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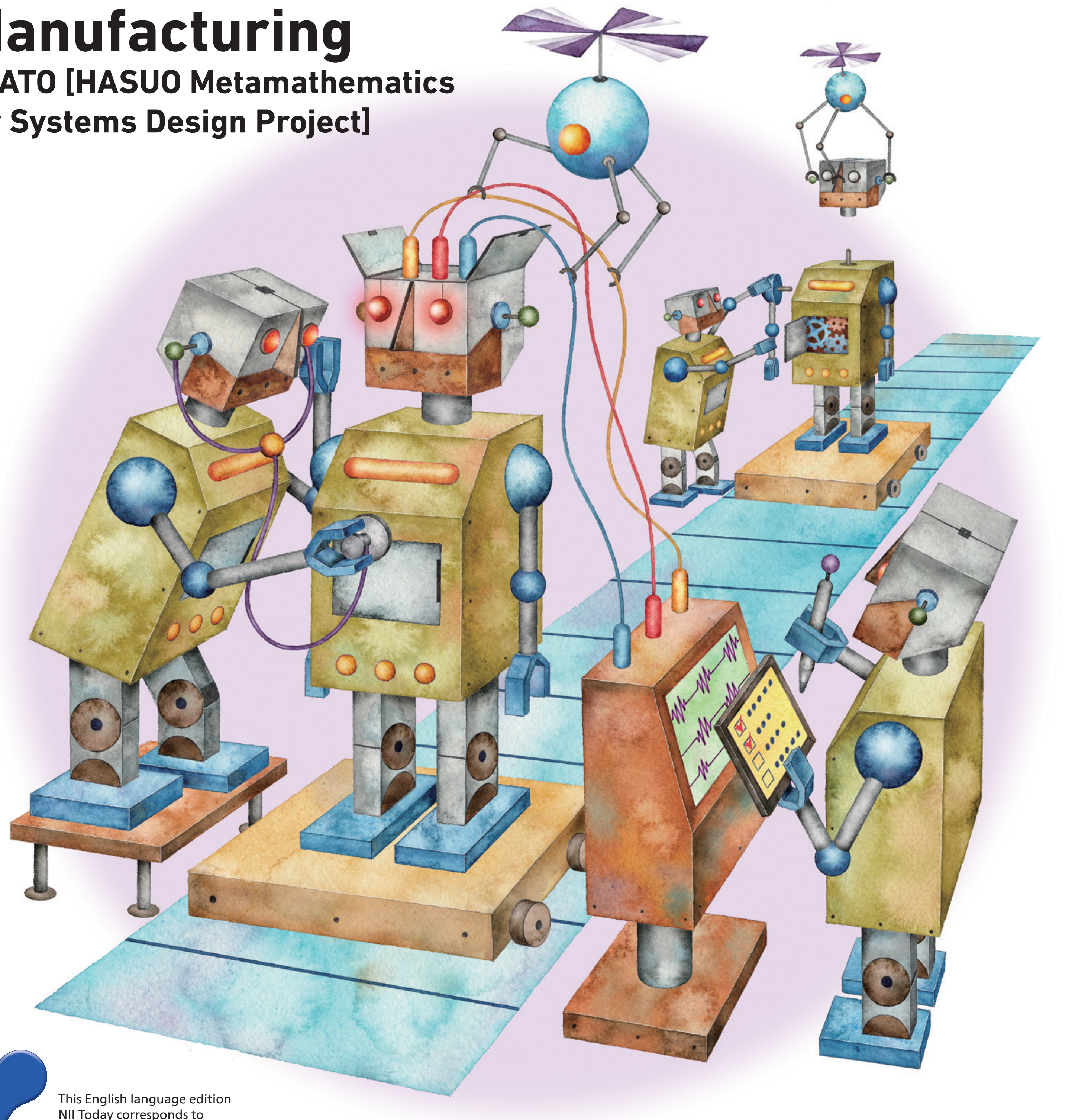
ERATO [HASUO Metamathematics for Systems Design Project]



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Supporting Design of Manufactured Products using Abstract Mathematics

Adjusting "formal methods" from software to manufactured products

Ichiro Hasuo Associate Professor, Information Systems Architecture Science Research Division, National Institute of Informatics
Associate Professor, School of Multidisciplinary Sciences, SOKENDAI (The Graduate University for Advanced Studies)
Research Director, JST ERATO HASUO Metamathematics for Systems Design Project

Interviewer : **Nobuyuki Yajima** Senior Researcher, Nikkei BP Intelligence Group

"We can certainly bring concrete improvements to real-world manufacturing, such as shortening time needed for testing," declares NII's Associate Professor Ichiro Hasuo. Selected by the Japan Science and Technology Agency (JST) for the ERATO scheme, the HASUO Metamathematics for Systems Design Project running from October 2016 until March 2022 will develop theories and methods to support the design of manufactured products and accrue at least five concrete real-world improvements. I asked Associate Professor Hasuo what they are aiming for, how they will proceed, and why they can say with confidence that they will achieve their goals.

Yajima You were involved in establishing mathematical theories useful in quality assurance of computer software, so why did you decide to enter into the polar opposite world of design support for manufactured products?

Hasuo The highly abstract world of mathematics for software and the entirely tangible world of manufacturing may be considered to be quite far apart, but I do not feel that I am doing something completely different. The reason is that I have been researching an area of mathematics called category theory for a long time, and this project also involves category theory.

Category theory can be thought of as a language for describing mathematical theories more abstractly. When a theory that supports various quality-assurance methods is described using the vocabulary of category theory, it increases the level of abstraction of the theory, and as a result, can make it possible to see the essence of the theory and understand it better in a general and universal manner. That instant of discovery and understanding feels really good. The joy of knowing and understanding something new is my motivation for continuing to conduct research.

Ichiro Hasuo

Of course, it cannot just be about having fun. Category theory makes it possible to grasp the essence of things with an overhead view, and when I thought about what it could be useful for, manufactured goods came to mind. The manufacturing industry is extremely important for Japan, so I thought it might also be possible to help the economy.

