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Recreating Human Attributes through Materials Science

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Artificial intelligence (AI) has rapidly evolved to the point where some is now far superior to humans at performing certain tasks.
This advancement has been made possible by powerful supercomputers capable of performing massive amounts of calculations and miniaturized, highly integrated transistors.
However, as the amount of information to be processed continues to increase, the computations needed to solve problems become more complex, making it increasingly difficult for AI to meet the ever-more-difficult requirements.

Unlike AI, the human brain is able to carry out sophisticated, plastic thought processes using very small amounts of energy.
AI equipped with these human brain attributes could be very valuable.
Some NIMS researchers have discovered promising ways of recreating the brain's functions using materials.
One effective approach to developing human-like technologies is the use of materials able to simulate the brain's thought and decision-making processes through precise utilization of physical phenomena.

What types of materials and mechanisms are needed to reproduce human attributes?
Materials scientists are in an advantageous position to tackle these problems.

Brain mechanisms that shape human nature

Human brains continuously engage in perception, thought, creativity, memorization and learning activities during their lifetimes. What are the mechanisms of these brain activities? Is it feasible to recreate them using physical devices? Brain scientists study brain functions, while some materials scientists seek to simulate them using materials. Their collaboration may potentially enable the creation of artificial brains and a deeper understanding of human nature.

Kazuya Terabe
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International Center for Materials Nanoarchitectonics (WPI-MANA)

Masamichi Sakagami
Director, Tamagawa University Brain Science Institute

The brain: a super high performance system

—First, please briefly describe your research activities.

Sakagami: My area of expertise is brain science. My initial research focus was electrophysiology, a study of the brain's electrical activities. Back then, I studied the functions of the brain's prefrontal region using monkeys. More recently, I've been investigating how interactions between various parts of the brain affect decision-making. In addition, I recently began chemogenomic research to better understand the correlation between different brain activities by allowing target neurons to express artificial proteins reactive to specific drugs. This can be achieved using viral vectors capable of carrying genetic materials to the target neurons.

Terabe: My specialty is solid-state ionics, a branch of materials science. I create devices and systems capable of controlling ions. Since joining NIMS, I've been working to develop nanoionic devices by controlling individual ions using a scanning tunneling microscope (STM). This effort led to the development of an extremely small atomic switch which may serve as an alternative to a transistor. Because atomic switches are very similar to the brain's synapses in function, I've started researching brain-like devices using them.

—Synapses use electricity to transmit information.

Sakagami: That's right. The brain generates electricity using ionic movements and transmits electrical signals. Simply put, the role of the brain is to convert sensory information into kinetic activity. The brain converts all kinds of sensory information (e.g., information about the relationship between the external world and the self, so that you know which direction you are facing relative to your surroundings) into electrical signals, leading to muscular movements.

Terabe: An artificial neural network (ANN) composed of software and hardware is a type of artificial intelligence (AI) system designed to simulate brain functions using electricity. The hardware performs computations based on software programs. While both components have significantly advanced, hardware performance is approaching its technical and theoretical limits. Although transistors—an essential semiconductor device—have evolved dramatically with miniaturization and greater integration, further substantial improvement would be difficult using conventional devices and their processing techniques.

—Google developed the AlphaGo AI, which has defeated professional Go players.

Terabe: Yes, but it consumes huge amounts of energy. Despite the fact that AlphaGo is specialized only in playing the game of Go, it requires 200,000 watts of electricity. By contrast, a human brain requires only 20 watts—equivalent to 10^4 times smaller power than that required by AlphaGo, being even smaller than that consumed by a light bulb. In other words, the brain is extremely energy-efficient. In addition, the brain is a very flexible system despite its very small size. Our team's dream is to create a human-like artificial brain using materials with innovative characteristics, including solid ion conductors.

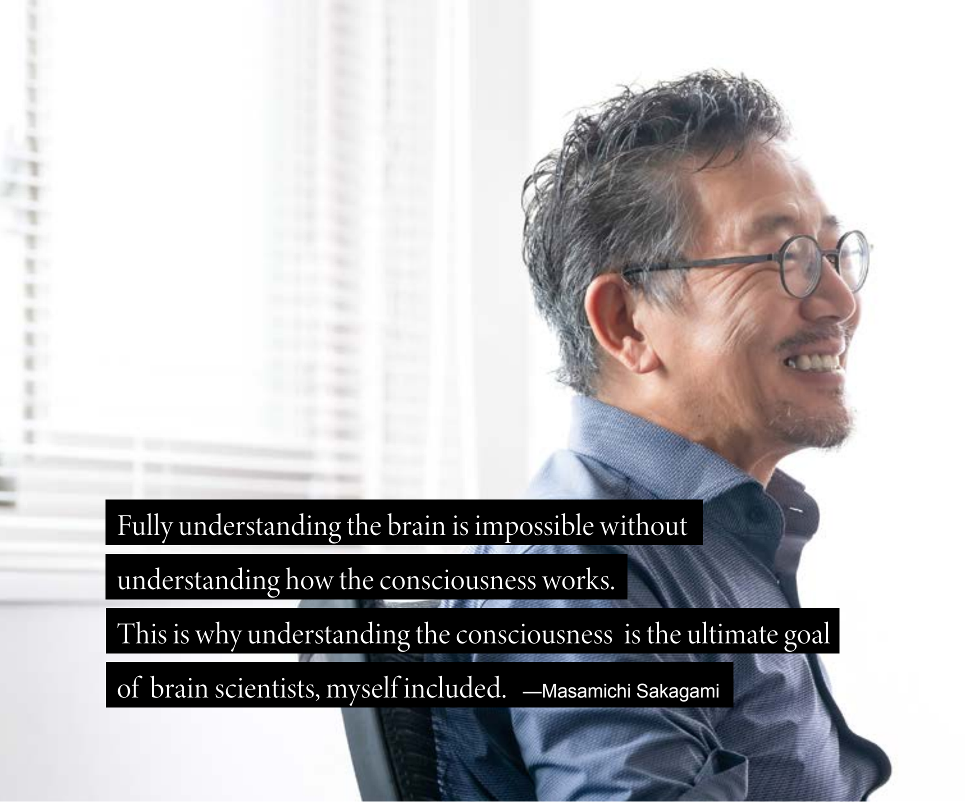
Sakagami: The human brain is indeed a flexible system capable of learning and making predictions. In frogs and other similar animals, sensory information is almost always converted into action. This is why a frog reflexively jumps toward an approaching fly. On the other hand, when humans are hungry, they can choose what to eat from various types of foods, such as Chinese or Italian. This ability to choose is made possible by the plasticity of the brain, which enables people to make predictions based on previous experience.

Is the brain's plasticity reproducible?

