This issue features Associate Professor Shu Tanaka and his research in quantum annealing and its various areas of hardware, software, and application.

The Joy of Pioneering the Frontier between Physics and Information Science

Perfectly harnessing the essence of quantum physics

Shu Tanaka's research was founded on an idea that left an impression on him as an undergraduate: "Understand information, which deals with the artificial phenomena, in the language of physics, which deals with the natural phenomena." Today physics and information stand at the forefront of science. Shu Tanaka's computation method makes use of quantum fluctuations to solve combinatorial optimization problems. He seeks to revolutionize the way in which we can improve efficiency in different areas such as shipping logistics, production systems, and the development of new materials.

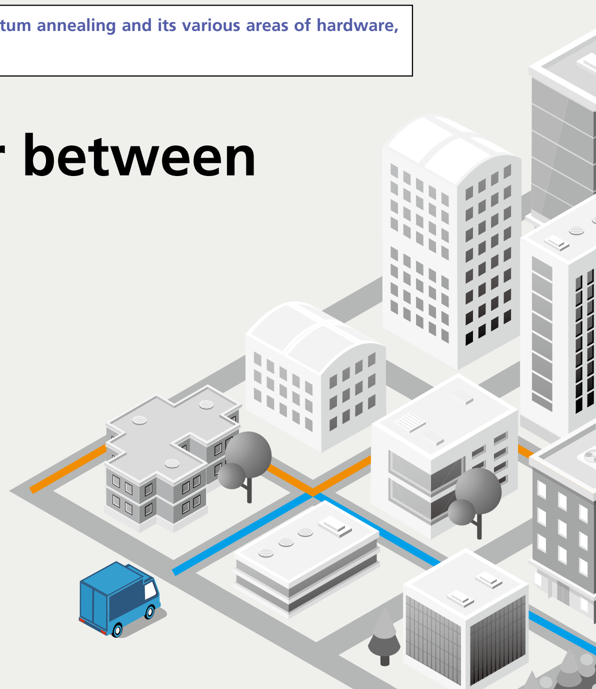

Fig.1 Optimizing a delivery plan
Quantum annealing can quickly find solutions to questions such as "What is the most efficient route to deliver a set of shipments?"

Is the world made up of combinatorial optimization problems?

From the moment we wake up in the morning, we make a series of choices on what clothes to wear, what to eat for breakfast, what route to take to school or work, and more. We make these choices based on various criteria such as how something looks, how efficient it is, and how safe it is. As Associate Professor Shu Tanaka explains, "The task of selecting the most optimal choice from a large number of options based on a set criteria is called a 'combinatorial optimization problem.' "

There are a countless number of these types of problems in industry and in one's own work, such as figuring out what is the most efficient order for carrying out a task. These problems can arise when making deliveries, operating machinery and equipment, and many other situations. One of the difficulties of this type of problem is that the number of combinatorial options explodes exponentially when there are, for example, more places to deliver a shipment. "It is there," he says, "that we needed to devise a smarter way, a better algorithm, to solve these problems. This is where a quantum computing technique called quantum annealing comes in. It holds great potential in solving combinatorial optimization problems at high speeds, and has been in the spotlight recently"(Fig. 1).

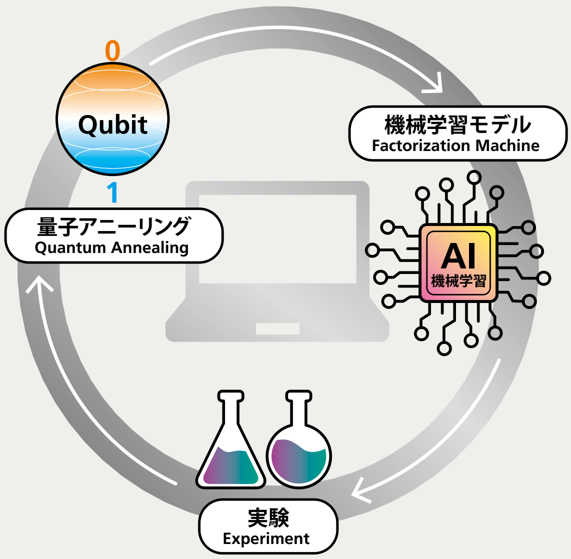

Fig.2 FMQA, a new computational method combining quantum annealing and AI
Based on the results of several experiments, a function is formulated and applied to an Ising model or QUBO format using machine learning and computed with a quantum annealing machine. This produces a viable solution for that point in time. The solution then informs under what conditions the next experiment should be conducted. The process is repeated several times to obtain the ideal conditions that generates the desired property.

Applying physical phenomena to computing techniques

Quantum annealing is a computing technique where one can efficiently arrive at the solution of an optimization problem. This type of quantum computing is currently garnering attention and can be positioned at the intersection of physics and information science.

"To optimize something is to 'maximize' or 'minimize' it," says Tanaka. "In either case, the optimization is handled the same way mathematically. Here, we can think in terms of minimization. In physics the lower an energy state something has, the more stable it is said to be. Quantum annealing is designed to apply this idea to combinatorial optimization problems. In other words, you can think of it as finding the most efficient solution to a combinatorial optimization problem by seeking out a stable state with low energy."