When the level of abstraction is raised, software and cars, for example, start to look the same. A car is a complex machine loaded with numerous computers, each containing software, so it can be regarded as a large piece of software. That being the case, I thought that the theories and methods of design support and quality assurance that have been developed in the world of software should certainly be applicable to cars. That is what the current project is looking at.

Yajima What will it involve specifically?

Hasuo We will extend the "formal methods" that enable design of high-quality software and apply them to manufactured products that include hardware and software. I said that cars are software, but of course, there are differences. Unlike software, cars have physical mechanisms, they use energy, and they must perform in real time. These factors need to be additionally addressed in the formal methods.

The project consists of four groups. The theory group will clarify the essence of formal methods using, for example, category theory; the practical group will extend formal methods based on theories so that they can be used for manufactured products; and the application groups will produce results by getting companies to use the extended formal methods at their manufacturing sites.

There are two application groups. One group will apply the theories and methods that we are researching in this project to problems that manufacturing industry currently faces, while the other group will apply them to the future challenge of autonomous driving.

Yajima How does this differ from implementing formal methods at production sites straight away, without introducing, for example, category theory?

Hasuo As I said earlier, we will apply the methods after understanding their generality and universality. We will be able to introduce the advantages of the formal methods to the sites in a targeted way. One of the features of this project is that we will be talking with engineers at production sites, listening to their needs, and proposing ways of applying the methods to meet their needs so that they are actually used in practice. If we do not increase the level of abstraction of the methods, then responding to individual needs will be all the more difficult. However, some things are only understood as a result of direct application, so we will handle this matter according to the needs.

Yajima Can you deliver outcomes at production sites where results are severely questioned?

Hasuo Yes, we can, because we are thinking of results like this... suppose, for example, that the needs of an engineer in industry are expressed to us as: "The software verification test takes a whole day, but we want to get it done in half a day." We will have a varied repertoire of essences of formal methods, so we will be able to propose a solution that suits the needs. Formal methods are delivering results in terms of simplifying complicated tests. I am confident that these essences can also exert power in the field of manufacturing.

Yajima So this is not a project that boasts, "We've created all these amazing theories and methods. Please use them."

Hasuo If we call an existing formal method 1, then the goal of the project is not to create a formal method 2, all at once, that has been extended for manufactured products. We are expecting formal method 2′ and formal method 2′′ to be gradually developed in response to needs. Furthermore, method 2′ and method 2′′ will not be created just by the research group in the laboratory, but rather together with the engineers at work, making use of their wisdom. By diligently accumulating results, we intend to accrue five success stories.

I still remember the words of my Ph.D. supervisor, who said, "Some theoretical research is only possible as a result of practical application," and "For that reason, go on site and get your hands dirty!" At the end of the day, this project is an academic research project and the aim is to establish theories, but in order to make the theories robust, we are attempting to adjust them to suit the needs of real-world industry applications. I am a theoretical researcher, but I am prepared to get my hands "dirty" on site.

Yajima Are there any challenges?

Hasuo Well, yes, I say that I am ready, but actually determining the companies that we will collaborate with and going to the sites are all in the future. I would be lying if I said that we theoreticians are not at all anxious about our ability to talk with practitioners. However, while speaking to industry people in preparation for this project, a trend towards investigating things outside of our own areas of expertise has definitely emerged within our group.

This project gathers together researchers who support the aims of the project, but everyone has different specializations, such as mathematics, software, and control. People who are experts in category theory are reading books about control theory and having discussions with people who specialize in control—these kinds of changes are taking place. This is because, even if people's areas of expertise are different, once the level of abstraction is raised, it becomes easier to talk to each other. I hope that will also be the case when we talk to practitioners in the manufacturing industry.

Yajima Talking with you, I finally understand the meaning of the name of the HASUO Metamathematics for Systems Design Project. "Meta" because the project aims will be achieved by way of abstraction, and then design will be carried out using mathematics, in other words, the metamathematics will support design. Could you not have done something about the name?

Hasuo I did want to spice it up... I know we need to have a more accessible catchphrase so that many people who are not particularly interested in mathematics or software are made aware of our efforts. I will think of one by 2022 at the latest. Leave it with me!

(Photography by Yusuke Sato)

A Word from the Interviewer

"If we ask for something in the abstract we might get something in the concrete." So wrote the English writer G. K. Chesterton, explaining that results cannot be achieved without clarifying the concept of things. These words came into my head as I listened to Associate Professor Hasuo explain his project.

He is literally aiming to obtain concrete results by asking for them in the abstract—to help solve problems in industry by further increasing the level of abstraction of inherently abstract formal methods. This approach is a hallmark of the project.

Formal methods are well established, but they are considered to be expensive and time consuming, and are used exclusively for special software requiring high reliability. If this project can uncover the essence of formal methods by raising the level of abstraction, then it seems likely that the results will spread into new areas such as the manufacturing industry.

Taking a broader view, this approach could contribute to one of Japan's biggest challenges—that of collaboration that goes beyond specific disciplines. The reality is that, for example, people belonging to different scientific societies struggle to understand each other, and people working for the same company but at different factories are unable to collaborate. I hope that Associate Professor Hasuo experiences the pleasure of getting to the essence of things in various fields, and at the same time, helps to promote Japanese collaboration through his research.

Nobuyuki Yajima

Senior Researcher, Nikkei BP Intelligence Group, Nikkei Business Publications, Inc.
Born in 1960. Studied mathematics at university with the aim of becoming a computer engineer, but joined Nikkei McGraw-Hill, Inc. (now, Nikkei Business Publications, Inc.) in 1985 and became a reporter for the *Nikkei Computer* magazine. Worked as the editor-in-chief of *Nikkei Computer* from 2009. Assumed his present post in 2016.

Interview

Control Theory Holds the Key to Integrating Information Systems and Physical Systems

Towards realizing a safe and reassuring "super-smart society"

Toshimitsu Ushio

Professor, Graduate School of Engineering Science, Osaka University
Osaka University Site Leader, JST ERATO HASUO Metamathematics for Systems Design Project

New technologies must be safe when they are utilized in our society. Peace of mind also becomes an important factor in human-friendly technologies such as robots and autonomous driving. We asked Professor Toshimitsu Ushio of the Graduate School of Engineering Science, Osaka University, about his role in the Heterogeneous Formal Methods Group (Group 1) of the HASUO Metamathematics for Systems Design Project. Group 1 aims to extend existing control theory from a systems engineering standpoint and construct theories that incorporate machine learning and optimization problems.