—Synapses constantly change through new experience and learning. As a result, people can change their ways of thinking and foresee future events. Is it possible for AI technologies to recreate the brain's plasticity?

Sakagami: Current AI software is very unlikely to achieve that. The brain contains some 100 billion neurons. On top of that, each neuron is interconnected with about 5,000 other neurons via synapses in an intricately entangled manner. These interconnected neurons exchange huge amounts of information in a crude manner, including a certain level of random information seemingly irrelevant to decision-making. AI software employs explicit mathematical formulae to solve problems. By contrast, the human brain has a certain degree of randomness, giving it flexibility. It also possesses neuroplasticity, enabling it to continuously reconstruct neural networks. Humans continuously learn throughout their lifetimes. The brain of a 50-year-old person is a product of cumulative plastic changes during 50 years of living. It would be virtually impossible to flawlessly recreate all these details using current AI technologies.

Terabe: Relative to the number of atoms in a material, 100 billion neurons in the brain is not that great a number (laughs). Atomic-scale materials with groundbreaking characteristics may potentially become available to recreate brain functions which AI software running on supercomputers is currently trying to achieve. For example, an atomic switch—consisting of an ion conductor sandwiched between two metal plates—can serve as an on-off switch. When electric current is passed through it, metallic ions in the its ion conductor migrate, causing a few atoms on either side of the conductor to be deposited or disappear, allowing it to behave like a switch (see the figure on p. 8). This nanoscale device can mimic the remembering and forgetting mechanisms of a synapse. In addition to atomic switches, efforts are underway around the world to create ANNs by inducing molecules, fine particles or metallic nanowires to self-assemble into ANNs. In these techniques, these molecules/particles/nanowires are placed in certain arrangements at the nano- or atomic-scale and are then irradiated with light, subjected to electric current or ionic movement to induce self-assembly. Although these efforts are still



in the very early stages, if considerable progress is made, they may produce exciting results within a decade or so.

Sakagami: I have great expectations for these technological advances. Recreating brain functions using materials may help reveal some of the brain's many unknown working principles. If a switch can be created to control ionic flow, it may potentially be used to understand the brain's bias-causing mechanisms. Theoretically, once the brain's working principles are understood, it may be feasible to quickly transfer the cumulative memories of a 50-year-old person to an AI.

Materials' behavior may potentially be used to uncover the mysteries of the consciousness

—What are your views on the brain's working principles?

Sakagami: Scientists seeking a deep understanding of how the brain works ultimately face the problem of the consciousness. For example, when a pen in front of a person reflects light, the retinal cells at the back of his or her eyes sense the light, inducing neural activities leading to the formation of the pen's image. These activities not only result in image formation in the brain but also allow us to feel the pen's shape and color. This mental activity is currently completely inexplicable in terms of electrical mechanisms. However, some mechanism must be responsible. If not, I'll have to pray and hope that God tells me how it works (laughs). I've been trying to find a physiochemical explanation, so far without success. Fully understanding the brain is impossible without understanding how the consciousness works. This is why understanding the consciousness is the ultimate goal of brain scientists, myself included.

Terabe: We're also very interested in the consciousness as a research problem. If we succeed in developing an artificial brain equipped with a full range of human brain functions, we will have to deal with this problem. At present, however, we have no clue how to tackle it using materials.

Sakagami: Some brain scientists have proposed that the consciousness can be explained only with quantum mechanics. If they are correct, the brain's working principles may be completely unrelated to electrophysiology—our current approach to brain research. Actually, I have a growing expectation that materials science may play a key role in understanding the consciousness.

Terabe: Although the brain's complexity is still largely unknown, it must be composed of a combination of physical materials. Moreover, given that ionic movement is involved in neural and brain functions, we may find major clues by focusing our research on it.

Sakagami: I feel that Dr. Terabe's approach is very promising. If the consciousness is a physical entity, there must be material evidence for its existence.

Terabe: The quantum mechanical approach has already been adopted in some research projects attempting to recreate the brain functions by incorporating quantum effects. For example, there is a technique called reservoir computing suitable for machine learning of time-series data. Many research projects have adopted this technique to study various quantum phenomena, such as ion-electron interactions and spin-wave interference. This type of research may find clues to understanding the consciousness.

Sakagami: Conventional brain science methods are approaching their limits in advancing our understanding of the consciousness. Collaboration between brain scientists and materials scientists focused on recreating the brain's working principles using materials may possibly result in a breakthrough.

Reconstructing the brain functions using solid-state ionics

—Human vision has been recreated using an artificial vision device.

Terabe: Our development of an artificial vision device was inspired by—although not a precise reproduction of—human vision mechanisms. In human vision, the edge contrast between the darker and lighter areas (i.e., the boundary between darker and lighter gray areas) is increased due to a neural process called lateral inhibition. The artificial vision device recreates this lateral inhibition function of human vision using ionic movement (see p. 14). This device works completely differently from conventional software-based information processing systems.

Sakagami: As a brain scientist, I was very impressed by Dr. Terabe's ionic vision device. Photoreceptor cells in the retina convert light into electrical signals which pass through bipolar cells and reach ganglion cells where the signals are processed into digitized visual information and sent to the brain. When electricity travels from photoreceptor cells to bipolar cells, it takes the form of analog signals. It is then converted into a pulsed current before it is used for communication between neurons in the brain. Similar to the brain's initial stage of visual processing, the ionic vision device performs visual processing using analog means: ionic movement.

Terabe: Research into artificial senses aims to recreate the brain's five senses, including vision, using materials with adequate characteristics. Europe, the United States and China have been promoting this type of research by investing huge financial resources in it. I envisage a succession of exciting results from these efforts.

—Decision-making devices also have similarities to living organisms.

Terabe: The decision-making device we have developed, termed as ionic-decision maker, also exploits ionic movement within a solid material. This device works based on a tug-of-war theory inspired by the foraging behavior of amoebae. We translated this theory into a mathematical model which was then used to develop the device capable of storing cumulative experience in the form of ionic concentration changes (see p. 10). We conducted experiments to compare the performance of this device with that of an AI system run by conventional software. We found that the probability of these two technologies giving the correct answer was virtually equal.

Sakagami: When brain scientists investigate the correlation between different brain-related phenomena, we also build mathematical models based on our hypotheses. Although our models have focused on the flow of pulsed current within the brain, the brain's initial information processing involves ions. Therefore, some studies aimed at measuring the flow of information within the brain may yield more accurate results by focusing on ionic flow in a manner similar to the ionic-decision maker. I feel that both the ionic vision device and the ionic-decision maker adequately represent the brain's initial information processing mechanisms.

The brain as a predictive system

—People's decision-making processes are more complex than these devices.

