Chapter 7　Strategic Objectives

7.1　Innovation of Bio-Sensing , Elucidation of Dynamics and Interactions between Biomolecules by Using Quantum Technology

Overview

In our country, world-leading technological developments have been generated through basic research related to light and/or quanta, and this research continues to date. For example, an organization in our country has developed an internationally recognized high-level quantum sensor technology, and overseas research groups have requested relevant materials. Furthermore, a microscope that makes use of quantum entanglement light is based on technology established in our country; moreover, high-precision structure and function analyses with an use of quanta beam have made substantial contributions to global research. These quantum technologies are expected to be applied to bioscience research and have just begun to be applied overseas. However, in our country, owing to limited integration between the fields of quantum technology and biosciences, the biological applications are not sufficiently advanced. Further, if these circumstances continue, it is feared that these high-level quantum technologies may leak out of the country.

Therefore, this strategic objective promotes the fusion of quantum technologies and biosciences to seek a bioscience frontier in order to understand, in an integrated manner, the functions of biomolecules in cells at the quantum level and to maintain the superiority of research in Japan. Thus, this objective enables applications to the development of new medical treatments, diagnostic methods, etc. At the same time, further developments are expected in relevant industries owing to new measurement devices and equipment that make use of quantum technology.

Targets to Achieve

In these strategic objective, the purposes are to link the newest quantum technology and bioscience research to solve new or rare human health issues, to obtain precise solutions targeting the activities and mutual interactions of biomolecules, and to seek industrial applications and new scientific fields (quantum bioscience), while providing a platform for multi-modal analyses and the complementary and synergetic use of measurement technologies that are cross-sectional with respect to temporal and spatial scales based on quantum technologies. Specifically, the objective attempts to reach the following achievements:

(1) A quantum sensor technology will be used to realize highly sensitive observations of weak temperatures, magnetic fields, electric fields, and the like in living bodies, generating a new tide of bioscience, medical, and industrial applications.

(2) The newest quantum technologies, such as quantum entanglement light and multiphoton, light quantum detection technologies, will be combined with super-resolution microscopy and/or innovative new probes to realize new imaging methods for within the body, i.e., quantum imaging, enabling the capture of statuses that have not been visualized at a high spatial resolution.

(3) Technology to enhance the usage of and measurement with quantum beams will be used to analyze precise structures and functions at the quantum level, including the electronic state of molecules in the living body and the behaviors and the state of chemical bonds of hydrogen atoms, thus clarifying the functions of living-body molecules, including mutual interactions among molecules and reactions.

Future Vision of a Society to be looked at during the research promotion

Through the achievements of the items stated in section 3, *Goals and Objectives,* contributions will be made to embody the society described below:.

- A society in which new methods for medical treatment and new medicines with high efficiency are developed based on the physical and essential understanding of life phenomena to improve health and longevity.

- A society in which an early and quantitative diagnostic and preventive measures for functional diseases, which may be called modern diseases, and diseases that are difficult to detect at an early stage are established, realizing the reduction of medical expenses.
- A society in which sensors, measuring devices, and diagnostic equipment with high additional values (small, minimally invasive, high accuracy) are deployed to the world market and in which there is an industrial competitiveness of Society 5.0.
- A society in which the international atmosphere is enhanced by leading a new field of science, and a scientific and technological nation is realized by the continuous generation of new medical treatments and technological advances.

Specific Research Examples

(1) Biosensing involving the development of quantum sensor technology (*related to the first item in *Goals and Objectives*)

Quantum sensors, such as the diamond nitrogen-vacancy (NV) center and the silicon cavity in silicon carbide (SiC), are used, for example, owing to their biocompatibility and to realize the quantitative measurement of temperatures, magnetic fields, electric fields, and the like with nanometer resolution with respect to cells, neurons, proteins, and biomolecules. Furthermore, the development of single-molecule NMR and nano-MRI is achieved using photo-/electric-detection magnetic resonance and/or electric spin resonance. The measurements of cardio-magnetism, neuro-magnetism, and the like are realized to develop industrial and medical applications.

(2) New living-body imaging (quantum imaging) (*related to the second item in *Goals and Objectives*)

The newest quantum technology is expected to enable the development of a new living-body imaging technology. A low-light imaging technology is established, for example, by introducing a new living-body imaging system based on the enhancement of resolution by a combination of photo and quantum technologies, such as multi-photons with a variety of super-resolution microscopes and/or quantum entanglement light applied to a multiphoton microscope. Moreover, a new imaging technology is sought, aimed at synergetic effects by the simultaneous and parallel developments of the above-mentioned imaging technologies and an innovative fluorescent probe. The multi-modal imaging is developed for analyses of the physical fields of a specific spot in a cell and the mutual interactions among biomolecules by combining existing modalities with a quantum sensor as a new probe.