Aiming to integrate information systems and physical systems

The prefix "hetero-" of heterogeneous means "different" and can be contrasted with the prefix "homo-", which means "same". Heterogeneous means "consisting of different things".

The role of computer control has increased dramatically in recent years, and safe operation of newly developing industrial systems requires quality assurance and control methods for both computer software (information systems) and working machinery (physical systems). The HASUO Metamathematics for Systems Design Project as a whole has its sights on application of formal methods to manufactured products, and within this project, the Heterogeneous Formal Methods Group (G1) is responsible for establishing theories for integrating information systems and physical systems.

There are two possible directions when integrating information and physical systems: one in which the information system is taken as the base and its methods and theories are extended toward the physical system, and one in which the physical system is taken as the base and its methods and theories are extended toward the information system. In Group 1, information systems expert Associate Professor Ichiro Hasuo and others will proceed in the direction of applying the "formal methods" of information systems that were developed for software quality assurance to the development of manufactured products.

Meanwhile, systems engineering expert Professor Ushio and others will approach from the opposite direction. Control engineering, which involves controlling the movement of physical objects, is essential in Professor Ushio's discipline of systems engineering, and it is based on control theory. Existing classical control theory deals with physical systems that are represented quantitatively by continuous variables. When these physical systems are integrated with systems that are represented qualitatively by discrete variables, such as computers, they are called hybrid systems. Professor Ushio is attempting to extend control theory to these hybrid systems.

For example, when developing a system to make a robot carry objects, setting up the work process of "carrying" can be

Toshimitsu Ushio

Completed a doctoral course at Kobe University in 1985. Currently serving as a professor at the Graduate School of Engineering Science, Osaka University. Since gaining his doctorate in the analysis of nonlinear phenomena in control systems, he has been engaged in research on control of discrete event and hybrid systems, and has recently become interested in formal control system design and reinforcement learning.

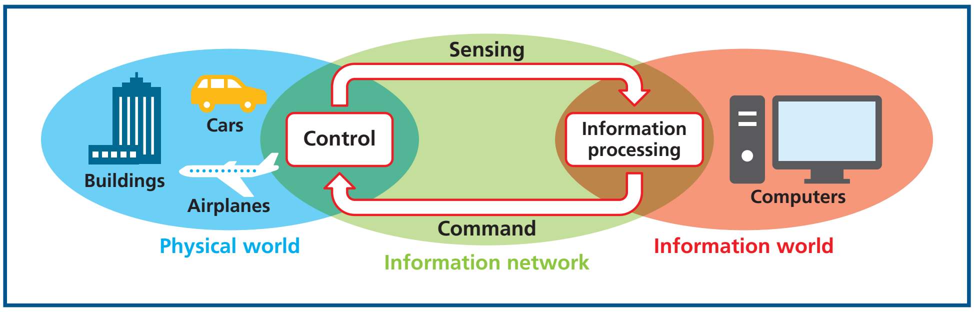


Figure Concept of a cyber-physical system

described using the qualitative logic of information science, but the problem of which carrying path will require the least amount of energy is solved using quantitative methods of control theory. The aim is to extend safe systems by successfully combining different methods.

A bridge between technology and society

Professor Ushio says that systems engineering and control theory play a particularly important role in the implementation of technology in society. This is because systems engineering and control theory have provided the methods that have allowed the leading technology of the age to be successfully put into practice. “It is widely known that the steam engine invented by James Watt was central to the Industrial Revolution, but it is not well known that he also invented the governor.” The steam engine would have been of no use if its stable output could not be guaranteed, but the control device known as a governor made that possible. A governor includes a centrifugal pendulum that makes effective use of centrifugal force, and its structure is such that as the output increases, the valve closes, and as the output decreases, the valve opens. Stable operation of the steam engine depends on the adjustment of the opening of the centrifugal pendulum and the closing of the valve. The theorization of this relationship is said to be the beginning of control theory. Subsequently, control theory contributed greatly to industrial development in the 19th century as people investigated how to achieve stable work of machines and devices.

The Kalman filter proposed by Rudolf Kálmán, winner of awards such as the Kyoto Prize in Advanced Technology and the United States National Medal of Science, was used in the Apollo program carried out by National Aeronautics and Space Administration (NASA) in the latter half of the 20th century. The noise in signals sent from rockets on the surface of the Moon to Earth was too great to be dealt with using existing noise filtering systems. The Kalman filter contributed greatly to the success of the Apollo program, and systems engineering played an important role in this. Nowadays, the Kalman filter is used in many engineering fields.

Today, in the 21st century, the Internet of Things (IoT) is growing, and the arrival of a super-smart society is imminent. Professor Ushio believes that future development of systems engineering and control theory is key to realizing a super-smart society. “How can we implement cutting-edge technologies in ways that are safe and give people peace of mind? I think that answering this question is our mission going forward. If this project produces a single solution, then I will be happy.”

Applying our research to robots that work with people

The research carried out in this project will also be useful in the development of human-friendly robots. In the case of autonomous driving, for example, “safe driving and reassuring driving are different,” says Professor Ushio. “If you are seated in the passenger seat of a self-driving car traveling at high speed, then you probably will not be able to relax even if you are told that it is absolutely safe.”

In autonomous driving, it is not enough to simply build safe systems. Systems must also reassure users by driving in a human way.

Moving a car accurately in line with a target motion has been the role of classical control theory. However, data-based machine learning techniques show promise regarding the question of how to set motion favored by human beings. The integration of formal methods and machine learning will be key in implementing safe and reassuring systems.

Robots that work with people, such as nursing-care robots, are required to respond to people's feelings, but considering globalization, it is important to think not just about individual differences in how people feel and act, but also about differences on the level of race and culture. “This could be useful in developing robots that can give peace of mind to foreigners living in Japan,” believes Professor Ushio.

