori promoted research and development toward practical deployment of optical lattice clocks. Dr. Katori’s research group miniaturized and made more robust the physical package for spectroscopically analyzing atomic clock transitions and the laser control system, reducing the size of the apparatus—which had been approximately 920 liters in the Tokyo Skytree experiment—to about 250 liters. In 2025, based on these achievements, Shimadzu Corporation commercialized the world’s first optical lattice clock. Furthermore, in 2026, the International Bureau of Weights and Measures (BIPM), RIKEN, and Shimadzu Corporation signed a memorandum of understanding to explore the role of transportable optical frequency standards. As a result, optical lattice clocks are being implemented in society not only as time standards but also as infrastructure utilized in a wide range of fields, including information and communications, precision measurement, and geodesy.

Dr. Katori’s achievements span the proposal and demonstration of the principles behind ultra-high-precision optical lattice clocks, their application to relativistic geodesy and spacetime sensing, and their practical implementation for societal deployment. These contributions significantly advance the information and communications technologies that underpin precise control, positioning, and synchronization, and serve as a prime example of C&C technology—a highly integrated fusion of high-stability lasers, photonics, electronic control, and vacuum and cooling technologies. These achievements can be highly regarded as outstanding accomplishments worthy

of the C&C Prize.

■Biography and Major Awards

[Biography]

1988: Graduated from the Department of Applied Physics, Faculty of Engineering, The University of Tokyo.

1990: Completed the Master's Program in the Department of Applied Physics, Graduate School of Engineering, The University of Tokyo.

1991–1994: Research Associate, Faculty of Engineering, The University of Tokyo

1994: Received a Doctor of Engineering (Dissertation Doctorate) from The University of Tokyo.

1994–1997: Visiting Researcher, Max Planck Institute of Quantum Optics, Germany.

1999: Associate Professor, Department of Cooperative Engineering, Engineering Research Institute, Faculty of Engineering, The University of Tokyo.

2005: Associate Professor, Department of Applied Physics, Graduate School of Engineering, The University of Tokyo.

2010–present: Professor, Department of Applied Physics, Graduate School of Engineering, The University of Tokyo.

2010–2016: Research Director, ERATO Katori Innovative Space-Time Project, Strategic Basic Research Programs (ERATO), Japan Science and Technology Agency (JST).

2011–2014: Visiting Chief Scientist, Katori Quantum Measurement Laboratory, RIKEN.

2014–2025: Visiting Chief Scientist, Katori Quantum Measurement Laboratory, RIKEN; Team Leader, Spacetime Engineering Research Team, Center for Advanced Photonics, RIKEN.

2017–2018: Director, Photon Science Center, Graduate School of Engineering, The University of Tokyo.

2018–present: Program Manager, JST Mirai Program Large-Scale Project, "Space-time information platform with a cloud of optical lattice clocks."

2023–present: Member, The Japan Academy.

2025–present: Team Director, Spacetime Engineering Research Team, Center for Advanced Photonics, RIKEN.

[Major Awards]

2005: JSPS Prize

2005: Julius Springer Prize for Applied Physics

2005: European Time and Frequency Award

2006: 20th Japan IBM Science Award

2008: 2008 Rabi Award

2010: 42nd Ichimura Academic Award (Special Prize)

2011: Commendation for Science and Technology by the Minister of Education, Culture, Sports, Science and Technology (Science and Technology Award, Research Category)

2011: 12th Award for Achievements in Optical and Quantum Electronics (Hiroshi Takuma Award)

2011: The Philipp Franz von Siebold Prize

2012: 2011 Asahi Prize

2013: Nishina Memorial Prize

2013: 54th Fujiwara Prize

2013: 53rd Toray Science and Technology Prize

2014: Medal with Purple Ribbon

2015: Japan Academy Prize

2017: 14th Leo Esaki Prize

2020: The Micius Quantum Prize 2020

2021: 2022 Breakthrough Prize in Fundamental Physics

2022: The Honda Prize

Group B

■Recipients

Dr. Andrew G. Barto

Professor Emeritus, University of Massachusetts Amherst

Dr. Richard S. Sutton

Professor, University of Alberta

Founder, Oak Lab Inc.

Dr. Christopher J. Watkins

Professor, Royal Holloway, University of London

■Citation

Pioneering Contributions to the Establishment of Reinforcement Learning Concepts and Algorithms

■Achievements

Artificial intelligence (AI) is a technology that enables computers to perform intellectual activities — such as perception, judgment, and decision-making — traditionally carried out by humans. It holds the promise of bringing about significant transformations in society, industry, and people's lives through increased productivity and the creation of new services. While supervised learning trained on a set of examples labeled with correct responses has been the mainstream approach to learning in traditional AI, a key challenge has been to enable systems to learn through interaction with the external environment and make autonomous decisions even in situations where correct responses are not provided in advance. Dr. Andrew G. Barto, Dr. Richard S. Sutton, and Dr. Christopher J. Watkins addressed this challenge by establishing the conceptual and mathematical foundations of reinforcement learning and developing practical, highly versatile reinforcement learning algorithms that do not rely on labeled training examples, thereby making significant contributions to the advancement of modern AI.

Although the idea of learning from rewards and penalties instead of from labeled examples had long been known, traditional application of machine learning assumed that the agent — the entity doing the learning — had access to labeled training examples, and methods for learning from rewards and penalties, often called learning by trial-and-error, had not yet been fully exploited in AI. In the early 1980s, Dr. Barto and Dr. Sutton combined psychology-based trial-and-error learning with the concept of sequential decision-making to establish the basic framework of reinforcement learning, with Markov decision processes as its mathematical foundation. Furthermore, in their 1983 study of the inverted pendulum problem, they proposed a method that would later serve as the prototype for the Actor-Critic method. This established a general framework for reinforcement learning that allows agents to learn to improve their behavior through continuing interaction with their environments.