(3) Super precision structure and function analyses at the atom/electron level (to collect functional information directly from a structure) (*related to the third item in *Goals and Objectives*)

A technology to enhance the use and measurement of quantum beams is used to directly research the functions of biomolecules. For example, the mutual interactions among molecules and reactions in a living body are resolved by combining behavioral information on hydrogen atoms and/or water molecules in linkage with and by the use of neutrons and x-rays with information on bond distances with a high reliability. Research will be aimed at understanding the functionality of the behaviors of outer electrons, the hydrogen bond, and the like, which are important for the mutual interactions of biomolecules, molecular targeted drugs, etc. Furthermore, the detailed atomic structures in relation to chemical reaction processes will be resolved by collecting chemical bond information and these data will be applied to determine the relationship between bioreactions and diseases. Moreover, applications to quantum bioscience will increase, including the development of solutions to quantum mechanics effects in enzyme reactions, electron transfer, information, and energy among molecules.

Based on these studies, a platform for multi-modal analysis will be formed by introducing newly established technologies. Thus, it is expected, for example, that anomalies in neurotransmission will be identified, measuring equipment for neuro-magnetism that works at room temperature will be developed, specific molecular targeted drugs will be generated, and the precision medicine industry will advance as a result of, for example, the identification of cancerous/non-cancerous transformation in neoformation, the detection of anomalies in deep regions, determination of the causes of and quantitative diagnostic indicators of functional diseases (depression, schizophrenia, etc.), the development of diagnostic equipment for such diseases, and the detection of the stimulation of nerve cells.

Domestic and Foreign Research Trends

(Trends in Japan)

In Japan, the seeds of technology with applications to biosciences have been generated from basic research related to light and quantum mechanics and these developments are continuing. For example, quantum technologies, such as quantum sensors, quantum entanglement light, and the enhancement of quantum beams, provide a basis for technology with which Japan leads the world; however, currently, young and able researchers at the diamond NV center in Japan are being recruited to the US and countries in Europe.

Furthermore, according to the mid-term summary published by the Quantum Science Committee, Advanced Research Platform Section, Council for Science and Technology in February of this year (2017), the field was positioned to strengthen its competitiveness on the basis of advancements in hybrid research that will identify new fields as well as establish advantages of work in our country in multiple phases. In this discussion, they pointed out high potential in this field in Japan, the wideness of the economic ripple effect to various industries, including medical care, energy, and manufacturing, and aimed for prompt policy measures in our country.

(Trends overseas)

In recent years, the trend in research to fuse the newest quantum technology and bioscience has been observed. In the National Quantum Technologies Programme in the UK and in the Quantum Flagship of the European Commission, the fusion with bioscience an explicit goal. Furthermore, Germany, as a base of the fusion for universities in Europe and the US, has advanced research aimed at medical and industrial applications; the establishment of research centers is planned to strengthen quantum sensors and quantum biology, respectively, at Universität Stuttgart and Universität Ulm. Under these international trends, manufacturing technology for high-leveled quantum sensors etc. by domestic research groups in our country is gaining interest; materials are already being provided upon requests from overseas research groups. Moreover, research to determine the quantum-mechanical effects in cells and/or tissues is ongoing and stimulating, and, in 2012, the first international conference on quantum biology was held in the UK.

Background of Consideration

The following surveys were conducted according to the *Guideline for the Preparation of Strategic Objectives and the Like* (Resolution by Strategic Basic Research Subcommittee, Science and Technology Science Council, June 8, 2015)

(Preparation for an analysis to examine domestic and overseas research trends by a scientometric method, using the Grant-in-Aid for Scientific Research (KAKENHI) Database and similar information)

We prepared analytic materials regarding research trends in Japan and overseas by using a scientometric technique to analyze research papers of co-citation relations or direct quotation relations in the Grant-in-Aid for Scientific Research Database, etc.

(Implementation of a questionnaire for specialists using analytical materials and the preparation of notable research trends)

We implemented a questionnaire on noteworthy research trends based on the analytical materials that we had prepared for respective field units of the Center for Research and Development Strategy (CRDS) for the Japan Science and Technology Agency (JST), for program directors etc., of the Japan Agency for Medical Research and Development (AMED), and for the experts participating in the network operated by the Science and Technology Foresight Center of the National Institute of Science and Technology Policy (NISTEP). We then analyzed responses to the questionnaire and identified "the Innovation of Biosensing by Application of Quantum Technology and the Solution of the Movement of Biomolecules and Interactions" as a noteworthy research trend.

(Holding of workshops and the preparation of Strategic Objectives)

We held a workshop to bring together experts from industry and academia involved in "the Innovation of Biosensing by Application of Quantum Technology and the Solution of the Movement of Biomolecules and Interactions," which was identified as a noteworthy research trend. At the workshop, we focused on notable trends in Japan and overseas, the social and economic impacts of research progress and technological developments, the visions for society arising from these advances, and the objectives that should be met during the research period. We then prepared Strategic Objectives based on the discussions in the workshop.

Relevant Matters in Cabinet Decisions, etc.