Sakagami: When people make a decision, they weigh the value of various conscious and subconscious thoughts and determine which are most important. This evaluation involves rewards and punishments. I said earlier that the brain can make predictions. People do this to determine how to act in ways that can enhance their lives (i.e., rewards) and to avoid acting in ways that are life-threatening (i.e., punishments). We envisage future rewards and punishments based on previous learning.

—To put it another way: a previous experience drinking a bottle of delicious water causes us to expect that the same bottle of water will be delicious in the future.

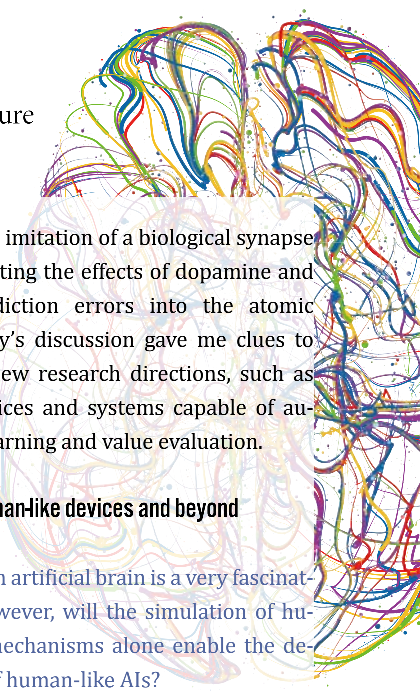
Sakagami: You said it. The key to this prediction process is a so-called reward prediction error: a difference between the reward expected and the actual reward that has just been experienced. When the actual reward greatly surpasses the expected one, a large amount of dopamine—a type of neurotransmitter—is secreted. This increases the value of the decision, which will then be reflected the next time a similar decision must be made. In other words, reward prediction errors are used to increase the accuracy of future predictions, and this mechanism is regulated by dopamine. Another interesting finding is that when people gain a reward in a totally unexpected manner, a large amount of dopamine is rapidly secreted as a result of the large reward prediction error. However, if they undergo the same reward experience repeatedly, the amount of dopamine secreted decreases and eventually ceases. This is because repetition of the same experience makes further learning unnecessary.

Terabe: I see. Learning and decision-making are facilitated by dopamine. By comparison, the atomic switch we have developed is activated when external stimuli (e.g., electric and magnetic fields and light) are applied to it. When the switch is turned on by a strong stimulus, it will become more prone to activation next time. On the other hand, when it is turned on by a weak stimulus, it will become more prone to deactivation. We have been using an atomic switch with these characteristics to recreate plastic synapses and neural networks, which are thought to play a vital role in memory and learning. I hope to achieve a more faithful imitation of a biological synapse by incorporating the effects of dopamine and reward prediction errors into the atomic switch. Today's discussion gave me clues to identifying new research directions, such as creating devices and systems capable of autonomous learning and value evaluation.

Pursuit of human-like devices and beyond

—Creating an artificial brain is a very fascinating idea. However, will the simulation of human brain mechanisms alone enable the development of human-like AIs?

Terabe: Current AIs are composed of mathematical models and operate according to numerical programs. Human-like qualities, such as human behavior and emotion, can't be recreated using a mathematical language. A famous research project called the Todai Robot Project was recently carried out with the aim of developing an AI robot (named Torobo-kun) capable of passing the University of Tokyo's entrance exams. Although this goal was not met, I was very impressed by the fact that Torobo-kun achieved a deviation score of about 60 in mock exams on some subjects. On the other hand, it performed very poorly in exams on the Japanese and English languages, which require examinees to understand the contextual meaning of written texts to answer correctly. These results support the notion that reading ability and creative thinking are human-like attributes.



Sakagami: Humans are unique in that only they can take goal-directed behavior. For example, they may first set a long-term goal, then anticipate processes needed to meet the goal and finally plan necessary actions to get there from the future to the present. This creative ability made it possible for humans to build great civilizations. Developing a future civilization requires mapping out detailed large-scale processes using mathematical formulae. A future AI equipped with an artificial cerebral cortex—the part of the brain said to play a central role in goal-oriented thinking—may be able to easily perform such a task. What if such AIs encounter situations where they need to make moral decisions during the process of building a new civilization? Metaphorically speaking, this question is similar to an autonomous AI car with faulty brakes. The AI might come up with only two possible options: either it will stay the predetermined course knowing the risk of running over five people ahead or it will turn the steering wheel and hit a person standing on the edge of a cliff. Although this is a question with no acceptable answer, humans have the ability to come up with more humane alternatives, which is important in enabling our civilization to survive.

Terabe: For humans and AIs to coexist, the sharing of moral values between them might become important. Materials scientists are expected to play a crucial role in creating truly human-like AIs that incorporate moral values. Our team does not intend to rapidly replace the current software-based AI with a much smaller, energy-efficient artificial brain. Rather, we envision a gradual replacement. First, we plan to replace some of the computer components containing integrated semiconductor circuits with our technologies while gaining a deeper understanding of the brain's working principles. We would then like to eventually develop an autonomous AI robot composed only of a hardware brain device/system. Although this might be an overly ambitious goal, I believe that it is achievable through collaboration between materials and brain scientists pursuing the recreation of truly human-like qualities.

(by Atsumi Takebayashi, Team Pascal)

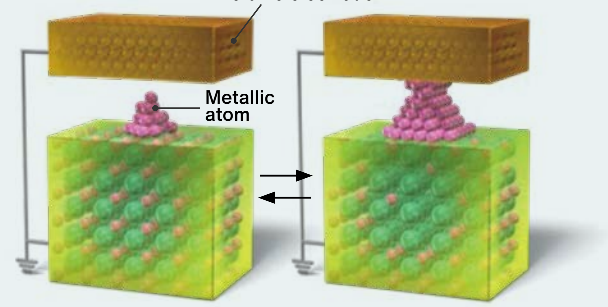
Focus

Recreating a synapse using an atomic switch

Neurons in the human brain communicate with each other via synapses. Synapses are able to retain previous communication mediation records, and their mediation efficiencies change depending on these records (i.e., synaptic plasticity). People tend to retain information they frequently encounter for longer periods of time (long-term memory) while easily forgetting information they encounter only occasionally (short-term memory). This tendency is thought to be related to synaptic plasticity.

An atomic switch device is a physical recreation of synaptic plasticity. This device's working principles are simple: when a voltage is applied to its two electrodes, metallic atoms are deposited on the surface of one of the electrodes, leading to the formation of a bridge between them (figure). NIMS used this switch to develop a synaptic device. The number of metallic atoms deposited between the electrodes of this device changes in response to the frequency and strength of the input voltage and the metallic atom bridge linking the electrodes disconnects as it degrades and shortens over time. NIMS has been conducting ambitious research aiming to create a brain-like computer and an artificial neural network using the synaptic device.