Subsequently, it became clear that, in reinforcement learning, optimizing long-term policies requires considering not only the reward immediately following an action but also rewards to be received in the future. In 1988, Dr. Sutton proposed Temporal Difference Learning. Temporal Difference Learning is a method that combines the advantages of the Monte Carlo method and dynamic programming;

it uses the difference between the current prediction and the prediction for the next time step (the temporal difference) to sequentially update the expected future cumulative reward. This method laid the foundation for long-term value estimation in unknown environments. Furthermore, Dr. Barto and Dr. Sutton developed the Actor-Critic method, in which an "Actor" that selects actions and a "Critic" that evaluates the results learn in coordination. In the Actor-Critic method, the Critic evaluates value using Temporal Difference Learning, and the Actor uses those results to learn a policy that maximizes cumulative reward. Thanks to these achievements, reinforcement learning evolved into a systematic academic field capable of long-term value estimation and policy improvement. In addition, the two authors published the seminal textbook "Reinforcement Learning: An Introduction" in 1998, contributing significantly to the popularization and advancement of reinforcement learning research.

Meanwhile, Dr. Watkins combined the reinforcement learning framework developed by Dr. Barto and Dr. Sutton with dynamic programming and conducted research on methods for learning optimal policies without prior knowledge of the environment model. He then proposed Q-learning in his 1989 doctoral dissertation. In Q-learning, a Q-value — representing the expected cumulative reward to be obtained in the future for each state-action pair — is maintained, and the Q-value is updated sequentially using the reward received after an action and information about the next state. By repeating this update process, the algorithm learns a policy that selects the action with the highest Q-value in each state. The most distinctive feature of Q-learning is that it learns an optimal policy solely from experience, without requiring a predefined environmental model, thereby achieving model-free optimal control. Because Q-learning has a relatively simple structure, it has become widely adopted as a representative algorithm for model-free control.

Reinforcement learning, pioneered by Dr. Barto, Dr. Sutton, and Dr. Watkins, has become a general-purpose decision-making technology not limited to specific tasks and has evolved into deep reinforcement learning through its integration with deep neural networks. Its applications have expanded to include game AI, communication network control, semiconductor design, and the optimization of logistics and energy management. Furthermore, reinforcement learning that utilizes human feedback has become a technology for improving the quality of generative AI responses, helping to ensure that they are safe, reliable, and aligned with human intent. It is also expected to play a crucial role in the future development of an AI-driven society as a core technology supporting behavioral learning in physical AI and next-generation robot control. The achievements of Dr. Barto and Dr. Sutton, who established the key concepts and mathematical foundations of reinforcement learning, and those of Dr. Watkins, who devised Q-learning and significantly advanced the practical application of reinforcement learning, have had an immense impact on the development of information processing and intelligent information technology. These achievements are highly regarded as outstanding contributions worthy of the C&C Prize.

■ Biography and Major Awards

[Biography]

- Dr. Andrew G. Barto
1970: B.S., University of Michigan
1975: Ph.D., University of Michigan

1977: Postdoctoral Research Associate, University of Massachusetts Amherst
1982: Associate Professor, University of Massachusetts Amherst
1991: Professor, University of Massachusetts Amherst
2007–2011: Chair of the Department of Computer Science, University of Massachusetts Amherst
2012–: Professor Emeritus, University of Massachusetts Amherst

- Dr. Richard S. Sutton
1978: B.A. in psychology from Stanford University
1980: M.S. in computer science from the University of Massachusetts Amherst
1984: Ph.D. in computer science from the University of Massachusetts Amherst
1985–1994: Principal Member of Technical Staff at the Computer and Intelligent Systems Laboratory at GTE in Waltham, Massachusetts
1995–1998: Senior Research Scientist, University of Massachusetts Amherst
1998–2002: Principal Technical Staff Member, AT&T Shannon Laboratory in Florham Park, New Jersey
2003–: Professor, University of Alberta
2017–2023: Distinguished Research Scientist at DeepMind and Co-founder of its Edmonton office
2018–: Fellow and Chief Scientific Advisor, Amii
2021: Canada CIFAR AI Chair
2023–2026: Research Scientist, Keen Technologies
2026–: Founder, Oak Lab Inc.

- Dr. Christopher J. Watkins
1989: Ph.D. from the University of Cambridge
1985–1990: Senior Research Scientist, Philips Research
1990–1992: Quantitative Analyst, IFM Trading Ltd.
1992–1994: Quantitative Analyst, Springfield International Investments
1995–1996: Member of Technical Staff, AT&T Bell Labs
1997–: Professor of AI, Royal Holloway, University of London

[Major Awards]

- Dr. Andrew G. Barto
2004: IEEE Neural Network Society Pioneer Award
2017: IJCAI Award for Research Excellence
2019: University of Massachusetts Neurosciences Lifetime Achievement Award
2024: ACM A.M. Turing Award (shared with Dr. Richard S. Sutton)
Fellow, American Association for the Advancement of Science (AAAS)
- Dr. Richard S. Sutton
2001: Fellow of the Association for the Advancement of Artificial Intelligence (AAAI)
2016: Fellow of the Royal Society of Canada
2018: Lifetime Achievement Award and Fellow of the Canadian Artificial Intelligence Association (CAIAC)

2021: Fellow of the Royal Society (FRS) of London

2021: IJCAI Award for Research Excellence

2024: ACM A.M. Turing Award (shared with Dr. Andrew G. Barto)