Kyurizukai
新版 窮理図解
2024 October
no. 41
Bulletin of Keio University Faculty of Science and Technology
https://www.st.keio.ac.jp/education/kyurizukai/
English versions are also available:
https://www.st.keio.ac.jp/en/kyurizukai/

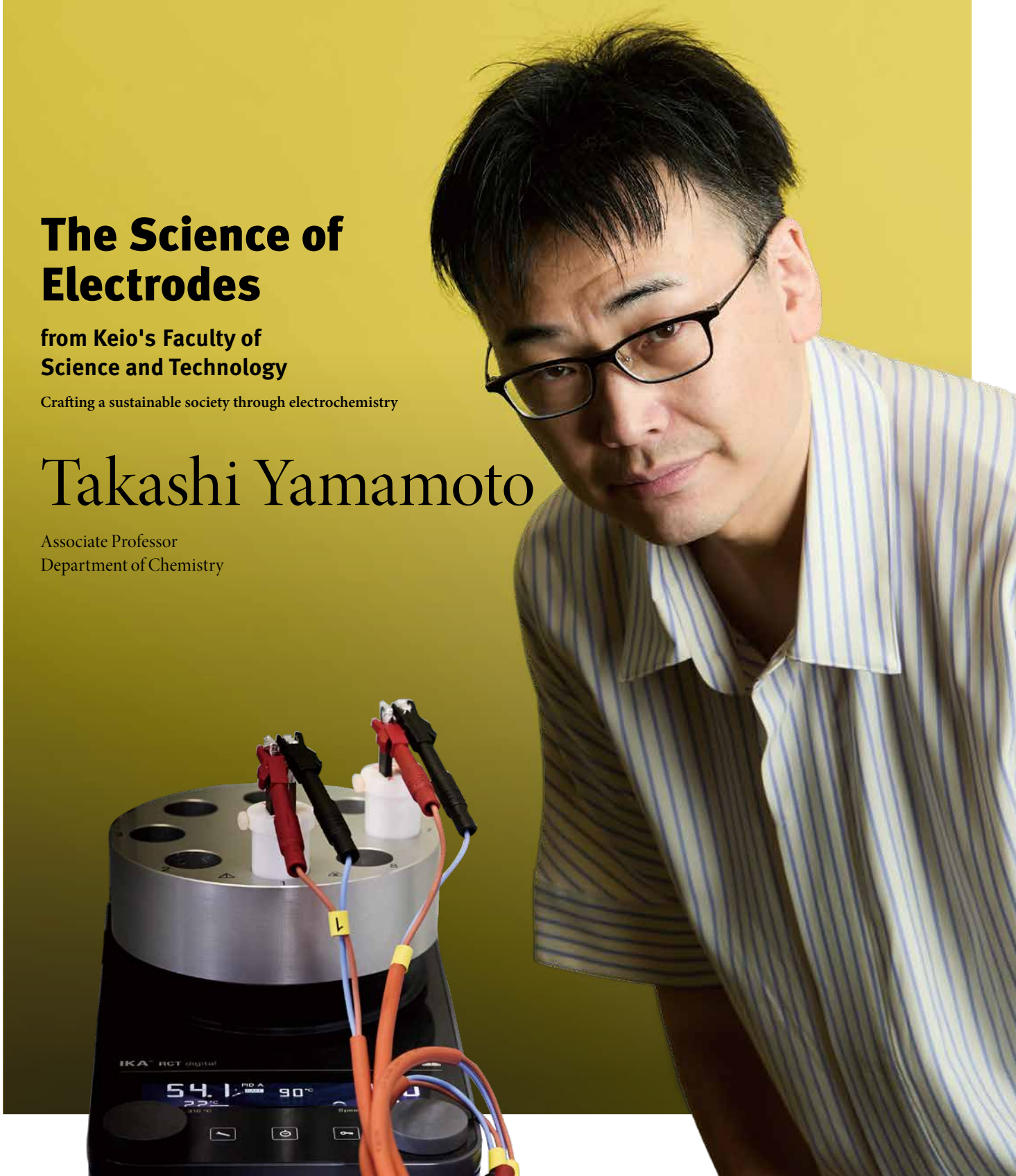
The Science of Electrodes

from Keio's Faculty of Science and Technology

Crafting a sustainable society through electrochemistry

Takashi Yamamoto

Associate Professor
Department of Chemistry



This feature explores how Associate Professor Takashi Yamamoto is using "electro-organic synthesis" to find green and sustainable ways for manufacturing processes.

