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Quantum Annealing

from Keio's Faculty of Science and Technology

Challenging the Frontier of Physics and Information Science

Shu Tanaka

Associate Professor
Department of Applied Physics and Physico-Informatics

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.

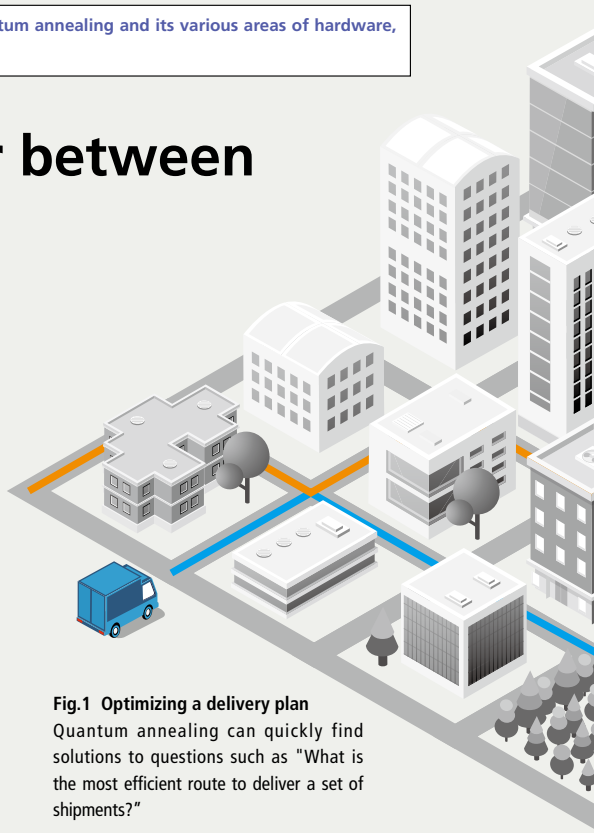


Fig.1 Optimizing a delivery plan
Quantum annealing can quickly find solutions to questions such as "What is the most efficient route to deliver a set of shipments?"

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).

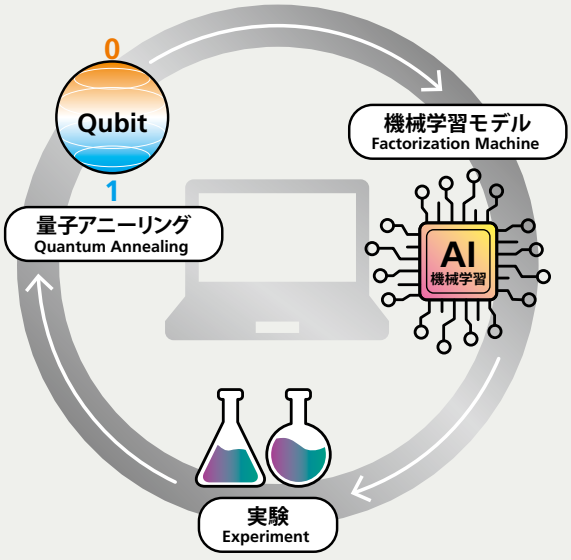


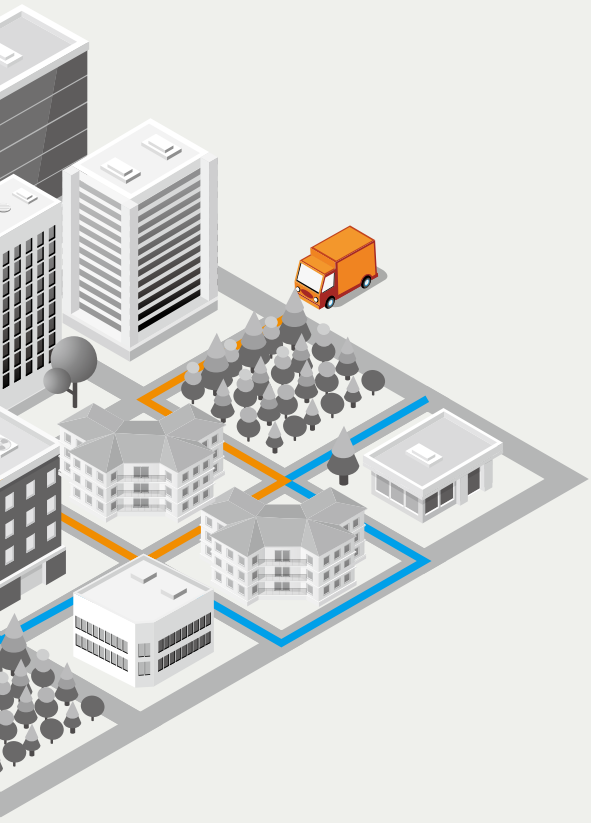
Fig.2 FMQA, a new computational method combining quantum annealing and AI
Based on the results of several experiments, a function is formulated and applied to an Ising model or QUBO format using machine learning and computed with a quantum annealing machine. This produces a viable solution for that point 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)