5th Science and Technology Basic Plan (approved by the Cabinet on January 22, 2016)

Chapter 2, (3), <2>, 2)

As a core technology for the generation of new values in individual systems and functions in the real world, our country tries to strengthen the following platform technologies:

- "Photo and quantum technology" leading to the differentiation of systems by the enhancement of a variety of components, such as innovative measurement technology, information and energy transfer technology, and processing technology.

Chapter 3, (1), <2>, 1)

There is a desire for basic scientific research in our country to be applied to promote the development of medical technology and to realize a longer life expectancy, improved health outcomes, and the continuity of the health care system. It is expected that these technologies will contribute to economic growth in our country by enhancing the competitiveness of industries related to medical care through the realization of drug discovery, health care equipment, and medical care technology developed in our country.

General Innovation Strategies for Science and Technology 2016 (approved by the Cabinet on May 24, 2016)

Chapter 1, (3), [A]

It is necessary to try to strengthen the following platform technologies for cross-sectional support:

- Photo and quantum technology: In order to contribute to the formation of a high-dimensional social and industrial infrastructure to meet social demands with respect to accuracy, sensitivity, capacity, energy-saving, and security, with cross-sectional support for a wide range of fields, including information and communication, medical care, environment, and energy, it is important to promote basic and applied research to improve measurement technology, imaging and sensing technology, information and energy transfer technology, and processing technology.

Chapter 1, (3), [B]

It is also important, from middle- and long-term perspectives, to promote basic research, such as the development of measurement technology, imaging and sensing technology, photo and quantum technology to enhance information and energy transfer technology and processing technology, thermal (phonon) control technology in the nano-field, which is important for high-level thermal management, and measurement, diagnostic, imaging, and biotechnology for the creation of useful substances, etc.

Other

- The quantum technology in this strategic objective connects the basis of the technology generated from long-standing basic research that led the world in the field of life sciences and has become useful for practical applications. On the other hand, "the cultivation of the next-generation photonics by the emergence and the use of new photo-functions and optical properties," the strategic objective started in FY 2015, and "the cultivation of a new physical property and information science frontier by high-level control of the quantum state," the strategic objective started in FY 2016, enable new, high-level control of the most advanced photo-functions and photo-physical properties and the state of quantum research based on the latest physics and solid-state physics, which will be positioned for highly advanced research connecting different fields and to be generated from the above-mentioned in the future. By facilitating the creation of the most advanced technology according to these strategic objectives, the acceleration of achievements is expected by the sequential introduction of these technologies to bioscience research under these strategic objectives.

7.2 Elucidation of Biological System of Extracellular Fine Particles

Overview

Between cells in the living organisms, "Extracellular fine particles" in the nano- to micro-size range are generated in living bodies or intrude from the outside. Extracellular fine particles are classified as those from a living body, e.g., extracellular vesicles, such as micro-vesicles and exosomes (endogenous), or those taken in from outside of a living body, such as PM2.5, pollen, and nano-particles (exogenous). In recent years, it has been reported that endogenous fine particles influence the development and malignant progression of many diseases, and thus this field of research has received a great deal of attention worldwide. Exogenous fine particles have also received a great deal of interest in the nation owing to the environmental implications, and the influence of PM2.5 and other substances on living bodies is gradually becoming clear.

In the research area on endogenous fine particles, response analyses at the tissue and/or cellular level in living bodies are increasing, and in the research area on exogenous fine particles, physiochemical analyses of fine particles and the development of measurement technologies are beneficial. However, as the two areas have different research communities, there have been few opportunities for mutual interactions. Therefore, this strategic objective is aimed at cooperation between these fields of research. Synergetic effects are expected, contributing to the resolution of the mechanism underlying mutual interactions between extracellular fine particles and living bodies, and to the development of technology for the detection, separation, and analysis of fine particles.

Based on the above-mentioned aims of this strategic objective, i.e., the development of technology for the detection, separation, and analysis of extracellular fine particles with high precision and high efficiency, it will be possible to determine the physiological effects of extracellular fine particles in living bodies and the mechanisms underlying biological responses. In addition, the technology can be applied to control the kinetics of extracellular fine particles in living bodies. It is expected that the achievements of these research platforms will have a wide range of applications in society, including medical applications, e.g., drug development, diagnosis, and medical treatment technology, industrial applications in fields closely related to fine particles, e.g., foods, cosmetics, and materials, and environmental applications.

Targets to Achieve

This strategic objective includes the elucidation of biological system of extracellular fine particles, which requires the development of relevant technology and control of the kinetics of fine particles in living bodies, and advancements in research aimed at future medical and industrial applications.

Endogenous corpuscles and exogenous corpuscles, which are different in size and physical properties, are studied by different research communities. By sharing common issues in the fields, which have had few exchanges to date, it is possible to strengthen and combine the advantages of the two research areas by creating a foundation for integration and to compensate for disadvantages by the fusion of fields and merging studies.