Electrifying Organic Synthesis

Synthesizing organic compounds using electricity, known as "electro-organic synthesis," has received a world-wide attention for its potential in reducing CO_2 emissions and reagent wastes, thereby realizing a more sustainable manufacturing process. In this increasingly competitive field, Associate Professor Yamamoto hopes to replace conventional manufacturing with new methods through his own unique approach.

Organic compounds essential for our daily life

We are surrounded by man-made objects. Among them, organic compounds (carbon-based substances) play a vital role in our daily life, as plastics, elastics, synthetic fibres, and pharmaceuticals.

Synthesis of organic compounds generically requires "special reagents", e.g. catalysts, to accelerate chemical reactions. In addition, huge amounts of energy are often required because some reactions take place at high temperature. Of course, while most reagent wastes produced from the reactions are properly collected and disposed of, the environmental impact could be significantly reduced by excluding such reagent wastes from the process.

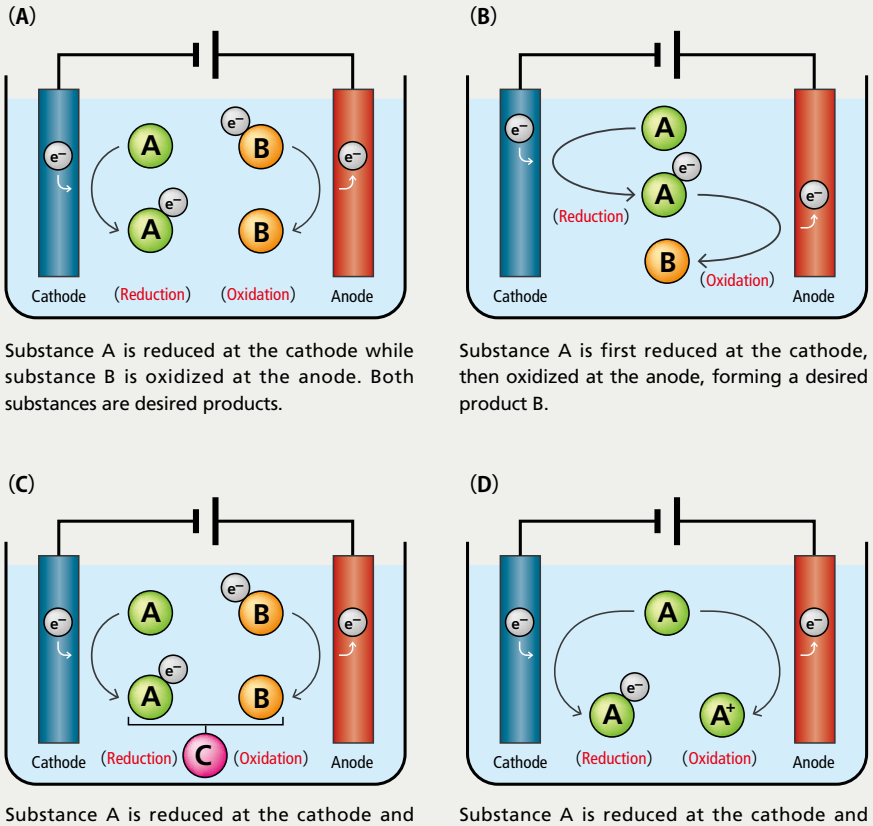
This is the background of "electro-organic synthesis". Associate Professor Yamamoto at the Department of Chemistry is one of the leading researchers in this exciting field.