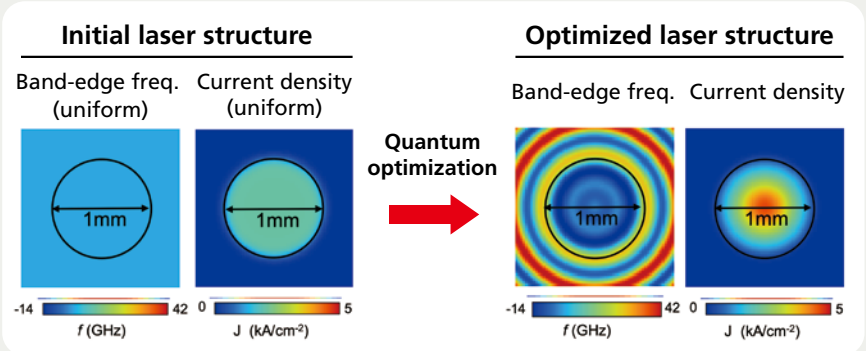


Fig.3 Results of structural optimization of photonic-crystal lasers via quantum annealing
The distribution of frequency and injected current are completely different between the conventionally designed photonic-crystal lasers (left) and those using quantum annealing (right), indicating that a device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

Even when things felt they weren't going well, I would ask, "What can I do now?" This helped me gain a lot of valuable experiences.

"I went from place to place before I landed my permanent research position," says Associate Professor Tanaka. Yet even throughout that period of uncertainty, he made use of his circumstances, and he has since established his own place in the new research field of quantum annealing. Now that he is the laboratory head, he shows a tougher side, saying, "Life is not so easy." Yet at the same time, he hopes that students with different backgrounds will be able to demonstrate their abilities and play an active role in their respective fields.

I understand that you are an Edokko (someone born and raised in Tokyo), correct?

I was born in Edogawa Ward in Tokyo, and went to the Tokyo Metropolitan Ryogoku High School. It was also where the famous writer Ryunosuke Akutagawa graduated before me. I guess my tendency to not worry about details is what makes me feel I am an Edokko. I went to the Tokyo Institute of Technology (Institute of Science Tokyo from October 2024) for my undergraduate and went on to the University of Tokyo for my graduate studies. Since I did not have a lot of financial leeway, I chose to study at a public educational institution.

When I think about it now, I wonder if everyone was desperately trying to do the same. This is probably a feeling that many people have to some degree when they are young. In the end, I realized that there is no point in rushing things, and that first and foremost, it is important to fulfill your role as a university student, for doing so will be a huge boon for the rest of your life.

What did you study in university and graduate school?

Throughout my schooling I studied physics. When I was in junior high or high school, I became really drawn to physics when I saw pictures and videos of magnets floating over superconductors. I thought, "If I learn physics, I'll be able to study about these kinds of phenomena, too!" It was from that point that I started thinking about a career in physics.

In my fourth year of university in 2002, the first place I officially began research at was Professor Hidetoshi Nishimori's laboratory at the Tokyo Institute of Technology. In his physics lab at the time, Professor Nishimori was already working on quantum annealing. I was actually not interested in quantum annealing at the time, so I ended up choosing the option to tackle a problem with just pen and paper. It's something that many aspiring physicists dream of doing. Since I was a senior in college, I had only touched upon the relational expressions in physics reading them in existing papers at the time. Still, a very high level of mathematics was required.