Engineering from a meta (higher order)-perspective

Systems engineering covers diverse physical phenomena, and the best mathematical methods to deal with those phenomena are also diverse. Professor Ushio has learned the necessary mathematics each time he has had to deal with a different phenomenon. What has he discovered after working on numerous phenomena? “Systems engineering truly is meta. It is a discipline that addresses the meta-level in the sense that it attempts to find common frameworks and principles among many phenomena. Mathematics essentially tries to do things on a meta-level, and systems engineering attempts to design things based on the mathematics.” Although the level of abstraction is different, the two disciplines aspire to the same things.

This area of research is attracting attention globally, but tackling it from a meta-perspective is a feature of this project. “The basic theories will not actually be applied for 10 or 20 years. This project aimed at establishing a theoretical foundation focusing not only on software but also on the design of manufactured products is extremely significant,” says Professor Ushio. We hope that the results will be of service to the next generation.

(Interview/Report by Yuko Hiratsuka.
Photography by Yusuke Sato)

Using Formal Methods at Increasingly Complex Manufacturing Sites

Quality improvement by linking with AI, and evolution to next-generation technologies

Fuyuki Ishikawa

Associate Professor, Digital Content and Media Sciences Research Division, National Institute of Informatics
Visiting Associate Professor, Graduate School of Informatics and Engineering, University of Electro-Communications
Visiting Associate Professor, School of Multidisciplinary Sciences, The Graduate University for Advanced Studies
Group Leader, Formal Methods and Intelligence Group, JST ERATO HASUO Metamathematics for Systems Design Project

The HASUO Metamathematics for Systems Design Project aims to incorporate software engineering knowledge into the manufacture of products to support specification, design, construction, and maintenance. Specifically, it will employ "formal methods" used for purposes such as software quality assurance. By combining formal methods with expertise built up in the manufacturing industry, the project will raise the level of reliability, safety, and speed in increasingly complex manufacturing. NII's Associate Professor Fuyuki Ishikawa serves as Group Leader of the project's Formal Methods and Intelligence Group (Group 3), and we asked him about the evolution of manufacturing using formal methods and his group's objectives.

Used in a wide range of system assurance

Formal methods are techniques of symbolic, mathematical logic used to assure the quality of software. NII's Associate Professor Ishikawa explains the characteristics of formal methods as follows:

"Today, mathematics is used in all structures and manufactured products. For example, optimal design of buildings and bridges is achieved by performing structural calculations that take into account events such as earthquakes, floods, and other natural disasters. Likewise, mathematics is used to enhance the quality and safety of software. Developers ensure that a piece of software works properly by using mathematical logic to determine whether its behavior is well-defined and whether there are any errors, and if so, fixing any errors in advance."

Formal methods are already employed in many different settings. They were used in France's underground train systems to ensure high reliability. The reliability of each part was successfully improved by carrying out validation as programs were being developed. Formal methods are also put to practical use in system development and security for automobiles, and they are starting to be applied to international standards under the leadership of Europe and the United States.

As an example of the use of formal methods in quality assurance, cars developed, manufactured, and sold by Toyota were found to have a fault that caused the gas pedal to get stuck and the car to suddenly accelerate, and this led to a large-scale recall in the United States from 2009 to 2010. NASA investigated the cause of the fault using formal methods. They found no defect involving the software control, and the possibility of software being the cause of the fault was eliminated.

The above is an example of using powerful verification techniques for quality assurance, but formal methods are also

Fuyuki Ishikawa

effective for other purposes.

For example, formal methods were employed in developing the second generation of FeliCa technology used in Osaifu-Keitai (a mobile payment system in Japan), and the process was changed so that specifications were described rigorously using a format with fixed syntax and semantics. This successfully eliminated ambiguity due to notation in Japanese or English. Developers inside and outside the company correctly understood the notation, and so there were very few problems attributable to the specifications. Improvements were also made in the ways that formal methods were used after that stage, and no problems were reported in later processes as a result of missing, unclear, or erroneous descriptions.

Assuring safety of increasingly complex manufacturing

There are several reasons behind the interest in formal methods shown by the manufacturing industry in recent years.

The first is that the complexity of manufacturing is increasing. Taking cars as an example, developers are grappling with the complexity of centrally controlling the various electronic devices and sensors installed in cars. Today, a single car can be equipped with more than 100 sensors, and it is becoming increasingly difficult to validate requirements such as reliability and safety assurance without compromising performance too much. The use of formal methods makes it possible to meet these requirements.

The second reason is that safety assurance and accountability are demanded of manufacturers. The latest cars are equipped with collision avoidance systems, and automakers are expected to ensure the safety of these systems, and at the same time, they have a responsibility to explain their safety. Interest in formal methods is increasing as a way to deliver on safety assurance and accountability by carrying out automatic verification using formal methods.

The third reason is that new functions and applications are becoming widespread. Autonomous driving is probably the best example of this. Formal methods make it possible to calculate what conditions are required for safety in a situation in which a person jumps out in front of the car during autonomous driving. “Using formal methods makes it possible to improve the safety of autonomous driving by implementing ‘powerful verification’ that deals theoretically with an infinite number of cases all together rather than just simulating each case one by one.” Further, combining artificial intelligence (AI) with formal methods will allow more efficient verification and help to improve quality. “When physical movement is involved, as in the case of cars, complexity dramatically increases.

Introducing AI will make it possible to narrow in on the target to a certain extent while studying the characteristics of the problem. Combining this kind of AI approach based on experience and statistics with formal methods could allow more efficient and effective verification than ever before,” says Associate Professor Ishikawa.

Quality improvement and new technologies

Amid this interest in the formal methods of software engineering by the manufacturing industry, what is the role of the Formal Methods and Intelligence Group (Group 3) of the HASUO Metamathematics for Systems Design Project led by Associate Professor Ishikawa?

The group’s role is “to combine an approach based on human/AI experience and statistics with existing formal methods,” says Associate Professor Ishikawa.

“We aim to develop interdisciplinary theories from a practical standpoint by first exploring what kind of effects the formal methods of software engineering will have on the increasingly complex manufacturing performed by the manufacturing industry, as well as what the industry actually wants.”