Electro-organic synthesis?

Do you remember learning about electrolysis in junior high school? When an anode and cathode are immersed in water (H_2O) and electricity is applied , hydrogen (H_2) is generated at the cathode and oxygen (O_2) is generated at the anode. "Electro-organic synthesis" applys such electron transfer events to create new organic compounds from other organic compounds (Figure 1). A chemical reaction is driven by electricity instead of special reagents.

Main achievement during a short-term study at the University of Mainz

Yamamoto started researching electro-organic synthesis in 2016, when he stayed at Johannes Gutenberg University Mainz (University of Mainz) in Germany. "At that time, I was struggling to keep up with the speed of research field that I had been working in, so I was feeling quite anxious about my future. Fortunately, I was given the opportunity to study abroad through the Keio University Ishii-Ishibashi Fund for Young Researchers. At the time, I had been working as a



Substance A is reduced at the cathode while substance B is oxidized at the anode. Both substances are desired products.

Substance A is first reduced at the cathode, then oxidized at the anode, forming a desired product B.

Substance A is reduced at the cathode and substance B is oxidized at the anode. They react to form a desired product C.

Substance A is reduced at the cathode and oxidized at the anode, resulting in desired products.

Fig.1
Paired electrosynthesis for more efficient use of electricity
Reduction (receiving electrons) and oxidation (losing electrons) occurs at the cathode and anode, respectively. Activated species by this process react to produce a desired substance. Even though electro-organic synthesis does not use special reagents, energy is wasted if the electricity is not used efficiently. In order to avoid this problem, researchers in electro-organic synthesis have been developing "paired electrosynthesis," which leads to the synthesis of target substances at both the cathode and the anode.

senior assistant professor with Professor Yasuaki Einaga. I wanted to try breaking new ground that can be continued when I returned to Japan. Since Professor Einaga is working on the chemistry of diamond electrodes, I searched a research topic related to the diamond electrodes." Thus, I began research on electro-organic synthesis using diamond electrodes with Professor Siegfried R. Waldvogel at the University of Mainz.

In 2017, he succeeded in synthesizing α-diisoeugenol from isoeugenol (Figure 2). "Even though the starting material was the same, when solvent was changed and applied an electric current, the products were different from what I expected. Even though I had been studying chemistry for a long time, I was so shocked that such a thing happens."

This is not the only thing to shock Yamamoto. In chemical synthesis, stereoisomers—isomeric molecules that have the same chemical formula, but different spatial arrangements of their atoms—are obtained mixed together without any special trick. Because stereoisomers have different properties, it is necessary to separate them once mixed. Therefore, one of the major challenges in chemical synthesis lies in easily produce only the stereoisomer of interst. To return to Yamamoto's experiment,only α-diisoeugenol was produced and no other stereoisomers were present.

Based on what he learned and achieved in Germany, Yamamoto is now working electro-organic synthesis using diamond electrodes at the Einaga Group.

Intense competition in green and sustainable manufacturing

The situation has changed since Yamamoto has started researchin electro-organic synthesis,. "Attempts to synthesize substances using electricity have a long history, dating back to the 1800s. In the late 1900s, the field of electro-organic synthesis made great progress, but the number of researchers working in this field did not increase significantly because of the lack of equipment that anyone could easily handle. Now, however, the situation is completely different. Various companies sell electrosynthesis equipment that is easy to use, lowering barriers to starting research in electro-organic synthesis. Electro-organic synthesis not only avoids the use of special reagents, but also allows power to be supplied from renewable energy sources such as solar power and wind. Therefore, electro-organic synthesis is undergoing a worldwide development race, as enables manufacturing that can reduce CO_2 emissions."