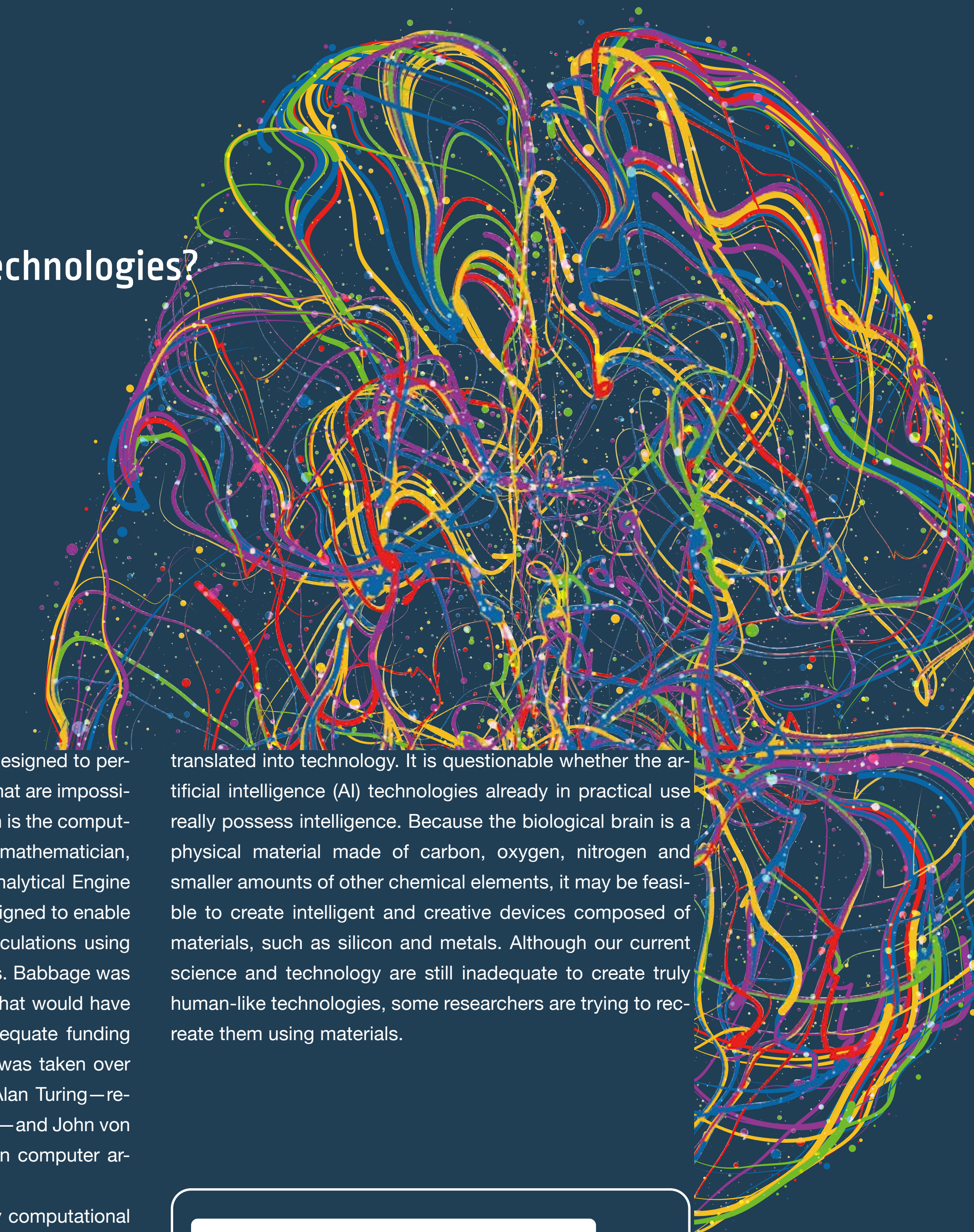
In addition, atomic switches have been incorporated into an FPGA—a high-performance integrated circuit—to function as a circuit line switching mechanism*. An FPGA circuit allows its users to alter it, changing its processing tasks. The atomic switch-integrated FPGA circuit is highly energy-efficient and radiation resistant. It was commercialized in 2017 by NEC Corporation, a company with which NIMS has conducted joint research for many years. The FPGA business has since been transferred from NEC to its spin-off company, NanoBridge Semiconductor, Inc. This company has been actively testing the compatibility of atomic switch-integrated FPGA products with a wide range of equipment, including radiation-resistant equipment used in aerospace, healthcare and radiation facilities and IoT devices to be installed in automobiles and robots.



Working principles of the atomic switch
When a voltage is applied to the two electrodes of the switch, metallic atoms are deposited on the surface of the lower electrode (made of a mixed electronic and ionic conductor), leading to the formation of a bridge between the two electrodes and activating the switch. When a voltage of the opposite polarity is applied to the electrodes subsequently, the deposited atoms form a solid solution with the mixed electronic and ionic conductor, breaking the link between the electrodes and deactivating the switch. This switch was used to create a synaptic device capable of changing its information retention capability in accordance with the frequency and strength of the input voltage. These changes in input voltage parameters cause the strength of the link between the two electrodes to change. The device's information retention capability will eventually degrade with time. Thus, this device successfully recreated the human brain's efficient learning functions.

***Atomic switch-integrated FPGA:** FPGA stands for a field programmable gate array. Software-controlled transistors have conventionally been used to connect/disconnect circuit lines. By replacing them with atomic switches, power consumption was reduced by approximately 90% and the size of the integrated circuit was reduced by approximately 67%. The performance of the atomic switch-integrated FPGA was tested in outer space for one year in a JAXA satellite launched in 2019. This experiment demonstrated that this circuit is highly resistant to radiation and electromagnetic noise in outer space.

COLUMN



What are human-like technologies?

Tomonobu Nakayama
Distinguished Emeritus Scientist
Director, Global Networking Division

Humans have invented many technologies designed to perform tasks for humans or carry out missions that are impossible for humans to achieve. One such invention is the computer. Charles Babbage (1791-1871), an English mathematician, devised a mechanical computer called the Analytical Engine in the early 19th century. This Engine was designed to enable its users to write programs to customize calculations using conditional branching and looping commands. Babbage was never able to complete the construction of what would have been the world's first computer due to inadequate funding and many other hardships. Babbage's work was taken over decades later by other scientists, including Alan Turing—regarded by some as the father of the computer—and John von Neumann, who established the von Neumann computer architecture.

Computers now fulfill almost all of our daily computational needs. They can carry out calculations for a wide range of purposes, including shopping and consumption tax expense calculation, the design of safe buildings through massive amounts of complex computations and image analysis and verification using huge amounts of data. Unlike humans, they perform these tasks without complaining, procrastinating or needing to be motivated. Most people wouldn't see human-like qualities in these flawlessly efficient machines. However, an increasing number of more human-like technologies are being put into practical use. These include avatars that attend virtual international meetings, vocaloids that sing popular songs, android receptionists and robots designed to perform nursing care tasks and wait tables. At their core, these human-like technologies are nevertheless controlled by mindless computers.