Today, when I see students grumbling about physics calculations, I think back to those days and can't help telling them, "It's a good thing they're even solvable. Doing research means you have to take on solving problems that you don't even know if you can solve."

What led you to study quantum annealing, which you discussed in the research introduction section?

It was during my doctoral studies. I was working under Professor Seiji Miyashita at the University of Tokyo, and one day I came across a paper on quantum annealing that I thought was very interesting. When I mentioned this to Professor Miyashita, he encouraged me to give researching it a shot. When you look at the word "physics," you can see that it deals with "the physical." It was therefore a surprise to learn that non-physical things like information can be handled by a physical phenomenon called "quantum annealing."

Did you go on to continue researching about quantum annealing from that point onward?

Actually, no. I was unable to get a permanent position for a long time and went through multiple universities. Because I worked on research topics that I encountered at each of those universities, I did not work exclusively on quantum annealing for many years.

Including the laboratories at the Tokyo Institute of Technology and the University of Tokyo, where I spent my time as a student, the Department of Applied Physics and Physico-Informatics in the Faculty of Science and Technology at Keio University counts as my tenth department. In particular, my post at Kinki University from April 2010 was decided around February 15, about 40 days before I was set to start there. The fact that I had not been able to find a full-time position by that point was breaking my heart as a 29 year old.

It was around 2014, while I was at Kyoto University, that I began to focus on quantum annealing research, which I had been working on as side work since I received my Ph.D. It was at that

time that a company expressed interest in a paper I had published in 2009 on my research combining machine learning and quantum annealing. This helped get me serious about quantum annealing research.

While it was a rough time back then, it seems you had a really difficult time after graduation.

It was certainly tough, but I also saw friends who were similarly struggling to find jobs during the so-called "Employment Ice Age," and I think I was able to make the most of the circumstances I was in at the time without being too discouraged. In my post-graduation career, I worked primarily with supercomputers and other computer simulations to gain insight into the properties of novel materials. One day, however, I began to think, "wouldn't it be a good idea to know about experiments that actually create substances." And when I was in the Ohkoshi Laboratory at the University of Tokyo's Department of Chemistry, I underwent training in chemical experiments and learned how measurements and synthesis are actually done.

The active learning from researchers in other fields and, above all, the fact that they were right next to me where I could converse with them on a daily basis, fostered a sense of diversity in me. It was sometimes difficult to dive into a different field of study and conduct research while working through cultural differences, but I believe I developed insight and communication skills from that experience. I feel that this experience served me well in my various roles, such as head of a national project and CTO (Chief Technical Officer) of the venture company Quanmatic.

What kind of place is Keio University compared to all your experiences thus far?

Although each student's circumstances are different, I believe that Keio University is a very good place to be. The Hiyoshi Campus is home to students from a variety of fields, not just science. Spending a period of time there while still young cultivates a broad perspective. Then as the student progresses in their schooling and moves on to the science-focused Yagami Campus, they turn to concentrate on their own specialty.

Keio University has faculty members and colleagues all unique in their makeup, and people in the administrative department are very supportive. Even if for some reason you cannot go abroad to study or do something special, Keio students are in a good environment to learn and experience a lot. I hope that all students will absorb as much as they can there and use that experience to take a very active role in the future. And I hope I can help in any small way I can to make that a possibility.

◎ **Some words from students . . .** ◎

- The professor told me, "Why not come back again? You can visit as many times as you want until you feel this place is for you." I did so and through the visits I felt that the vibe with the professor and students was good. I thought, "This is the only place for me!" I would like to go to graduate school and develop myself more in this world (4th year undergraduate student).
- I am from the Shu Tanaka Group's first cohort of students. Although studying is not my forte, Professor Tanaka taught me about the difference between study and research and showed much kindness in guiding me through the process. I thought about joining the workforce after graduation, but I went on to a doctoral program and am doing research day-to-day. (1st year doctoral student).
- I earned my Ph.D in 2023 through the Shu Tanaka Group while simultaneously working in the private sector. This was my first research endeavor in the field of physics, but my professor eliminated all the reasons why I thought it was impossible and set me on a new path. He is a student-oriented person, and no matter how busy he is, he speaks individually with every student in the lab once a week. (project assistant professor).