One specific challenge is improving the quality of manufacturing. “We will provide tools for verifying traditional ways of manufacturing, as well as for exploring more effective manufacturing methods. This will make it possible to verify the manufacturing methods that achieve optimum quality of the completed car in satisfying not only safety but various requirements, including good mileage, high speed, and comfort. Also, in terms of efficient manufacturing, using formal methods that incorporate AI will make it possible to perform reliability assurance with a certain amount of confidence. For example, it will be possible to judge whether 25 types of test are sufficient for something that has traditionally undergone 30 types of test, or whether this should be increased to 40 types of test.”

A second challenge is new technologies. Here, autonomous driving is the most recent topic. “In order to determine what is happening on the road and perform autonomous driving safely, it is necessary to examine an infinite number of cases. Safety is assured by verifying these cases using tools based on theory, rather than just manually checking them individually. In this project, we intend to collaborate with the Formal Methods in Industry Group (Group 2) to carry out verification using the actual autonomous car that Group 2 is working on.”

This verification will be implemented in cooperation with domestic automakers. The intention is to apply the knowledge gained here to fields other than the automotive industry.

Another benefit that Associate Professor Ishikawa hopes the current project will bring is interaction between experts from different fields. Experts from different fields, including mathematics, software science, control, and artificial intelligence, are participating in the project. Group 3, which Associate Professor Ishikawa is leading, will pursue technologies for using formal methods and conduct experiments together with private companies. He is hopeful of a new synergy that could lead to experts in different fields writing papers together.

“There are many things that we want to do, that is, many potential projects to choose from, but our first priority will be traffic control,” says Associate Professor Ishikawa happily.

The spotlight will also be on the results of this project for strengthening Japan’s manufacturing capability.

(Interview/Report by Katsuyuki Ohkawara.
Photography by Yusuke Sato)

About the JST ERATO HASUO Metamathematics for Systems Design Project

ERATO HASUO Metamathematics for Systems Design Project
National Institute of Informatics & Japan Science and Technology Agency

Aiming to construct theories using abstract mathematics in order to incorporate continuous elements into formal methods

In the manufacturing industry today, progress is being made towards fundamentally changing the way manufacturing processes—from design to production—are carried out by introducing automation and software support based on advanced information processing technologies. In light of this, the HASUO Metamathematics for Systems Design Project aims to introduce results from the field of software science into traditional manufacturing technologies and build software tools for supporting various aspects of manufactured product development—from specification development to design, implementation, and maintenance.

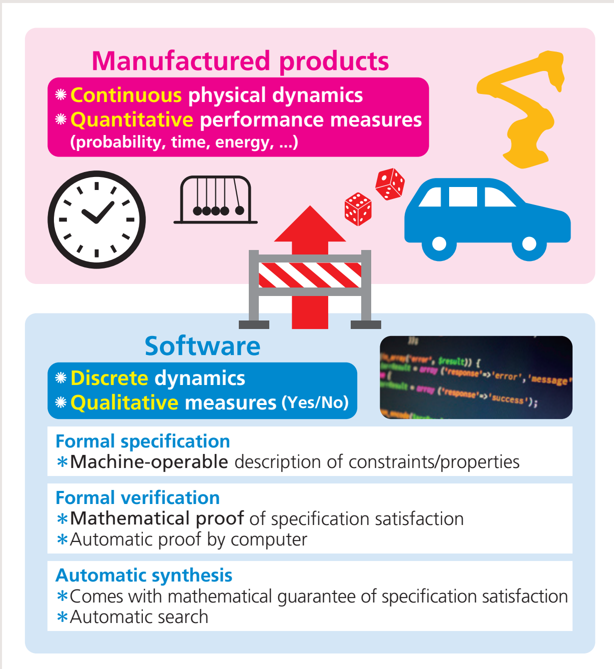
Specifically, by incorporating mathematically based system design techniques used in software science known as "formal methods", the project will explore methodologies for software support covering quality assurance and efficiency in "cyber-physical systems", such as cars and other manufactured products. Up until now, formal methods have dealt with "discrete elements" involving calculation by computer, but in order to apply formal methods to physical information systems, they must be extended to encompass "continuous elements" of physical systems such as continuous dynamics, probability, and time (Figure 1). This project's unique approach to this theoretically difficult problem is to analyze mathematically the extension processes themselves and acquire universal knowledge by constructing higher-order (meta-level) theories that will allow various formal methods to be extended simultaneously (Figure 2).

This meta-level approach is a very theoretical one that employs various abstract mathematical techniques, such as logic and category theory. At the same time, a hallmark of this project is its focus on applying these theoretical research results to real problems faced by industry.

Application to specific industry needs and promoting pioneering initiatives in autonomous driving

The project includes two approaches to application. The first is to support real-world product design processes using formal methods in collaboration with domestic and foreign companies. Rather than trying to reform entire design processes, this will involve specific, practical efforts, such as reducing the time

Figure 1 Extending formal methods: From software to physical information systems



Formal methods developed primarily for software have delivered a variety of results, including mathematical proof (verification) that software operates as expected and automatic synthesis of software that operates as expected. The idea of trying to apply formal methods in a similar way to cyber-physical systems that possess enormous complexity arising from computer control is a natural one, but there are several hurdles that must be overcome. For example, continuous dynamics, which are generally described using differential equations, are not dealt with in conventional software science. Also, rather than qualitative properties answerable with "yes" or "no", the properties of cyber-physical systems that must be satisfied are more often quantitative, such as "after how many seconds will it be completed", "how much energy is needed", and "what is the probability that it will be completed". Therefore, it is necessary to extend formal methods.