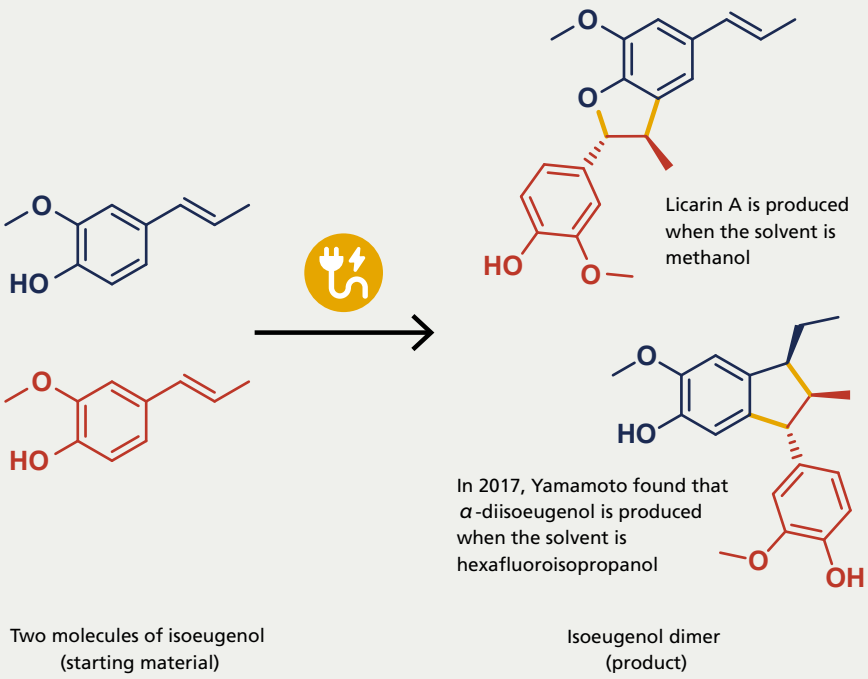


Fig.2
Electro-organic synthesis using isoeugenol as a starting material
This is the main achievement that Yamamoto had done in University of Mainz. When hexafluoroisopropanol was used as a solvent, α-diisoeugenol was formed from two isoeugenol molecules (bottom). Previously, it was known that licarin A was formed when methanol was used as a solvent (top). It was a big surprise that changing the solvent had a strong impact on the product. Yellow lines indicate newly formed bonds.

Competing with the world through research that only I can do

However, Yamamoto is not anxious about the future of his research as he used to be. This is because he is absolutely confident in the electrode material that is a significantly important factor in electro-organic synthesis.

"The diamond electrodes prepared at the Einaga Group have several excellent properties for electro-organic synthesis that other electrodes do not have. I will explain two representatives. First, the highly reactive radical species that are produced by applying electric current are stable at the surface of diamond electrodes. Second, diamond electrodes can be used over a wide range of voltages. Overall, diamond electrodes enable to realize chemical reactions that would not be possible with commonly used electrodes."

Yamamoto is also attempting to make own improvements to their diamond electrodes. "My previous research project was developing the optical and magnetic properties of inorganic nanosheets towards next-generation devices. I can make a modification of the electrode surface based on the experiences and techniques I acquired from those studies. It is really interesting to see how changing the properties of electrode surface influences on a yield and selectivity of products. I aim to pioneer a new 'science of electrodes' by establishing a fundamental theory behind these phenomena."

Yamamoto also talked about the various things he aims to accomplish. His ultimate goal is to "realize chemical reactions in electro-organic chemistry that even high school students can understand." "An example would be to replace the reactions that are already in textbooks and used in industry (e.g. reactions that require high temperatures and pressures) with electro-organic synthesis. Realizing this goal would be the only way I can say that I have achieved green and sustainable manufacturing."

Electro-organic synthesis is currently facing a wave of intense competition. Yamamoto is drawing on his breadth of experiences and making strong strides forward to achieve his impressive goals as a researcher.

(Interview and text writer: Akiko Ikeda)

Being thorough and carving a path within a school that values independence

Yamamoto describes himself as unable to move on from something until he is convinced that he has examined it from every possible angle. Along the way, he is able to give his all to issues that demand his undivided attention. One can only imagine how this painstakingly accumulated expertise and experience might be used to fuel future research and education at the university.