Specifically, the following achievements are expected:

(1) The advancement of detection, separation, and analysis technologies for extracellular fine particles.
(2) Elucidation of biological system of extracellular fine particles.
(3) The development of control mechanisms for extracellular fine particles in the living body.

Future Vision of a Society to be looked at during the research promotion

Based on the achievements of the items stated in section 3, *Goals and Objectives,* the following contributions to society are expected.

- A society in which medical innovations are realized by the application of the research to develop new drugs, diagnostic methods, medical treatment methods, etc.

- A society in which the continuous development of industries is realized by the creation of foods, cosmetics, and materials that are safe and have new functions.
- A society in which citizens can live safely and securely owing to environmental measures that address social needs.

Specific Research Examples

(1) The advancement of detection, separation, and analysis technologies for extracellular fine particles.

The technology (detection, separation, and analysis) to handle extracellular fine particles in living bodies, which is currently difficult, will be enhanced. For example, separation and/or refinement devices for extracellular fine particles and the elemental technology necessary to meet the above-mentioned goals will be developed. Furthermore, the use of artificial intelligence and other approaches will be considered to enable analyses of particle diameters and shapes as well as overall analyses of the component elements of extracellular fine Particles with high precision. These developments will enable the detection of corpuscles emerging specifically in a part and/or a state of a living body and analyses of their influences on the living body.

(2) Elucidation of biological system of extracellular fine particles.

The complex response mechanisms within living bodies to extracellular fine particles will be clarified. For example, it is necessary to characterize the physiological functions of extracellular fine particles in a variety of species and the biological response mechanisms in specific tissues and cells in a living body. The actual state of the exposure of living bodies to extracellular fine particles needs to be analyzed, and to get information on kinetics of particles in living bodies after they are taken in is very important. Furthermore, the development of methods for the observation, analysis, and simulation of the behaviors of corpuscles at a fine scale in living bodies is necessary for the above-mentioned aims.

(3) The development of methods for the control of extracellular fine particles in living bodies

Based on the knowledge revealed in the abovementioned aim, a method for the control the kinetics of extracellular fine particles in living bodies can be developed. For example, the development of a method to control particles at the level of tissues and/or cells, such as the formation, accumulation, intake, and discharge of inclusion bodies, and the development of the necessary technologies will be advanced, including functional materials and methods for observation and evaluation.

Domestic and Foreign Research Trends

(Trends in Japan)

As for endogenous fine particles, the *Japanese Society of Extracellular Vesicles* was established in 2014 and its membership has increased year after year, including members not only from academia, but also from private sector. Furthermore, research on fine particles, with exosomes as a typical example, has extended our knowledge of "autophagy," leading to the 2016 Nobel Prize in Physiology or Medicine, and, thus the time is ripe for globally important research achievements in Japan.

As for exogenous fine particles in the *Consortium for Measurement Solutions for Industrial Use of Nanomaterials* (COMS-NANO) hosted by the National Institute of Advanced Industrial Science and Technology and private corporations, a nanoparticle measurement system is being developed as a platform based on industrial-academic-government cooperation. Furthermore, active research in our county has focused on the discovery and analysis of kinetics of particles in living bodies, the development of control technology, and the discovery of the accumulation mechanism (i.e., the enhanced permeability and retention [EPR] effect) of corpuscles in tumor regions.

(Trends overseas)

The number of relevant papers in this research field has been on the rise, indicating that the field is gaining global attention. As for endogenous particles, the major project of the NIH in the US ("Extracellular RNA communication" program) was started in 2013, while a subcommittee was established in 2016 at prestigious international conferences, such as the Gordon Conference and Keystone Symposia. In CANCER-ID, a project progressing with the support of

Innovative Medicines Initiative (IMI), a partnership among government and private parties for the research and development of medicines in Europe, exosome research has been conducted. Furthermore, there are high activities related to measurement technologies and the standardization of exogenous corpuscles, such as the establishment of the Nano Define Project in Europe.

Background of Consideration

The following surveys were conducted according to the *Guideline for the Preparation of Strategic Objectives and the Like* (Resolution by Strategic Basic Research Subcommittee, Science and Technology Science Council, June 8, 2015).

(Preparation of an analysis to examine domestic and overseas research trends by a scientometric method, using the Grant-in-Aid for Scientific Research (KAKENHI) Database and similar information)

We prepared analytic materials regarding research trends in Japan and overseas using a scientometric technique to analyze research papers of co-citation relations or direct quotation relations in the Grant-in-Aid for Scientific Research database and others.

(Implementation of a questionnaire for specialists using analytical materials and the identification of notable research trends)

We implemented a questionnaire on noteworthy research trends based on the analytical materials that we prepared for respective field units at the Center for Research and Development Strategy (CRDS) for the Japan Science and Technology Agency (JST), for the program directors and others of the Japan Agency for Medical Research and Development (AMED), and for the experts participating in the network operated by the Science and Technology Foresight Center of the National Institute of Science and Technology Policy (NISTEP). We then analyzed responses to the questionnaire and identified "Characterization of the Mechanism of the Biological Response Activated by Extracellular fine particles and the Control of fine particles" and "Determination of Region- and State-Specific Mechanisms of the Living Body Mechanism for Intrabody Targeting and the Application to Medical Platform Technologies" as noteworthy research trends.