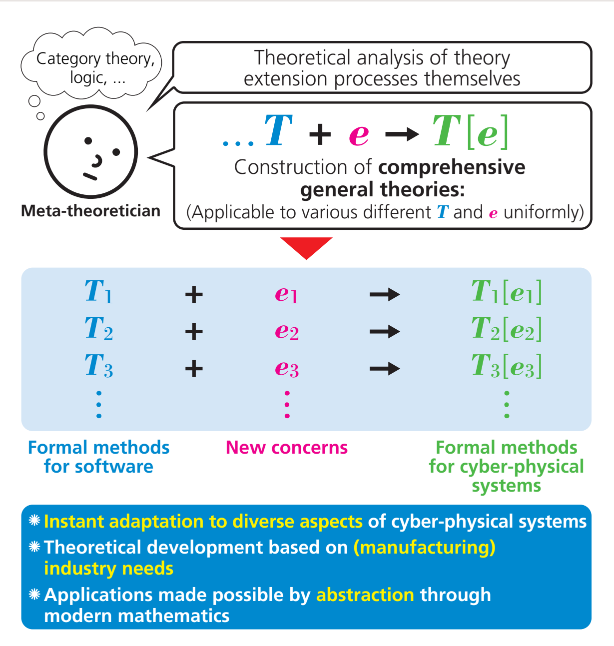
required for a certain test from three days to half a day. This will be made possible by formulation based on a theoretical approach and a flexible response to problems. The use of theoretical results will facilitate matching with specific industry needs.

The second approach to application is to investigate the role of formal methods in pioneering software-based product design processes. Here, in collaboration with researchers developing the autonomous driving system Autonomoose at the University of Waterloo in Canada, the project conducts groundbreaking research on industry application of formal methods using Autonomoose as a testbed.

The above research is carried out by four project groups (Figure 3). Group 1 conducts concrete extensions of formal methods through collaboration between researchers specializing in software science and control theory. Group 3 aims to implement practical methods from a practical software engineering perspective through collaboration between researchers specializing in areas such as machine learning. Both of these groups are responsible for implementing research results in collaboration with domestic and international companies. Group 2, based at the University of Waterloo, Canada, carries out groundbreaking research on industry application. Group 0 follows up the research activities of these groups and generalizes the results from an abstract mathematics perspective, as well as matching results to different topics. The majority of the members of Groups 0, 1, and 3 are based at NII in Tokyo, where they conduct interdisciplinary research unconstrained by group boundaries.

This project is part of the ERATO program of the Japan Science and Technology Agency (JST), and research began in October 2016 (scheduled to continue until March 2022). In addition to the above-mentioned industry applications, the project aims to offer a new form of applied mathematics that addresses social issues with the flexibility only attainable through the abstraction and generalization of modern mathematics, and this will be part of the project's long-term significance.

Figure 2 Unique methodology: Metatheoretical transfer

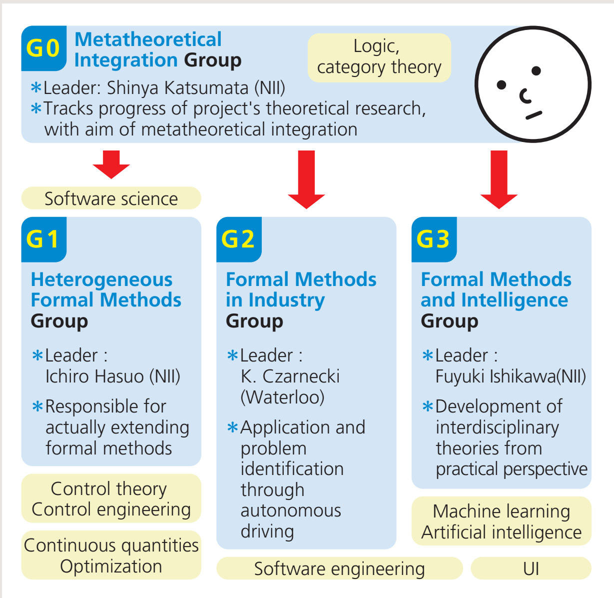


To apply formal methods originally geared toward software to cyber-physical systems, the original method or theory T must be extended so that it is capable of addressing a new concern e, such as continuous dynamics. The necessity of these types of extensions is recognized worldwide, and various research studies have been carried out. However, most of these existing studies have addressed individual cases one by one, and established an extension T[e] for a specific T and a specific e.

We would like to establish a flexible methodology capable of addressing various issues through our unique theoretical approach.

Specifically, we will look at several examples of extension of a particular theory T and a particular concern e, and by analyzing these examples mathematically, we will construct a theory of theory extension. This is called a metatheory because it explains the theories from a higher level (higher order). Efforts to construct metatheories provide theoreticians with the pleasure of gaining an “understanding of the essence”, but metatheories have another benefit in terms of application in that formulating the general theory of extension $T + e \rightarrow T[e]$ (without restricting T and e to something specific) makes it possible to extend many individual theories simultaneously. The flexibility of this kind of general theory has great appeal when applying formal methods to cyber-physical systems as diverse and heterogeneous systems.

Figure 3 Project organization



Collaboration between different math-based disciplines through intervention of Group 0 as “mathematicians who are good listeners”.

NEWS 1

Easy-to-understand explanations of cutting-edge informatics

Start of FY2017 Public Lectures "The Forefront of Informatics"

The FY2017 Public Lectures titled "The Forefront of Informatics" have begun. This is a program of free lectures in which researchers from NII and other institutions explain cutting-edge research and topical issues in the field of informatics to the wider public in an easy-to-understand manner. There will be seven lectures this year.

The first lecture was held on July 12. Assistant Professor Kazunori Sakamoto of the Information Systems Architecture Science Research Division gave a lecture titled "Motivational Artificial Intelligence—AI that Increases the Desire to Learn by Incorporating Individuality" (top photograph).

First, Assistant Professor Sakamoto used examples from psychology research to explain that learners have various individual characteristics and that different methods of learning will be effective depending on these individual characteristics. He demonstrated that self-control is an important factor in success by explaining the Stanford marshmallow experiment, which found that children with the self-control to delay gratification were more likely to be socially successful in the future than children without self-control. He also explained that motivation is important in developing self-control and that providing an appropriate incentive is necessary for motivation, but this incentive will be different for each learner.