I understand that your father also worked as a professor at a university.

That's true. He specialized in soil microbiology and taught at Shimane University. As a child, I would often visit my father's lab, which made me want to follow in his footsteps by studying agriculture. As fate would have it, I actually failed the exams for the national university I applied to for agricultural studies. As a result, I ended up going to Keio University. That's how I got my start in chemistry.

One ironic story I like to share from that time was how my older brother accompanied me on the bullet train when I was visiting Tokyo to finish up some admissions' paperwork for Keio. He looked out the window and shouted, "You can see the Pen Mark logo!" I still remember how I felt gazing up dejectedly at the Pen Mark on one of the Yagami Campus buildings.

How was your time at Keio as a student?

I was surprised by the gap between what I had studied of chemistry in high school compared to what they taught in college. I was especially worried that I would fail organic chemistry. If you don't study, you don't know how electrons move, and if you don't know how electrons move, you don't know how they'll react. I had my organic chemistry classes on Fridays. Afterwards, I would go get dinner somewhere in Hiyoura (the shopping district on the opposite side of Hiyoshi station from the university), head back to the university by 7 p.m., and study for around two hours at the Media Center (the library on Hiyoshi Campus) until it closed. I wasn't really involved with extracurriculars as an undergrad. I had enough on my plate living by myself for the first time in a completely new city.

How did your working relationship with Professor Yasuaki Einaga develop when you joined his laboratory as a fourth-year student?

I was in the first-ever cohort for the Einaga Laboratory. He was still relatively early in his career, and we had a lot of free time to get to know each other in the lab. It has made it easy to continue working on research together. The ways that we approach our research, though, are quite different. He's what I would call an "elevator type," someone who has a goal and moves linearly towards that goal. I am more of a "staircase type." I like to be sure of my footing and test what I can do every step of the way. I think these differences have actually contributed greatly to our success in working together. Because I am so thorough and don't like to move on without covering all of my bases, my current students seem to think of me as being incredibly detail-oriented [laughs].

Can you tell us more about your experiences studying abroad and working at other universities?

I studied abroad in 2007 at Florida University to learn from Professor Daniel Talham. I admired how detailed his work was and I had always been interested in the types of research he was doing. In person, he was someone who really valued language. He was the one who taught me what it means to explain something accurately.

After returning to Japan in May of 2008, I studied polymers at the Tokyo Institute of Technology (renamed October 2024 to "Institute of Science Tokyo") under Professor Tomokazu Iyoda. He was incredibly strict. Maybe it was because I never met his expectations of how much research I should be completing as a project researcher, or maybe it was because he wanted me to model what it meant to be a researcher for my underclassmen. Either way, I couldn't escape him even in my dreams [laughs]. However, I can't deny that those experiences shaped who I am now as a researcher. I also learned that for every breakthrough research paper or shiny-new technology, there are innumerable mundane and rough experiments taking place behind the scenes.

Fast-forwarding to April 2009, what was it like to return to Keio University?

When I told my family that I would be starting as a faculty member in April, the first thing my father said was, "Don't forget that you are an educator before you are a researcher." I was shocked. It was the first time I had to come to terms with the fact that I would be teaching, despite the fact that I had spent every

As a faculty member, I want to be seen as someone who can provide meaningful answers to my students' questions.

Takashi Yamamoto

Specializes in electro-organic synthesis and solid-state chemistry. Yamamoto graduated with a bachelor's degree from Keio University's Department of Chemistry in the Faculty of Science and Technology in 2002. He then went on to complete a doctoral program at the Graduate School of Science and Technology in 2007, receiving his Ph.D. in Science. He began working at Keio University after completing positions as a postdoctoral research fellow with the Japan Society for the Promotion of Science (JSPS), a visiting research fellow at the University of Florida, and an industry-academia-government project researcher with the Tokyo Institute of Technology's Laboratory for Chemistry and Life Science. At Keio, he was hired as a non-tenured assistant professor with the Faculty of Science and Technology in 2009, was promoted to assistant professor in 2011, became a senior assistant professor in 2014, and assumed his current role as an associate professor in 2023. From 2016 to 2017, he also worked concurrently as a visiting research fellow at the University of Mainz.

waking hour until then focused exclusively on my research and experiments.