Given that human behavior is governed by the brain, brain-like devices—not necessarily computers—should serve as the core components of human-like technologies. What types of brain attributes need to be reproduced? If intelligence and creativity are the target attributes, they need to be described using a scientific language so that they can be translated into technology. It is questionable whether the artificial intelligence (AI) technologies already in practical use really possess intelligence. Because the biological brain is a physical material made of carbon, oxygen, nitrogen and smaller amounts of other chemical elements, it may be feasible to create intelligent and creative devices composed of materials, such as silicon and metals. Although our current science and technology are still inadequate to create truly human-like technologies, some researchers are trying to recreate them using materials.

Another Story of Brain and Materials

CONVERGENCE No.27
【Newsletter by International Center for Materials Nanoarchitectonics(WPI-MANA)】

Featured Topics
When The Artificial Brain Says 'Sleepy'

Masashi Yanagisawa
Director, International Institute for Integrative Sleep Medicine (WPI-IIIS)
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Tomonobu Nakayama

Extremely energy-efficient decision-making device

Takashi Tsuchiya

Principal Researcher
Nanoionic Devices Group
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Artificial intelligence (AI) applications—now popular globally—process complex information through elaborate computations. By contrast, the device Takashi Tsuchiya's group has developed uses ionic transport and electrochemical phenomena to perform learning and decision-making tasks.

Amoebae's survival strategy as a source of inspiration

Today's information society requires rapid analysis of huge amounts of data for appropriate decision-making. As AIs become increasingly sophisticated, the number of calculations computers need to perform is also increasing, requiring large amounts of electricity. To create a more energy-efficient system, Tsuchiya's group focused on the perception and decision-making mechanisms possessed by living organisms. Amoebae—single-celled organisms—are known to be able to make decisions and take actions critical to their survival using simple, very-low-energy mechanisms.

An amoeba retracts its arms (pseudopods) to avoid exposure to light while extending them to forage. It gathers environmental information using its multiple branching pseudopods and decides which pseudopods to use for foraging. Although amoebae lack a brain, they are able to quickly and efficiently make decisions and take actions to minimize the risk of light exposure while maximizing the chance of catching food.

"These amoebic mechanisms can be used to optimize human decisions/actions in various situations," Tsuchiya said. "For example, many players of pachinko (a Japanese pinball-like gambling game) seek to find more profitable pachinko machines. Achieving this will require trying out of a number of machines, but the more machines they try, the more money they have to spend. They therefore want to find a profitable machine with the smallest possible investment. Similarly, pharmaceutical researchers want to develop safe drugs while minimizing development costs by reducing the number of necessary clinical trials and thereby the chance of patients developing side effects. In mathematics, these problems are called multi-armed bandit problems. The amoeba's behavioral model can be an effective means of solving them. Our group has constructed a tug-of-war model—a mathematical representation of spatiotemporal dynamics in amoebic behavior. Because an amoeba has a constant body volume, when it extends one pseudopod, it needs to retract another in a manner similar to a tug of war. This model enables us to find the best behavioral pattern in trade-off problems."

Multi-armed bandit problems can be solved using conventional computers. However, computations need to be performed for each trial, and as the problem becomes more complex, the amount of computational resources needed increases exponentially. To avoid this, Tsuchiya's group considered an approach to solving such problems by running the tug-of-war model using a device with an ion-conducting solid material.

The group tackled the question of how to run the tug-of-war model using materials by thoroughly analyzing the model and spending time and effort choosing optimum materials. After much trial and error, the group ultimately created a device, termed as ionic-decision maker, capable of making decisions in a manner similar to living organisms. How does it work?

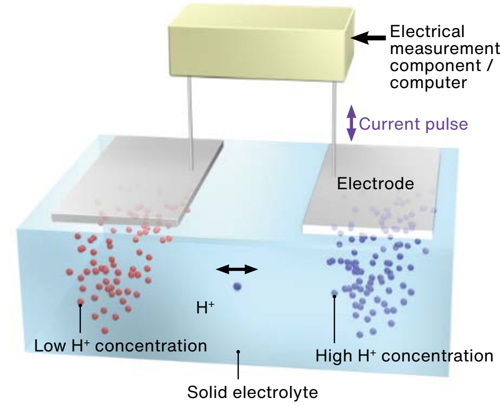


Figure 1. Schematic of the ionic-decision maker

When a 2-Hz electric current pulse is applied to the device, hydrogen ions in the solid electrolyte migrate, inducing electrochemical reactions (e.g., charging of an electrical double layer and redox reactions) at the interfaces between the electrolyte and the electrodes. This in turn causes the concentrations of hydrogen ions, hydrogen molecules, oxygen molecules and other chemical constituents to change, generating a voltage between the electrodes. Leveraging these electrochemical reactions, this device is able to perform quick learning and adaptive decision-making tasks.

Decision-making mechanisms

The device's basic structure is simple: it is composed of a solid electrolyte made of Nafion, in which hydrogen ions can move freely, with platinum electrodes attached to it. Connected to this basic structure are an electrical measurement component, which applies electric current and measures voltage, and a computer which controls measurements and processes data (Figure 1).

Let's take a look at the device's decision-making mechanisms using a multi-armed bandit problem related to radio communications (e.g., cell phone communications) as an example.

Assume that a caller is allowed to make a call using one of two available communication bands (channel A or B). To prevent these channels from becoming too crowded, a device was designed to select the optimum channel for callers to use for more efficient communication (Figure 2).

The number of electrodes in the device corresponds to the number of options (i.e., the number of available communication channels). The device's computer was preset to follow two rules: 1) it selects the channel corresponding to the electrode generating the highest voltage and 2) when communication through the chosen channel is successful, a positive current pulse is applied to the electrode corresponding to that channel and when it is a failure, a negative current pulse is applied to the electrode. In addition, the probabilities of successful communication associated with channels A and B are predetermined (e.g., 0.8 for A and 0.2 for B).

"In this example, when communication is completed successfully through channel A, a positive current pulse is applied to electrode A," Tsuchiya said. "As a result, hydrogen ions migrate toward the interface of electrode A, inducing various chemical reactions (e.g., charging of an electrical double layer and redox reactions) which in turn increase the voltage of electrode A. On the other hand, when communication fails, hydrogen ions migrate away from electrode A, decreasing its voltage. When this trial is repeated many times, the number of successful communications will be recorded in the form of changes in hydrogen ion concentrations in the Nafion electrolyte. As the communication success rate of a channel increases, the voltage of the electrode corresponding to that channel also increases, reinforcing the chance of the channel being selected by the device. No information processing is necessary. This device can give the correct answer repeatedly by allowing the fixed amount of hydrogen ions within the Nafion electrolyte to migrate between the electrodes in a manner similar to a tug of war."