"Annealing" is a term that comes from metallurgy and materials science. To form an alloy, the metal atoms that make up the alloy are broken apart by heat, and the temperature is slowly lowered. This produces a stable molecular arrangement. The method of making computations scientists call "simulated annealing" takes its cue from this process. However, while simulated annealing uses heat, quantum annealing uses quantum fluctuations instead. With quantum fluctuations, the values written to a qubit are quantum superpositions of 0s and 1s. As the

quantum fluctuation is weakened from that state, those 0s and 1s settle and become stable, and the values generated at that time mark the solution to the combinatorial optimization problem.

As Tanaka explains, “Quantum annealing is a computing method that was published in a 1998 paper by Professor Hidetoshi Nishimori of the Nishimori Group at the Tokyo Institute of Technology (now the Institute of Science Tokyo as of October 2024), which I joined for my research in 2002. The Nishimori Group was truly a laboratory that approached information science with physics.”

Methods such as quantum annealing that use the mechanisms of natural phenomena to compute something are called “natural computing.” Quantum annealing, in particular, has become popular among scientists, as it was the method used by the Canadian quantum computing company D-Wave to deploy the world’s first commercial quantum annealer in 2011.

Fusing AI and Quantum Annealing

To use the quantum annealing computing technique, the problem needs to be formulated as a function for the Ising model or Quadratic Unconstrained Binary Optimization (QUBO) model. However, while some problems can be simple to solve using such functions, others can be difficult. Some problems cannot even be formulated as functions in the first place.

“When tackling a combinatorial optimization problem related to a social issue, the first step is to formulate a function by referring to past research cases and looking for similar types or extrapolating from what existed at the time, since each problem already has some kind of fixed type. I think that the ability to think about how to formulate functions when encountering completely new types of combinatorial optimization problems is one of our strengths as professional researchers,” he said. With his wealth of experience and a keen intuition, Tanaka has worked with a variety of companies to implement optimization strategies in the distribution of advertisements, travel planning, transportation, and integrated circuit design. Now, he is focusing on combining AI and quantum annealing. It was during his doctoral program that he decided to fix his gaze on this field in particular.

“It all started when I was talking with a friend who was working on research in informational science, which got me wondering if I could do something interesting by combining machine learning and quantum annealing. In 2009, I presented a paper on this at an international conference on artificial intelligence. For a while after I received my degree, I did very little quantum annealing research, but then I was contacted by a company that expressed interest in this paper, and that led to a return to that topic,” he said.

After repeated discussions with researchers at the University of Tokyo and the National Institute for Materials Science, he came up with and developed a tool called Factorization Machine with Quantum Annealing (FMQA), which uses machine learning to convert problems into the Ising model or a QUBO format. Currently, he is hard at work developing various applications using FMQA, as well as working on R&D to advance it further (Fig. 2).

“For example,” explains Tanaka, “If you wanted to develop a new material that conducts electricity well by mixing several substances, you would first mix those substances in various proportions, measure the current passing through, and produce data showing that the ratio of this mixture conducts this much electricity. With FMQA, you would use machine learning based on those sets of data to create functions to be utilized with the Ising model or QUBO. A quantum annealing machine would then be used to search for the optimal solution to this function. The solution that emerges at this time would indicate the mixing ratio that should be tried next in the experiment.”

In other words, quantum annealing replaces the “intuition” of experimental scientists who look at the results of an experiment and link them to the next experiment. FMQA is run again based on the results of the experiments conducted according to this. As this process is repeated, the accuracy of the functions gradually improves, and it will eventually be possible to find a ratio with the desired conductivity. “We are working with companies and universities to explore the materials we can use and develop other applications using this method,” he adds (Fig. 3).

His paper on using FMQA was published in 2020, and it seems that people in various fields besides the materials field have expressed interest in it. “There have been quite a few companies who have approached us and said, ‘While we can’t announce it publicly yet, we are conducting research using FMQA,’” he says. FMQA is an optimization tool utilizing repeated trial-and-error experiments that lead us to a scientific discovery; in other words, it is a black box optimization algorithm. “I myself am very much looking forward to seeing the many different examples of ‘black box optimization’ that will emerge through the application of FMQA.”

(Interview and text writer: Shinko Yuri)

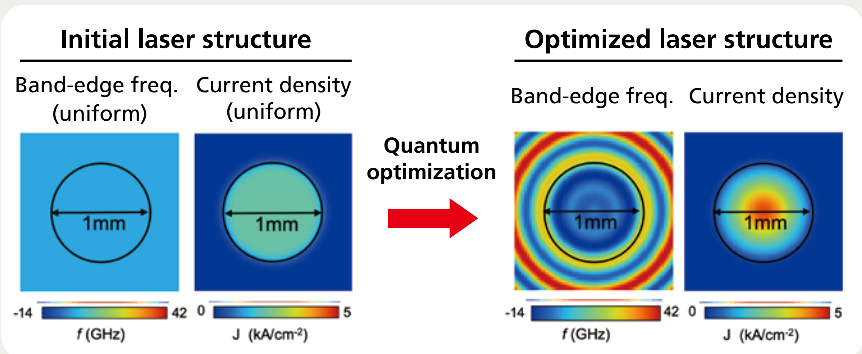

Fig.3 Results of structural optimization of photonic-crystal lasers via quantum annealing
The distribution of frequency and injected current are completely different between the conventionally designed photonic-crystal lasers (left) and those using quantum annealing (right), indicating that a device structure with nontrivial spatial distribution can be obtained.