I don't know if it was because I had left for a while, but returning to Keio University felt like coming home. It was a very comfortable transition. However, working as a faculty member and being responsible for teaching courses was an entirely new challenge.

I am always trying my best to be able to answer my students' questions as thoroughly as possible. Keio students are all incredibly bright and talented. They'll often look things up on their own before coming to me. In a way, I am the "last line of defense." If my students come to me, I want to make sure that I am approachable and a presence that can offer them advice and hints about what to do to make progress. This is what inspires me to keep learning every day and it is my personal interpretation of the phrase here at Keio, "learning while teaching, teaching while learning."

I have heard that you made a drastic change in your research in 2016. What inspired that decision?

I felt like I had become stagnant in my research, and when I looked at the amount of time I had left in my career as a researcher, I figured I still had time to pivot to a new field (as seen in my research overview). The laboratory where I studied (at Johannes Gutenberg University Mainz) was led by renowned scientist Dr. Waldvogel. There were many excellent students at the lab at the time and the program was designed to allow international students to participate easily. It was an "iron sharpens iron" environment, and I am very proud of the research results we produced (as seen in my research overview).

This made me realize firsthand that long hours in a laboratory are not always the "right" answer. The important thing is to be able to focus and give your full attention to the research at hand.

What would you like to say to any high schoolers who plan to enroll at Keio or to the college students already here?

For my research, I had studied with Professor Talham and Professor Waldvogel, both of whom are first class in their areas of expertise. If you want to be first class in any given specialty, you need to encounter things that are "first class." Eat "first-class" food, observe "first-class" art, come into contact with "first-class" items.

I personally think that Keio University is an incredibly liberating environment compared to other schools partly because of its commitment to Yukichi Fukuzawa's teachings about "independence and self-respect." Both students and faculty value each other's autonomy. In return, individuals have to practice self-discipline, but I think it's incredibly valuable that it is an environment in which people are challenged, not reproached for failing those challenges, and able to receive critiques on their processes. It's an environment that promotes growth in both students and faculty members, allowing us all to bloom at our own pace.

◎ Some words from students . . . ◎

● Professor Yamamoto has an amazing sense of humor and always enjoys talking with his students. I was working on some basic research about how to change an electrode's properties by altering the functional groups of a diamond electrode's surface. Professor Yamamoto is so knowledgeable about this type of thing that he knows how to give the perfect advice. His motto is "Never be aimless while conducting an experiment." There is a lot of repetition for our research, but I've learned to remain conscious of the reasons behind what I am doing while I am working. Professor Yamamoto is also wonderful about providing feedback on the reports we submit each week, pointing out grammatical errors or faulty logic. As a researcher, I feel like I am able to learn a lot from him as my professor (First-year master's student).

(Interview and text writer: Akiko Ikeda)

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

Takashi Yamamoto's ON and OFF

A few glimpses into his free time

Mainz

This short-term study abroad program in Mainz (Germany) became a huge turning point for me as a researcher. Because it meant so much to me, I thought I would take the time to introduce some of my favorite spots.

1. FSV Mainz 05 The football club in Mainz. I went to see all of the home matches while I was there!

Mainz Cathedral One of the three Kaiserdom ("Emperor's Cathedrals"). The morning market held outside in the square was always bustling with people.

Mett Raw pork sandwich. A student from the lab where I was studying went out of his way to make me one of these. According to the student, it can be hard to get your hands on Mett sometimes because of the strict criteria that go into its production.

The Collegiate Church of St. Stephan Blue stained-glass windows created by Marc Chagall. The gorgeous Chagall blue windows always drew me in and made me lose track of time.