(Holding of workshops and preparation of Strategic Objectives)

We held a workshop to bring together experts from industry and academia involved in the "Characterization of the Mechanism of the Biological Response Activated by Extracellular fine particles and the Control of fine particles" and "Determination of Region- and State-Specific Mechanisms of the Living Body for Intrabody Targeting and the Application to the Medical Platform Technologies," which were identified as noteworthy research trends. At the workshop, we focused on discussion of the notable trends in Japan and overseas, the social and economic impacts of the research progress and technological developments, the visions for society arising from these advances, and the objectives that should be met during the research period. We then prepared Strategic Objectives based on the discussions in the workshop.

Relevant Matters in Cabinet Decisions

5th Science and Technology Basic Plan (approved by the Cabinet on January 22, 2016)

Chapter 4, (2), <1>, 2)

Basic research based on national political strategies and requests is an important source of innovation, together with academic research aimed at challenges in the fields that are not sufficiently addressed by corporate efforts, and provides a foundation for further advancements, such as collaborations across fields and the fusion of different fields. (Omitted) Furthermore, rich interdisciplinary and field-fusing research is attempted.

Japan Revitalization Strategy 2016—to the Fourth Industrial Revolution (approved by the Cabinet on June 2, 2016)

II, 1-2, (2)-4), -5

(Omitted) will aim to make Japan the first country to propose a practical evaluation method for medical equipment, and promote its acceptance and use as an international standard.

Health and Medicine Strategy (approved by the Cabinet on July 22, 2014)
2, (1), 1)
(Omitted) will attempt to determine the pathology of various diseases by applying the cutting-edge scientific technology developed in our country (omitted). This will enable the development of a drug delivery system (DDS) and innovative medicines, medical equipment, and the like and facilitate the generation of future medicines, medical equipment, and medical technology. (Omitted) aims to strengthen the development of next-generation measurement, analysis, and evaluation technology, equipment, and systems.

Plan for the Promotion of Medical Research and Development (approved by the Headquarters for Healthcare Policy on July 22, 2014)
1-1, (1), <2>
(Omitted) aims to realize a society in which the development of the technology for the prevention of disease outbreaks and the spread of disease, the development of advanced medical care as well as new medicines and diagnostic and treatment methods, and the development of medical equipment are advanced.

Other

In "The Mechanism underlying the Outbreak of Diseases Such as Allergic Diseases, Autoimmune Disorders, and the Like and the Technology for Remedy" (FY 2008–2015), AMED-CREST, Japan Agency for Medical Research and Development (AMED), emphasis was placed on the control of whole immune reactions, and a target was established to develop integrated medical technology based on the movement of immunoregulatory cells. In "The Multidisciplinary Researches on Autophagy—from Molecular Platforms to Diseases" (FY 2013 - FY 2017), in a new academic field, funded by a Grant-in-Aid for Scientific Research, the target was to determine the mechanism by which vesicles form in cells. In "Non-Coding RNA Neo-taxonomy" (FY 2014 to FY 2018) and in "The Development of a Platform for Micro-RNA Measurement Technology in Body Fluid" project (FY 2014 to FY 2018) of the New Energy and Industrial Technology Development Organization (NEDO), studies focused on the understanding of and measurement methods for component factors in endogenous corpuscles have been progressing. The Ministry of the Environment implemented an immunological survey and other projects related to PM2.5 in "The Fund for Research on the Influence of Exposure to Air Pollutants" (FY 1999 to FY 2016). These projects are expected to accelerate new research and achievements by cooperation and information sharing among researchers and by the goals outlined in this strategic objective.

7.3 Development of innovative materials and device technologies based on understanding and manipulation of nanoscale thermodynamics

Overview

The problem of heat generation by electronic equipment limits the achievement of high performance from miniaturized devices and equipment using such devices, potentially hindering the advancement of the Internet of Things (IoT) concept. If heat could be controlled as freely, as electricity and light, heat control may assist in solving the problem of heat generation from electronic equipment.

Significant amounts of thermal energy are unused after emission from factories, automobiles, houses, and other sources; it is essential to efficiently use such thermal energy to achieve an energy-saving society.

In recent years, research has returned to the principles and general rules active at the nanoscale, regarding the emission, transportation, generation, insulation, storage, exchange, and radiation of heat, among others. Study of the temporal and spatial variations in heat (referred to henceforth as thermodynamics), has been especially lively; the seeds of heat-controlling technologies have developed quickly.

In these strategic objectives, the solution of basic principles and fundamental technologies are to be established quickly for the control and use of heat. The creation of new materials and the development of devices for the innovation of future societies and industries are addressed.