Next, Assistant Professor Sakamoto introduced his approach to this kind of psychological inclination as an information scientist and the software that he is developing equipped with artificial intelligence (AI) technology to provide each learner with an optimum learning method. This software is a learning app that analyzes the individual characteristics of the learner through a psychology questionnaire covering such factors as self-esteem, need for attention, and competitiveness. Then the app's AI recommends the best learning functions and incentive functions for the learner. "Some people want their abilities to be praised, while others want their efforts to be praised. By providing incentives that suit the learner's individual characteristics, it is possible to increase their motivation," said Assistant Professor Sakamoto.

The second lecture was held on August 25. Professor Hideo Kosaka of the Faculty of Engineering, Yokohama National University, gave a lecture on the latest diamond-based quantum technologies titled "Diamonds and Quantum Information—From Teleportation to Quantum Authentication" (bottom photograph). Professor Kosaka is a research team member in hybrid quantum science, a new field being researched at NII's Global Research Center for Quantum Information Science (Center Director: Professor Kae Nemoto, Principles of Informatics Research Division).

He first explained that the research and development of quantum computers and quantum cryptography communication networks is progressing rapidly worldwide and that quantum information technologies will become very familiar in the future. Next, he described quantum information technologies made from diamonds, which can maintain a quantum world at room temperature. Diamonds are known as the most valuable of

gems, but they are also valuable as quantum crystals that maintain a very fragile state—called a quantum state—for long periods of time. A complex defect in diamond consisting of a nitrogen (N) atom, which substitutes for the carbon (C) atom that should be present, and an adjacent vacancy (V) is called an NV-center. The NV-center becomes a natural quantum memory in which the quantum state of photons (the smallest unit of light) is transferred to electrons (the smallest unit of electricity) under the principle of quantum teleportation and is stored as spin (the smallest unit of magnetism). This specific ability of diamond makes it possible to develop technologies such as quantum repeaters, which will contribute to the development of long-distance quantum cryptography communication networks, and quantum authentication, which does not require passwords or certificates. It also has application in absolutely ensuring the safety of the Internet of Things (IoT) using the laws of physics called quantum mechanics. Professor Kosaka concluded by saying, "I think that the mission of quantum research is to strengthen security using quantum technologies and protect everyone's safety in a super-smart society. I hope that we will achieve this in the next 10 or 20 years."

NEWS 2

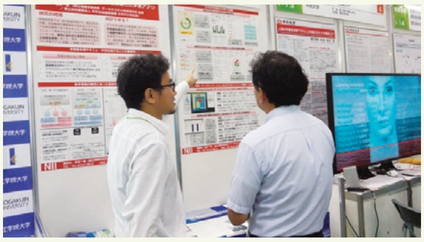
Exhibition of learning app equipped with artificial intelligence and PrivacyVisor

Exhibitor at Innovation Japan 2017 and JST Fair

Assistant Professor Kazunori Sakamoto of the Information Systems Architecture Science Research Division, NII, participated in "Innovation Japan 2017—University Fair & Business Match-Up," held at Tokyo Big Sight from August 31 to September 1. He gave a poster presentation and demonstration of Sumamochi, an app that uses artificial intelligence to motivate people to learn (top photograph).

Sumamochi is a learning app equipped with artificial intelligence technology that analyzes users' individual characteristics through a psychology questionnaire and app operating histories to recommend optimal settings that will increase users' desire to learn. Many of the visitors who experienced the tablet or smartphone demonstration of Sumamochi said that they would like to try using it in employee training.

"JST Fair 2017—Creation of Future Industry through Science and Technology" was held simultaneously. PrivacyVisor was presented and exhibited as an example of commercialization resulting from the industry-academia matching event "New Technology Presentation Meetings" organized by the Japan Science and Technology Agency (JST). PrivacyVisor is a pair of glasses incorporating technology that prevents face detection developed by Professor Isao Echizen of the Information and Society Research Division,



NII, and commercialized using eyewear manufacturing technology from the city of Sabae in Fukui Prefecture, Japan (bottom photograph).

NEWS 3

ERATO Festival Season IV

Presentation of papers accepted by top conferences

On August 3–4, the JST ERATO Kawarabayashi Large Graph Project directed by Professor Kenichi Kawarabayashi of the Principles of Informatics Research Division, NII, hosted ERATO Festival Season IV, a presentation of research papers accepted by top international conferences in the field of information technology during the year.

The Kawarabayashi Large Graph Project was selected as an Exploratory Research for Advanced Technology (ERATO) project of the Japan Science and Technology Agency (JST) in October 2012. It aims to develop high-speed algorithms useful for solving various problems using advanced mathematical theories that consider ever-expanding networks as "large graphs" (big data) consisting of nodes connected by edges. The project is also engaged in training young researchers in various fields to help raise the standard of computer science in Japan through fundamental research.

Young researchers and graduate students who presented papers at ERATO Festival Season IV. Professor Kawarabayashi is fourth from the left in the front row.

In this, the project's final year, excellent young researchers and graduate students from across Japan presented a total of 32 papers—the largest number ever—in fields including theoretical computer science, data mining, machine learning, artificial intelligence, and natural language.

Professor Kawarabayashi encouraged them, saying, "The majority of the speakers are graduate students or postdoctoral researchers who are the lead authors of papers accepted by top international conferences in the field of information technology, and I feel that they are finally reaching a world-class standard. I hope that they will work hard so that this trend continues in the future."

NEWS 4

Japan-Asia student exchange in science and technology

Welcoming Sakura Science Plan exchange students

The National Institute of Informatics welcomed a total of ten undergraduate and master's students July 3–21 through the Japan-Asia Youth Exchange Program in Science (Sakura Science Plan). The students came from Shanghai Jiao Tong University and the University of Science and Technology of China in China, Chulalongkorn University in Thailand, and Hanoi University of Science and Technology in Vietnam.

The Sakura Science Plan is a program run by Japan Science and Technology Agency (JST) that aims to nurture the outstanding foreign talent required by Japanese universities, research institutions, and private companies, as well as strengthen exchange in the field of science and technology between youth in Japan and Asia, who will shape the future. NII has been selected for this program for three consecutive years.