Nicolai Bergmann

A photo of me with Nicolai Bergmann, who has been teaching flower arrangement for over ten years. I felt very refreshed while working on an arrangement.

Florilège

I have been going to this French restaurant consistently over the last ten years. According to head chef Hiroyasu Kawate, the vegetable dishes are the real highlight.

OVERCOAT

This fashion brand has been a favorite of mine for years. I like the structural elements of the design (especially around the shoulders). This picture is of me with designer Ryuhei Oomaru.

Other Delicacies

I'm a bit of a foodie, so I wanted to show off some of the best dishes I tried while abroad.

私の本棚
My favorite books

Yūki Denki Kagaku: Kiso kara ōyō made (edited by Toshio Fuchigami, co-authored by Mahito Atobe & Shinsuke Inagi, Corona Publishing)

This is a textbook for what I am currently working on for my research, electrochemistry and electrochemical synthesis. I even took it abroad when I did my short-term study abroad program in Mainz. Because I have reread this book so many times and lent it out to students who were interested in these topics, the one in the picture is my third copy. An English version of this textbook also exists called *Fundamentals and Applications of Organic Electrochemistry*, which allows me to compare the vocabulary and expressions with the Japanese text.

"B'z LIVE-GYM Pleasure 2008 -GLORY DAYS-" (DVD, Vermillion Records)

I have been a huge fan of B'z for more than 30 years, ever since I was in junior high school. I have attended their live performances every single year for the last 25 years (including individual performances for Koshi Inaba and Tak Matsumoto when they took time off for their solo careers). Many of their concerts are unforgettable experiences for me, but if I had to choose a favorite, this is the easy winner. Whenever I am feeling physically or emotionally exhausted, I listen (and remember) what the band said before their second encore piece, "RUN," in order to give me the motivation to keep going. When I heard this live originally back on September 21, 2008, in the Nissan Stadium, I shed quite a few tears.

Shikou no Houhougaku (Osamu Kurita, Kodansha)

This book on critical thinking breaks down ideas so that they're extremely easy to grasp, teaching you to "look at the world using logic" and to "make an action plan when addressing problems." The model of analysis that this book presents works well for planning, implementing, and reviewing research, but it can also be applied to accomplish basic goals in one's daily life. I am sure that many high schoolers could benefit from applying a methodological approach to their thinking patterns when setting goals (such as getting good grades on tests or developing their skills during extracurricular activities). I have had the chance to work with the author, Professor Osamu Kurita (Department of Industrial and Systems Engineering, Faculty of Science and Technology, Keio University), on several occasions when we were on the same committee within the faculty. The depth of his insights during those times always impressed me, and reading this book helped me understand his thought process.

Words of Advice for Young Business People (Tsuneo Sasaki, Wave Publishing)

This is a book my father introduced to me as I was getting ready to take on my position in the world of education and research as an assistant professor. According to the author, he had worked to compile the "essence" of working and living happily based on his personal experiences for people in their twenties and thirties. It's a book I often recommend to my students while they're still in school. I pick it up every time my own position (job title) changes, and I am impressed that I always manage to discover new things on every reread. The author wrote another excellent book titled Look at you! You're the Boss Now. If you're interested, definitely give that a read, too.

It is difficult to say what is impossible, for the dream of yesterday is the hope of today and the reality of tomorrow.

Takashi Yamamoto

"Would you be interested in appearing in our research bulletin, the *Kyurizukai*?" This was the question I found in my email inbox at the end of March 2024, completely out of the blue. I spent some time wondering what to do, but ultimately, I thought that it would be a good opportunity, so I said yes. Looking at the overview of what was expected, there were no obvious hurdles with the "Research Introduction" or the "Interview" portions of the *Kyurikuzai*. The "ON hours, OFF hours" and "My Favorite Books" sections looked like they would take a little time, but my impression was that the "Column" (what I am trying to work on at this very moment!) might present a challenge. I was told that the topic could be open-ended, so I have decided to write on "the significance of looking back" and "what I hope to research in the future."