In fact, this experiment demonstrated that the probability of the ionic-decision maker selecting the correct channel increases with the number of communication trials, from 100 to 200 to 400 times (Figure 3). The accuracy with which the correct channel was selected was then compared with a conventional computer which performed complex calculations, and it was found that their accuracies were similar.

Tsuchiya's group also tested the device in solving more complex problems involving two callers and three communication bands (channels A, B and C). It was assumed that when the two callers try to use the same channel simultaneously, their communications would interfere with each other, leading to a reduction in overall communication volume. The device was found to be able to effectively avoid this conflict, yielding an overall communication volume close to the theoretical maximum.

Simulating human-like thought processes, including natural memory loss, with extremely high energy efficiency

Another unique feature of this device is its ability to adapt to environmental changes. This was achieved by giving greater weight to more recent learning outcomes than older ones.

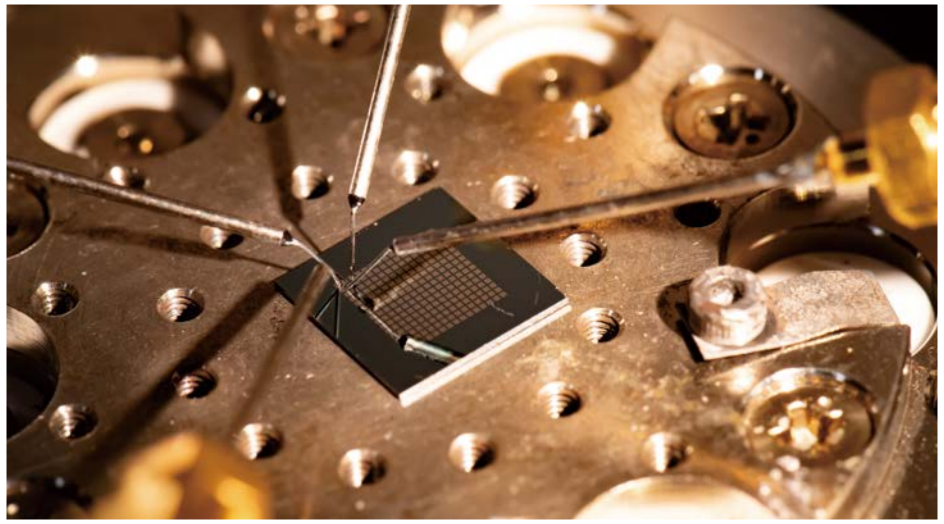
"When we choose something from a number of available options, we normally rely more heavily on newer experiences than older ones," Tsuchiya said. "For example, pachinko players may decide to leave their current machines and try different ones if they have performed poorly during the previous hour. Computer software can simulate this human approach to problem solving with a so-called "forgetting coefficient," although this requires complex computations. On the other hand, our device stores the cumulative learning outcomes in the form of hydrogen ion distributions across the Nafion electrolyte, which eventually evens out with time, leading to changes in the voltage difference between the electrodes according to natural physical laws. This mechanism can be used to make the device weigh more heavily on newer experiences than older ones."

According to Tsuchiya, the amoeba-inspired model his group has developed is very simple, but its information processing patterns are very similar to those of humans because the model has incorporated the fundamental survival instincts and strategies developed by living organisms. Another major advantage of this device is that its electricity consumption is extremely low.

"All organisms, including amoebae and humans, use ions to process information and make decisions," Tsuchiya said. "These biological processes are very energy-efficient. A supercomputer equipped with the latest AI system has thousands of GPU chips which consume hundreds of watts of electricity to operate. By contrast, the human brain needs only 20 watts to perform complex and creative thought processes. Similarly, our ionic device is far more energy-efficient than a semiconductor device and its integration into an AI system may potentially reduce the amount of electricity needed to operate it."

The ionic-decision maker actually consumed only approximately one-2,000th of the electricity by a conventional computer in solving the same problem in the communication channel experiment described above. "I hope to break new ground in the development of AI technologies by increasing the sophistication of this ionic device and incorporating it into a conventional computer," Tsuchiya said. He has taken a confident step forward in the development of more human-like AI.

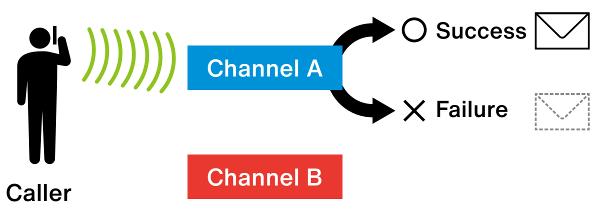
(by Yutaka Ōkoshi, Team Pascal)



Ionic-decision maker

The center of this photo shows an ionic-decision maker composed of a hydrogen ion conductive solid electrolyte and a series of electrodes on its surface. A mesoporous silica film is used as a solid electrolyte. The search for electrolyte materials more suitable for mass production and integration is underway.

Figure 2. Multi-armed bandit problem example in radio communications



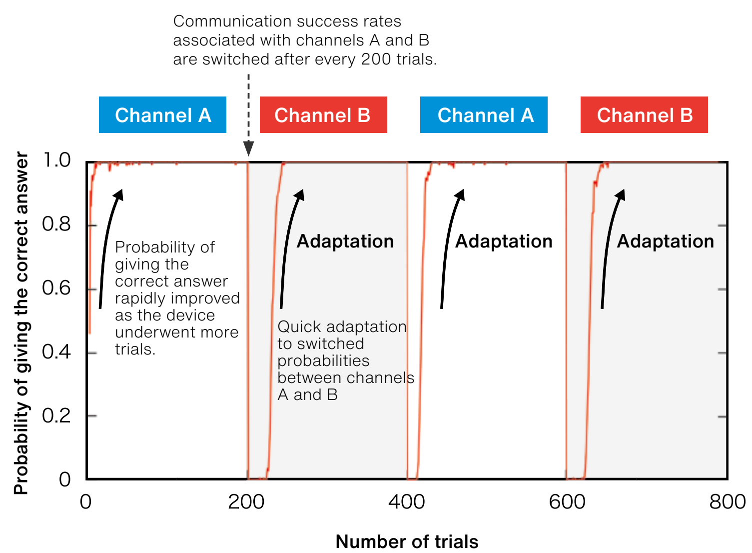


Figure 3. Probability of the ionic-decision maker giving the correct answer

Before the device was trained with data on channels A and B, its initial probability of giving the correct answer was about 0.5 (i.e., random chance). However, as it was trained repeatedly through a series of trials, its probability of answering correctly approached 1.0 (i.e., giving the correct answer every time). This result indicates that the device is able to learn to select the optimum channel more accurately through trial and error as it undergoes more trials. After 200 trials, communication success rates associated with channels A and B were switched in order to simulate a situation in which the previously optimum channel becomes busy. The device was able to quickly adapt to this change and select the new optimum channel.