The exchange students carried out research under the guidance of supervising faculty members for a period of about three weeks. They also visited venues such as the National Museum of Emerging Science and Innovation (Miraikan) with students from The Graduate University for Advanced Studies, where NII has established a Department of Informatics. These visits promoted interaction between the students and provided opportunities for the exchange students to experience Japanese progress in science and technology.

On the final day, the exchange students presented their research results and had a lively exchange of ideas about each other's research. Comments from the exchange students included, "In the future, I would like to do research in Japan."

Exchange students who visited Japan through the Sakura Science Plan. In the front row, from the right are Professor Tomohiro Yoneda, Associate Professor Hitoshi Okada, and Professor Zhenjiang Hu, who served as supervisors.

SNS "Hey, this is great!" Hottest articles on Facebook and Twitter (June–August 2017)

National Institute of Informatics, NII (official) Facebook
www.facebook.com/jouhouken/

▶ **Start of online course "Research Data Management in the Era of Open Science" on JMOOC's official platform gacco**

NII will offer a free online course titled "Research Data Management in the Era of Open Science" using gacco, a distribution platform certified by the Japan Open Online Education Promotion Council (JMOOC), from November 15 this year. Course registration starts on August 23. This is the second time that NII has offered a massive open online course (MOOC).Please visit the webpage below for details.
http://www.nii.ac.jp/news/release/2017/0818.html (08/18/2017)

National Institute of Informatics, NII (official) Twitter
@jouhouken

Development of latest AI system capable of retrieving images from classical documents based on sketches and pictures/ Joint research by NII and the National Institute of Japanese Literature (06/08/2017)

Bit on Twitter! Twitter
@NII_Bit

Me with Ayaka Ikezawa (@ikeay) who was MC at NII Research 100! #NIINow (06/10/2017)

* Some text edited/omitted.

Essay

Celebrating 50 years of the ACM Turing Award

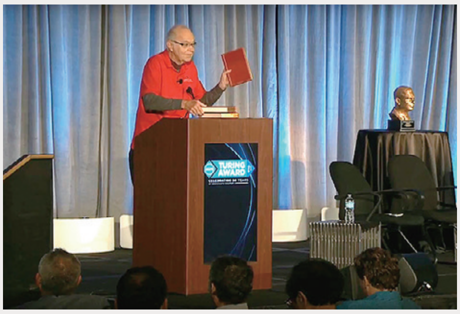
Masaru Kitsuregawa
Director General, National Institute of Informatics

A ceremony celebrating the 50th anniversary of the ACM Turing Award was held in San Francisco in June 2017. Established by the Association for Computing Machinery (ACM), the award—also known as the Nobel Prize for computing—has been granted to 64 people during the 50 years since it began, in recognition of their contributions to the field. At the ceremony, past recipients of the award were involved in panel discussions on diverse topics in computer science. Videos of all of these discussions can be viewed on the ACM website. (http://www.acm.org/turing-award-50/video)

A talk given by Dr. Donald Knuth (1974 Turing Laureate) during the ceremony titled "Computer Science as a Major Body of Accumulated Knowledge" features in the Journal of Information Processing (Vol. 58 No. 11 Nov. 2017) published by the Information Processing Society of Japan. Dr. Knuth is a leading computer science researcher who has been active in the field since its very early days. He is well known as the author of the book "*The Art of Computer Programming,*" which has been translated into Japanese. Covering many types of algorithms and their analysis, including complexity, this book is a seminal work in computer science, and Dr. Knuth was awarded the Turing Award for the book in 1974.

Dr. Knuth has contributed enormously to computer science in a wide range of areas, from programming techniques to groundbreaking electronic publishing tools, and reflecting back upon his work, he said that, "Computer science shares with mathematics the great privilege that we can invent the problems we work on. We don't have to base it on the way nature happens to have decided to go. So we can invent our own universe as we can design our own languages and our own axioms." A Japanese transcript of Dr. Knuth's lecture is available on the NII website.

(http://www.nii.ac.jp/about/upload/acm_NIIToday77.pdf)



Dr. Donald Knuth delivering his lecture (from ACM website)

Future Schedule

October 3-6 | CEATEC JAPAN 2017 (Exhibitor)

October 8 | Inter-University Research Institute Corporation Symposium 2017 (Exhibitor)

October 18 | "The Forefront of Informatics" 2017 Public Lectures: 4th Lecture "The Science of Designing Movement—A Control Engineer's Perspective" (Speaker: Associate Professor Masako Kishida, Principles of Informatics Research Division). For details and registration, go to the following website: http://www.nii.ac.jp/event/shimin/

End of October | 2nd SPARC Japan Seminar 2017. Details at http://www.nii.ac.jp/sparc/.

November 7–9 | 19th Library Fair & Forum (Sponsor/Exhibitor)

November 11 | 3rd Karuizawa Saturday Salon "Making Internal Organs from iPS Cells: A Cross-Border Challenge" (Speaker: Research Professor Hiromitsu Nakauchi, Division of Stem Cell Therapy, The Institute of Medical Science, University of Tokyo/Professor, Stanford University)/"Beethoven—A Pioneer of Romantic Music" (Performers: Junko Ohtsu (violin), Tomoko Okada (piano), Genichi Watanabe (cello))

November 16 | "The Forefront of Informatics" 2017 Public Lectures: 5th Lecture "Infrastructure That Reflects the Times—From the Telephone to Science Information Network SINET" (Speaker: Associate Professor Takashi Kurimoto, Information Systems Architecture Science Research Division)

December 12 | "The Forefront of Informatics" 2017 Public Lectures: 6th Lecture "Knowledge Discovery from the Mass of Images/Videos/Music on the Web—Making Life More Fun using Multimedia Information" (Speaker: Assistant Professor Yi Yu, Digital Content and Media Sciences Research Division)

December 13–15 | 2017 Annual Meeting of the Academic Exchange for Information Environment and Strategy (Exhibitor)

Notes on cover illustration Here, I compared the concept of "meta" (higher-order) that is central to the ERATO HASUO Metamathematics for Systems Design Project with a situation in which robots themselves assemble and inspect robots. I wanted to make a difficult concept a little bit more tangible.

Bit (NII Character)

Weaving Information into Knowledge
NII

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