If you read through my interview, you can see that I was asked a pretty thorough range of questions (and I certainly talked quite a bit). Thanks to this line of questions, I was able to remember how I felt about chemistry and what I was thinking about during different stages of my life, whether as a student, postdoctoral researcher, or faculty member. It was especially poignant to think about my career trajectory as a researcher and how much this was influenced by my time at the Tokyo Institute of Technology under Professor Iyoda and my exposure to electrochemistry and electrochemical synthesis at the University of Mainz with Professor Waldvogal. It made me realize how important it can be to take a moment on a regular basis to remember those times and how far I have come.

Now I would like to expand briefly on my future research plans which I touched on at the end of my "research introduction."

While my research used to focus on "controlling the optical properties of inorganic nanomaterials through their magnetic properties," through the various people and places I've encountered, my research has turned to "electro-organic synthesis with diamond electrodes." Now that I have accumulated a decent amount of expertise in electrochemical synthesis, I am thinking about ways that I might integrate my current work with topics that I used to research. While I am still only in the conceptualization stage, my core idea is to see whether it is possible to make "spin/space" electrochemical material transformations (electrochemical synthesis) by precisely aligning the "spin" of magnetic materials with the spatial properties of coordination compounds.

My ultimate goal is to use the rest of my career as a researcher to pioneer a new "science of electrodes" by drawing from the whole of my experiences.

* The title is a quote from the American rocket scientist Dr. Robert H. Goddard. It is one of my favorite quotes. I learned it from a rocket engineer when I was studying abroad in the U.S.

理 工 学 Information

The 25th Annual Science and Technology Exhibition, KEIO TECHNO-MALL 2024 The Origin of *Jitsugaku* and Building Bridges to Future Generations

The KEIO TECHNO-MALL is an event that showcases research findings from Keio University's Faculty and Graduate School of Science and Technology. It also serves as a platform to facilitate technology transfer, joint research, and other collaborations between industry, government, and academia. Keio University will be making an appearance again this year at the Tokyo International Forum which will be taking place on Friday, December 13, 2024.

This year, in addition to representatives from Shonan Fujisawa Campus (SFC) and the Office for Open Innovation, Keio will also be sending people to present on behalf of the Keio University Hospital. This group of talented individuals will show the incredible discoveries that Keio University makes possible through its diverse organizational structure and how working together as a consolidated whole creates a path forward for the greater Keio community.

We will be posting information for potential attendees at the link below near the end of October. We look forward to seeing you there.

https://www.kll.keio.ac.jp/ktm/

Editor's postscript

Every time Associate Professor Yamamoto—a self-described "free spirit"—would make a quick stop at our office, he would always get a laugh out of our staff before leaving. Incredibly openhearted and good-humored, he also revealed another side of his personality and his more serious approach to everything he is involved in as we delved into his research and private life. Getting a chance to home in on a researcher's personal nuance and humanity is the main draw of the New *Kyurikuzai*. I feel like we accomplished this in our 41st issue and hope our readers feel the same. (Fuhito Sugihara)

Cover of current issue : With his electro-organic synthesis equipment.
Hair design by taro (RE:-ORGANIC & DETOX-)

新版 窮理図解

New Kyurizukai
No. 41 October 2024

Editing: "New Kyurizukai" Editing Committee
Photographer: Keiichiro Muraguchi
Designers: Hiroaki Yasojima, Yukihiko Ishikawa (GRiD)
Cooperation for editing: Sci-Tech Communications, Inc.
Publisher: Toshiyuki Murakami
Published by : Faculty of Science and Technology, Keio University
3-14-1, Hiyoshi, Kohoku-ku, Yokohama, Kanagawa 223-8522
For inquiries (on "New Kyurizukai" in general) :
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For inquiries (on industry-academia collaboration) :
kll-liaison@adst.keio.ac.jp
Website version:
https://www.st.keio.ac.jp/en/kyurizukai/