COLUMN

NIMS' spintronic materials vital to the development of brain-like computers

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—What are the advantages of spintronic technologies? What types of brain-like computers have been developed using these technologies?

A succession of brain-like computer models designed to simulate brain functions involved in thought processes have been proposed in recent years. The most common example of a brain-like computer is an artificial neural network—a mathematical model inspired by a biological neural network. Spintronic technologies could be a key player in developing the computational and memory functions of artificial neural networks. Existing computer hardware carries out arithmetic and logical operations using the binary digits 0 and 1. By contrast, spintronic technologies using electron spin direction are not only able to perform binary operations but can also carry out operations using intermediate spin states between 0 and 1 and interactions between multiple spins. These technologies could enable a simulation of the energy-efficient brain.

Among the various approaches to developing brain-like computers being researched, the clear advantages of using spintronic technologies are their great endurance to material degradation caused by repeated writing and their high energy efficiency. Complex computations require many cycles of memory rewriting—a cause of material degradation in some memory devices. By contrast, rewriting via the electron spin used in spintronic technologies is virtually free of material degradation. In addition, spintronic technologies use magnetic interactions rather than higher-energy electric interactions, making them highly energy-efficient.

These advantageous characteristics of spintronic technologies are likely to make them most useful in edge computing—an efficient data processing architecture in which most computations are performed at the sources of data or by computing resources located in close proximity to them (i.e., edge devices), thereby limiting the need for more distant cloud computing. One promising edge device service is reservoir computing capable of real-time learning of time-series data, such as audio and video data. R&D efforts to enhance the computational capabilities of computer hardware using spintronic properties have been intensifying.

—What is the current status of brain-like computer R&D?

Development of a spintronics-based brain-like computer has been led by Tohoku University and the National Institute of Advanced Industrial Science and Technology (AIST). Its hardware is equipped with non-volatile memory or spin torque oscillators, both of which have the same basic component: a magnetic tunnel junction (MTJ) device. Tohoku University and AIST played a leading role in developing the MTJ device.

An MTJ device is composed of two ferromagnetic layers separated by a tunnel barrier layer (figure). AIST developed a crystalline MgO tunnel barrier material which was then put into practical use by electronics companies. MTJ devices equipped with this material have been used around the world for more than a decade. Looking at overseas activities related to spintronics-based brain-like computers, research organizations in France and the United States and Samsung Electronics Co., Ltd. in South Korea have produced notable results. However, these organizations have been focusing most of their efforts on the development of effective hardware using existing MTJ devices, and are therefore making only limited efforts in materials research aimed at improving the performance of MTJ devices. Developing new materials is indispensable to increasing the output and endurance of these devices. NIMS has been researching MTJ device materials and has developed many promising materials.

—What are NIMS' accomplishments in brain-like computer development?

We have developed several half-metal ferromagnetic materials potentially capable of increasing an MTJ device's output. We have also obtained tunnel barrier materials with stable crystalline structures, including MgAlO and MgGaO, which may potentially be used to lower a device's electrical resistance. Using these materials, through theoretical and other approaches by controlling interfacial structures, we have been working to enhance the performance of MTJ devices. As a result, we achieved the world's highest magnetoresistance ratio in 2022 by using an MTJ device equipped with pure Fe ferromagnetic layers (the de facto benchmark used for barrier performance evaluation) and with a Mg_2Al-O_x tunnel barrier layer integrated into it.

In addition, we are developing MTJs with a (111) crystallographic orientation—instead of the conventional (100) orientation—to utilize the fascinating properties of (111)-oriented ferromagnetic alloy layers, as a potential way of improving the MTJ device's thermal stability and integration capability. We also began challenging research attempting to form quantum wells in ferromagnetic layers. NIMS has been engaged in these R&D activities with the goal of developing hardware for practical, energy-efficient brain-like computers capable of human-like thought processes.

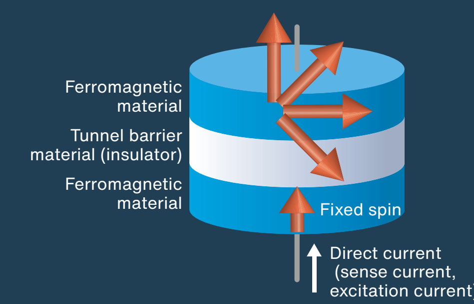

Figure. Magnetic tunnel junction (MTJ) device

This device is composed of two ferromagnetic layers separated by an insulating layer. The total spin direction of the bottom ferromagnetic layers is fixed. The device's electrical resistance can change significantly depending on "the spin direction of the electrons" or "the proportion of reversed spin area" in the top ferromagnetic layer. The resistance of the device can be translated into either the binary digits 0 and 1 or intermediate values between 0 and 1. In addition, a network of multiple, interacting MTJ oscillators may potentially be able to perform computations.

Artificial vision device capable of ‘optical illusions’: Toward AI with complex human visual functions

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When people look at their surroundings and form a visual image of them, their visual systems automatically increase the edge contrast between the darker and lighter areas of the image through a neural mechanism called lateral inhibition. Tohru Tsuruoka and his colleagues have succeeded in developing a small, energy-efficient device capable of recreating visual lateral inhibition. Lateral inhibition is known to occur in all five human senses, suggesting a wide range of potential applications for the device.

Optical illusion: an advanced visual function

Artificial intelligence (AI)-based pattern recognition using automated deep learning has greatly advanced in recent years. Pattern recognition techniques have been used in various fields, including image analysis, automated driving technologies and facial recognition systems.

Optical illusions caused by lateral inhibition play a vital role in human visual information processing. Human eyes are capable of correcting (e.g., intensifying or weakening) the brightness, color and shape of captured images. These optical illusions occur naturally to help the brain efficiently process visual information. Increasing the edge contrast between darker and lighter areas is particularly important, as it facilitates clearer recognition of colors and shapes.

Recreating lateral inhibition using the information processing capability of a conventional computer would require complex circuits and programming. Tsuruoka’s research group considered unconventional ways of reproducing human sensory perception and information processing systems. As a result, the group developed and publicized an ionic vision device in 2021.

“The advantage of this device is its ability to identify the outlines of objects in an image (i.e., edge detection) using only ionic movements within a solid material and electrochemistry,” Tsuruoka said. “Although edge detection can also be achieved using conventional image sensors, this method requires labor-intensive programming to process the image data and relatively large hardware, including circuits dedicated to the sensor. In addition, a huge amount of electricity is needed to perform these complex calculations. By contrast, the device we developed is able to detect edges using only input signals; no programming or complex circuits are necessary. Because the device is compatible with miniaturization, it has many potential applications.”