(Interview and text writer: Akiko Ikeda)

For the full text of this interview
https://www.st.keio.ac.jp/en/kyurizukai/

Having a problem you can solve is something to appreciate when you don't know how a research topic will turn out

Shu Tanaka

Shu Tanaka specializes in Ising machines, quantum annealing, statistical mechanics, computational physics, and condensed matter theory. He graduated from the Department of Physics, Faculty of Science, University of Tokyo in 2008 and completed his doctoral degree at the Graduate School of Science in 2008. He holds a Ph.D in Science. After working for the Institute for Solid State Physics in the University of Tokyo, Kinki University, the Department of Chemistry in the University of Tokyo's Faculty of Science, the Yukawa Institute for Theoretical Physics in Kyoto University, the Waseda Institute for Advanced Study, the Green Computing Systems Research Organization in Waseda University, he has been in his current position since 2020. Since 2022, he has served as Core Director of the Human Biology Microbiome Quantum Research Center (Bio2Q) at Keio University and CTO of Quanmatic, a start-up company he founded. He is also serving as Chair of the Center of Innovation for Sustainable Quantum AI as of 2024.

Shu Tanaka's ON and OFF

Continuous ON and OFF

Desks and chairs in the laboratory at its launch. This is where my lab began.

At the KEIO TECHNO-MALL 2023 (December 15, 2023).

Graduation ceremony held on March 2024. I opened my lab in 2020 and in 2024 saw the members of its first cohort group graduate and enter the workforce.

Farewell party for Victor Fischer, who came to our lab as an exchange student from the Technical University of Munich.

All lab members from the master's level onward participated in an international conference in Glasgow, England. Here we are having dinner together on the last day of the international conference.

International Conference held in Innsbruck, Austria. It's a bit of a treat to be able to view the architecture of the different countries we visit whenever we attend international conferences.

The founding members of the quantum startup Quanmatic. The work here is different from my university work and I learn something new every day.

Inside the laboratory. At the lab, I'm surrounded by bright, motivated students and wonderful researchers.

私の本棚

My favorite books

Kingdom (Yasuhisa Hara, Shueisha)

This is a manga set in the late Warring States Period of China, and being such a huge bestseller it is well known by a large number of people. Given that it is a manga, the characters' personalities are exaggerated quite a bit. Still, when I was reading it I would think, "There are people around me who are just like this," or, "I can relate to this part of that character." It remains one of my favorite series. I have read it many times and thoroughly enjoyed it because I like stories with drama that unfolds between a large roster of characters. It is easy to see why it is so popular with businesspeople. I'm currently reading it through the Kindle app on my iPhone.

Raising Your Resolution: Four Perspectives and Methods to Bring Clarity to Ambiguous Thoughts through Depth, Breadth, Structure, and Time (Takaaki Umada, Eiji Press)

I met the author, Mr. Umada, through an acquaintance, and that led me to pick up this book. This book articulated its thought process well, allowing me to discover new ideas. I have been working with the university startup Quanmatic as its Chief Technology Officer (CTO) since its inception. This requires me to use a different "brain" than I do at Keio. I am interested in reading not only this book but also other books on how to think with a business mindset. I've applied the ideas from these books to my research and laboratory activities, and I have come to realize the importance of having a diversity of experiences. By the way, I mainly use the Kindle app on my iPad to read these books.

The Non-Designer's Design Book (Robin Williams, trans. Norihide Yoshikawa, MyNavi Publishing)

I picked up this book when I was an undergraduate student after a friend recommended it to me. As the book title suggests, it introduces the concept of design for non-designers and has an abundance of examples. Since it is intended for non-designers, it is very informative, with guides that tell you what you need to do at the bare minimum. Since I pay attention to the design of things in my research lectures and poster presentations as well as the handouts used in my teaching, I sometimes go back to it and use it in my work.

Quantum Spin Glasses, Annealing and Computation (Shu Tanaka, Ryo Tamura, Bikas K. Chakrabarti, Morikita Publishing Co.)