Targets to Achieve

In these strategic objectives, the purposes are to create new materials and to develop devices through the fundamental understanding and control of heat, thereby solving the problems related to heat and the efficient usage of thermal energy. Specifically, the following goals are set:

(1) To fundamentally understand nanoscale thermodynamics and to construct fundamental technologies to control heat.

(2) To create renovative materials that solve the problems relating to heat and the efficient usage of thermal energy.

(3) To develop new devices that solve the problems relating to heat and the efficient usage of thermal energy.

Future Vision of a Society to be looked at during the research promotion

Through the achievements of the items stated in section 3, *Goals and Objectives,* contributions will be made to embody the society described below:

- A society in which the restrictions in relation to heat control are overcome in broad applications, including electronic and optical devices, electronic equipment, houses, automobiles, and other structures, and in which the pursuit of functionalities and designs yet to be seen is possible.
- A society in which heat is freely controlled temporally and spatially in factories, automobiles, and any such location, and in which otherwise wasted heat energy is used efficiently.

Specific Research Examples

(1) To fundamentally understand thermodynamics at the nanoscale and to construct fundamental technologies to control heat

The understanding of thermodynamics in nanoscale must be advanced, and a uniform scientific principle addressing nanoscale to macroscale cases will be constructed. Furthermore, the basic and fundamental technologies enabling heat control will be developed. For instance: a proposal will be made for new functional materials that have both high thermal insulation performance and light transparency performance, thereby verifying the principle of thermodynamic control; a control technology will be developed to eliminate interfacial thermal resistance; heat emission technology enabling the further high integration of semiconductor integrated circuits will be advanced.

(2) To create renovative materials solving the problems relating to heat and the efficient usage of thermal energy

Renovative materials with heat control functionality at the nanoscale will be created. For instance: super heat-insulating materials with lower heat conduction than that of vacuum insulation panels, materials with anisotropic thermal conductivities in specific directions, and heat storage materials usable in many temperature ranges are to be advanced.

(3) To develop new devices that solve problems relating to heat and permit efficient use of thermal energy

A trial device that uses heat control technology at the nanoscale is to be made to confirm the basic functionalities and characteristics of the device. For instance: a heat rectifier device and a heat switch, super-low power consumption sensor, next-generation nonvolatile memory, high-density thermal storage system that can store and emit heat in a short time, and other similar devices will be developed.

Domestic and Foreign Research Trends

(Trends in Japan)

- In March 2016, on the occasion of the 63rd Spring Academic Lecture Meeting, the Japan Society of Applied Physics held the *Phonon Engineering* and *its Widening Applications* special symposium, cosponsored and jointly supported by the Heat Transfer Society of Japan, Japan Society of Thermophysical Properties, the Surface Science Society of Japan, the Society of Chemical Engineers, Japan, the Society of Nano Science and Technology, the Thermoelectrics Society of Japan, the Physical Society of Japan, and other parties. The Heat Transfer Society of Japan held *The Expression of Nanoscale Heat Emission Function and the Development of the Application,* the 52nd National Heat Transfer Symposium. The Physical Society of Japan held the *New Development of Material Physics toward Phonon Engineering* 71st Annual Meeting Symposium. Further similar sessions were held to begin forming research communities focusing on nanoscale heat control and/or phonon engineering.

- Furthermore, the Japan Society of Applied Physics established, in September 2016, a joint session on phonon engineering for inter-field research cooperation; in January 2017, the Society established the *Phonon Engineering Research Group* in the new field. Further similar activations of research relating to nanoscale heat control are underway in each academic society.
- Between 2015 and 2016, in addition to the above-mentioned activities, the Heat Transfer Society of Japan, the Chemical Society of Japan, the Surface Science Society of Japan, the Society of Chemical Engineers, Japan, and other parties hosted symposiums and research sessions on nanoscale heat control, and published special features in their academic journals.

(Trends overseas)

- In Europe and the US, researchers are beginning to take positive action in addressing heat control in the field of nanoelectronics. In May 2014, the 10th Nanotechnology International Conference on Communication and Cooperation (INC10) was held, where several large-scale projects relating to heat control from Japan, the US, and Europe were presented, including 16 projects in the US, 14 projects in Europe, and 2 projects in Japan. In comparison with Europe and the US, the small number in Japan seems notable.
- In 2013, EUPHONON was established for the purpose of establishing a community of EU nanophononics researchers, covering the fields of solid-state physics, nanoelectronics, and biology, with a budget of approximately 58 million yen per year. In the US, no program specializing in nanoscale heat control has yet been established; however, many papers are published and new ideas presented. They have been eager to address the use of phonon control in nanostructures for heat design and analysis, as well as creating phonon-controlling materials.
- In China, the Phononic Thermal Energy Center (Tongji University) was established. The number of papers relating to phonon engineering and thermoelectric materials is conspicuously increasing, advancing their energetic endeavors.
- The number of published papers regarding phonon engineering has sharply increased from 20 (2000) to 130 (2010) to 280 (2014) (source: *Strategic Proposal*, CRDS-FY2014-SP-04) globally. 34% were contributed by China, 21% by the US, 15% by France, 11% by Germany, and 6% by Japan (source: calculated based on the data available in *Web of Science*). For Japan to take leadership in this field, increased community formation and support of research activities is necessary.