Retina-inspired device

Visual lateral inhibition is known to take place in the retina at the back of the human eye. The retina has a multilayered structure containing hundreds of millions of neurons. It converts light into electrical signals.

This light-to-signal conversion is first carried out by the photoreceptor cells in the retinal layer. The electrical signals are then transmitted to and processed by the neurons in the second retinal layer. The processed signals are then passed on to ganglion cells in the third retinal layer before traveling through the optic nerve to the brain, where the image information is recognized.

During this process, horizontal cells and bipolar cells in the second retinal layer produce lateral inhibition. The horizontal cells which interconnect individual photoreceptor cells strengthen or weaken the electrical signals received from the photoreceptors and transmit them to bipolar cells (Figure 1).

Tsuruoka and his colleagues became aware of close similarities between the functions of horizontal cells and the effect of ionic movements in a solid material. This discovery eventually led them fabricate a device composed of a solid electrolyte (lithium phosphorus nitride) capable of conducting lithium ions with a series of channels (i.e., mixed electronic and ionic conductors made of lithium cobalt oxide) on its surface. Platinum electrodes are attached to the ends of the channels (Figure 2).

“Light perceived by human eyes is converted into electrical signals by the photoreceptors,” Tsuruoka said. “We simulated this process by first converting image information into electrical signals and applying the corresponding pulsed voltage to the device’s channels. Low voltage is applied to the channels representing the darker areas of the image, while high voltage is applied to the channels representing the lighter areas. This causes lithium ions to migrate between the two adjacent channels representing the boundary between the darker and lighter areas (channels 4 and 5 in Figure 2). Lithium ions in the channel supplied with high voltage (channel 5) leave the channel and migrate through the solid electrolyte to the channel supplied with low voltage (channel 4). This ionic movement recreates the lateral inhibition occurring in the retinal horizontal cells, which strengthen or weaken electrical signals. Channels with increased lithium ions are subject to increased electrical resistance and decreased voltage; conversely, channels with decreased lithium ions are subject to decreased electrical resistance and increased voltage. Thus, ionic concentration changes cause the low voltage channel (channel 4) to have an even lower current, while the channel whose voltage has been high (channel 5) is caused to have an even higher current. As a result, there is an increase in the current difference between the two channels, which represents the boundary between the darker and lighter areas of the image. This recreates the increased edge contrast produced by lateral inhibition.”

Figure 1. Schematic of the retina’s signal transduction process

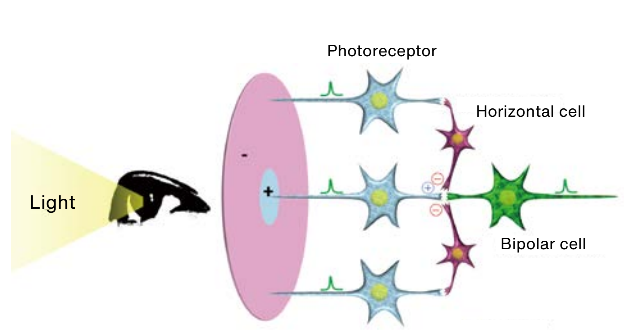
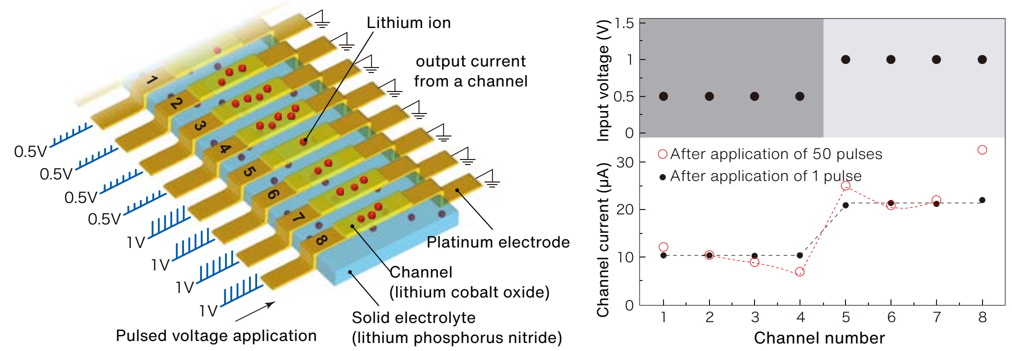


Figure 3. Original image (left) that was processed by the ionic vision device and the resulting output image (right)
The boundaries between the darker and lighter areas of the original image are accurately depicted with increased edge contrast.

Figure 2. Schematic of the ionic vision device
This device is composed of a sold electrolyte (lithium phosphorus nitride) with a series of eight channels (lithium cobalt oxide) on its surface with platinum electrodes attached to them. To verify the device’s ability to detect the boundary between the darker and lighter areas of an image, a 0.5 V pulsed voltage (representing the darker areas) was applied to channels 1–4 while a 1 V voltage (representing the lighter areas) was applied to channels 5–8. The difference in output currents between channels 4 and 5 (representing the boundary between the darker and lighter areas) increased significantly after 50 pulses were applied. This contrast enhancement well reproduces the lateral inhibition that appears near the boundaries of light and dark in human vision.



To verify the performance of the device, Tsuruoka’s group actually converted image information into electrical signals and applied the corresponding voltage to the device. The group confirmed that the output image had increased edge contrast between the darker and lighter areas of the original image (Figure 3).

Applying lateral inhibition to the other human senses

Human eyes automatically produce optical illusions to correct not only edge contrast but also other visual features, such as tilt, size, color and movement. These illusions are believed to play an important role in the brain’s ability to recognize different objects in the external world. Because the ionic vision device developed by Tsuruoka’s group may be used to recreate other optical illusions in addition to increased edge contrast, it may potentially be used for a wide range of applications.

Moreover, intensification of stimuli caused by lateral inhibition is known to occur in the other human senses, such as hearing, touch, smell and taste. This device may also potentially be used to develop, for example, a new sensing system capable of making the voice of a target person stand out amid background noise.

“All living organisms, including human beings, effectively use ions to perceive the external world, carry out thought processes and make decisions,” Tsuruoka said. “We believe that our ionic device is more similar to biological systems than conventional semiconductor devices in that it uses ionic movements. This ionic device with its biologically-inspired working principles is suited for recreating biological systems. I hope that our future research will contribute to the development of more human-like AI.”

(by Yutaka Ōkoshi, Team Pascal)

Ionic vision device
Eight ionic vision devices fabricated on the surface of a silicon substrate. Each device has a series of 24 mixed electronic and ionic conductor channels on a solid electrolyte.

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