This is the first technical book that I wrote in Japanese. I originally wrote it in English, and then translated it into Japanese. I can still recall the difficulties I had in compiling all my technical knowledge on quantum annealing and related fields into this book. The contents are extremely specialized. It is very useful for teaching lab students and preparing them for the lecture on quantum computing offered through the Department of Applied Physics and Physico-Informatics.

Writing Techniques for Science and Engineering (Koreo Kinoshita, Chuko Shinsho)

This is a well-known book. I picked it up during my first year as an undergraduate because it was being displayed in the book section of my university co-op. It was actually very difficult for me when I first got it, but when I was a graduate student I went back and read it again. I was writing more due to my research activities and was able to understand it a little better. Now that I do a lot of writing for my job and provide feedback to students in my lab on their writing, I am re-reading it again. This is one of the books I value the most in teaching someone how to write.

Grateful for My Environment and the People I Met

Shu Tanaka

It has already been five years since I opened my laboratory at Keio's Department of Applied Physics and Physico-Informatics in the Faculty of Science and Technology in April 2020. In March 2024, I gave a sendoff to the lab's first cohort of students, and it is safe to say that all the different events of the laboratory have finally come full circle. The timing of this opportunity to be featured in the New Kyurizukai also allowed me to reflect on my own career path to date. And I realized again the importance of having a mindset where you do what needs to be done given your situation at the time and be thankful for the encounters you make there.

There were many twists and turns from my student days to my current position. However, by keeping positive, I believe I was able to make it this far without losing heart. Of course, the process was not smooth sailing in the slightest. I often compared myself to others, and I caused a lot of worry and trouble for a lot of people. Nevertheless, the one thing I came to value was the ability to work hard at what needs to be done, making the most of the environment I was given while leaning on the support of the wonderful people around me.

Compared to when I was a student, today there is an overabundance of information, and it is easy to feel outshined by those we perceive to be doing "better" than us. Because of that, some may feel rushed to accrue experiences that set them apart. It is good to be motivated by outside influences, but it is also good to adjust your mindset so you can think a little more calmly. If we take full advantage of our current environment, we can get something out of it. We may not be privileged enough to have special experiences for one reason or another. You can apply that positive mindset to make the best of your circumstances in those cases, too. Taking full advantage of the environment around you may seem like a modest undertaking, but I believe it will allow you to develop a variety of skills and provide a strong foundation for future work.

I myself am currently engaged in a number of tasks in different capacities, including leading a laboratory, organizing various R&D projects, and serving as CTO of the startup company we founded, Quanmatic. I feel that I am able to carry out these tasks because of the support of the people around me, as well as the experience I have gained by taking advantage of the environment around me. And now, in full appreciation for this wonderful environment, I hope to lay the foundation for future work in the years to come, and beyond.

理 工 学 Information

Keio's Faculty and Graduate School of Science and Technology Advancing the KeiDGs for Their 100th Anniversary

Artist: Ryoko Utsunomiya
Art Direction: TokyoDex

Keio University's Faculty of Science and Technology and Graduate School of Science and Technology are working to advance the Keio Diversity, Equity, and Inclusion Goals (KeiDGs) as action goals as we set our sights on 2039, the 100th anniversary of the faculty and graduate school's founding. KeiDGs are objectives that incorporate the concept of diversity, equity, and inclusion (DE&I)—whose significance has become increasingly apparent in recent years—into education and research while also framing it along with the spirit of Keio's founder, Yukichi Fukuzawa.

Based on these goals, a working group established by the faculty and graduate school is actively aiming to implement various measures and events. The Faculty of Science and Technology and the Graduate School of Science and Technology will forge ahead, advancing the KeiDGs to shine not only as they approach their upcoming 100-year anniversary, but also in the years to come.

For more details on the activities of the KeiDGs, be sure to check out the following website.

https://dei.st.keio.ac.jp/en/

Editor's postscript

For this 40th issue of the New Kyurizukai, we featured Associate Professor Shu Tanaka and his research on quantum annealing and quantum computing. When we consider the scope of how combinatorial optimization can be applied and how it can impact society, we naturally dream of a brighter future.

Through the interview and comments from students, you can see how sincerely Tanaka works with each and every member of his laboratory. In turn, this created a warm, welcoming atmosphere in the lab, with students naturally gravitating around him. (Fuhito Sugihara)

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