Background of Consideration

The following surveys were conducted according to the "*Guideline for the Preparation of Strategic Objectives and the Like"* (Resolution by Strategic Basic Research Subcommittee, Science and Technology Science Council, June 8, 2015).

(Preparation of analysis to examine domestic and overseas research trends by a scientometric method, using the Grant-in-Aid for Scientific Research (KAKENHI) Database and similar information)

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(Implementation of a questionnaire for specialists using analytical materials and preparation of notable research trends)

We implemented a questionnaire on noteworthy research trends based on the analytical materials that we had prepared for respective field units of the Center for Research and Development Strategy (CRDS) for Japan Science and Technology Agency (JST), for the program directors etc., of the Japan Agency for Medical Research and Development (AMED), and for the experts participating in the network operated by the Science and Technology Foresight Center of the National Institute of Science and Technology Policy (NISTEP). We then analyzed the responses to the questionnaire and identified "Innovation of the Nanoscale Heat Control Technology for the Solution of the Problems of Heat" and "Creation of the Renovative Technology in Relation to the Chemical Process through the Use of Thermal Source etc. in Middle and Low Temperature Ranges" as a noteworthy research trend.

(Holding of workshops and preparation of Strategic Objectives)

We held a workshop to bring together experts from industry and academia involved in the "Innovation of the Nanoscale Heat Control Technology for the Solution of the Problems of Heat" and the "Creation of the Renovative Technology in Relation to the Chemical Process through the Use of Thermal Source etc. in Middle and Low Temperature Ranges," which were identified as noteworthy research trends. At the workshop, we focused on notable trends in Japan and overseas, the social and economic impacts of progress in research and technological developments, the visions for society arising from these advances, and the objectives to be met during the research period. We then prepared Strategic Objectives based on the discussions in the workshop.

Relevant Matters in Cabinet Decisions, etc.

General Innovation Strategies for Science and Technology 2016 (approved by the Cabinet on May 24, 2016)

Chapter 1, (3), 2), [B]

As a cross-sectional technology to support fundamental technology, an early construction of materials and nanotechnology (omitted) is advanced. Further, to enforce these fundamentals, (omitted) it is also important to promote, from a mid- to long-term viewpoint, the basic researches of the heat (phonon) control technology (omitted) etc. in the nano-area, which is important for a high-level heat management.

Chapter 2, (1), 1, 1), [C], 3)

- The development of heat storage and insulation technology, the technology for using the heat of renewable energy, etc.

5th Science and Technology Basic Plan (approved by the Cabinet on January 22, 2016)

Chapter 2, (3), 1

It is necessary to further enforce the technology as a core of creating new value in which our country has advantage (omitted).

Chapter 2, (3), <2>, 2)

- The “material and nanotechnology” to lead to the differentiation of the system by the enhancement of various components such as innovative structural materials and new functional materials

Chapter 3, (1), <1>, 1)

In each of the fields of industries, consumers (households, businesses), and transportation (vehicles, watercrafts, aircrafts), further research and development of energy-saving technology etc. and its diffusion are tried.

Other

- Efforts relating to thermoelectric exchange, thermal storage and insulation, heat barriers, and other phenomena have been made, focusing on research and development from the perspective of industrial application, by Thermal Management Materials and Technology Research Association (TherMAT).
- The research and development of thermoelectric exchange materials is partially included in the “Creation of Innovative Environmental Power Generation Technology Using Minuscule Energy” (established in 2015) by Japan Science and Technology Agency (JST) Crest/Presto, “Interfacial Phase Science for the Highly Efficient Use of Energy” by CREST, and “Highly Efficient Use of Energy and Interfacial Phase” (established in 2011) by Presto.

Establishing a new fundamental technology for research and development that leads other countries will be enabled by this early formulation of strategic objectives based on the unified understanding of heat and heat control itself as the mainstay, while utilizing the knowledge obtained from the relevant projects mentioned above.

7.4 Construction of revolutional material development methods through fusion among experiments and theory/data science

Overview

The research and development of materials is undergoing innovation based on advancements in informatics technology. In the search for new substances based on materials informatics, several achievements have been made in the acceleration phase. However, in materials processes such as substance synthesis and material structure control, theories, modeling tools, and other informatics are insufficient for expressing the behaviors of actual substances, which obstructs innovation. The development of studies in the efficient search for optimum materials processes, the construction of new processes for creating materials, and the like is necessary, recognized as similarly essential in industrial fields.

With established strategic objectives, the period of development from the search for substances to the creation of materials will be significantly shortened via collaboration between experiments and computational or data science etc. (referred to henceforth as data science etc.), studies contributing to the creation of various materials will be advanced, and industrial competitiveness will be enhanced. Furthermore, contributions will be made to nurture human resources that understand both experiments and data science.

Targets to Achieve

In these strategic objectives, the purposes are to establish collaboration with data science etc. based on experiments in substance synthesis and material structure control, regarding various materials regardless of organic or inorganic origins. Thereby, a method can be constructed that leads to the development of renovative materials.
Specifically, the following goals are set.
(1) To construct a behavioral prediction model of existing materials and to synthesize materials by using it.
(2) To construct a structure control model of materials and to develop materials by using it.

Future Vision of a Society to be looked at during the research promotion

Through the achievements of the items stated in section 3, *Goals and Objectives,* not only materials development based on intuition and experience, but also the quick and efficient development combining material data and theoretical modeling and/or actual behavior modeling will become mainstream. This will contribute to the embodiment of the society described below:

- A society in which new functional materials, structural materials, and others are created based on high-level data science etc.
- A society in which research and development efficiency is highly enhanced, for example, with research phases shortened to 2 to 3 years from the conventional span of 10 years.
- A society in which the limitless pursuit of enhanced productivity and reduced cost is supported by high-level data science etc., permitting industrial advancement.
- A society in which the relation between desired performance and materials is clarified and end users, designers, and developers may select possible new functional materials for creation.

Specific Research Examples

(1) To construct a behavioral prediction model of existing materials and to synthesize materials by using it

Efforts will be made to construct a method enabling the prediction of substance behaviors in experiments and the synthesis of substances. For instance, the conditions of a reaction and data on the variance of the substance are translated into data through synthesis experiments, which are analyzed using methods of data science etc. to construct the optimum synthesis and reaction paths that will embody the desired substance composition and characteristics. The synthesis of new substances and the optimization of existing processes are among the objects of these efforts.

(2) To construct a structure control model of materials and to develop materials by using it

Efforts will be made to construct a method that enables the prediction of variance in the organization structure in the material control processes and to develop materials with controlled organization. For instance, analyses using data science etc. in experiments on the organizational control of inorganic and organic substances can be applied to construct a technology that presents the treatment process necessary to create a desired material organization and organization structure. Furthermore, the development of organization control and materials and/or the optimization of an existing organization control method are among the objects of these efforts.

Domestic and Foreign Research Trends

(Trends in Japan)

Our country is ranked highly internationally in fields relating to trial-manufacturing processes and/or the production of object materials. The fields of synthesis optimization for materials and the control of material organization are strong in terms of the total number of papers published in and since 2006, providing an advantage in materials research and experiments. In addition, although object materials are limited, the studies on the search for and discovery of unknown substances based on calculation and/or theory have been advanced in the “Materials Research by Information Integration” Initiative (Mi^{2}i). The regions from material processing to material production, life-expectancy prediction, and so forth are focuses in the “Innovative Structural Material” of the Cross-ministerial Strategic Innovation Promotion Program (SIP). The Project of the Super Rapid Development Platform Technology for Super Advanced Materials focuses on multi-scale simulations; these were formed as projects earlier than others. Furthermore, studies concerning material informatics and integration, such as the Artificial Intelligence, Big Data, IoT, and Cyber Security Integration Project at AIP (Advanced Integrated Intelligence Platform Project) and efforts at specific corporations, have been increasing the momentum of progress. However, studies of the actual creation of unknown materials are regarded as problems; the advancement and development of further study is recognized as necessary.

(Trends overseas)

The number of papers related to materials and informatics increased with the average annual growth rate of 9.8 percent* from 2006 to 2015; it can be said that this is regarded as an important and developing research area. Regarding particular countries, the US, a leader in the Materials Genome Initiative, invested 500 million dollars in the five years since 2011, which far exceeded others in the scale of investment. EU invested a small amount in each of the various projects advanced by Germany, Switzerland, Spain, and others. In China, Shanghai University has established the Shanghai Materials Genome Institute on campus. Each country has promoted endeavors in various phases, including the cultivation of human resources and researches.

*This figure was obtained using keywords such as “material,” “data,” and “informatics” based on the data available on the Web of Science.

Background of Consideration

The following surveys were conducted according to the *Guideline for the Preparation of Strategic Objectives and the Like'*(Resolution by Strategic Basic Research Subcommittee, Science and Technology Science Council, June 8, 2015)

(Preparation of analysis to examine domestic and overseas research trends by a scientometric method using the Grant-in-Aid for Scientific Research (KAKENHI) Database and similar information)

We prepared analytical materials regarding research trends in Japan and overseas by using scientometric techniques for analyzing research papers of co-citation relations or direct quotation relations in the Grant-in-Aid for Scientific Research Database, etc.

(Implementation of a questionnaire for specialists using analytical materials and preparation of notable research trends)

We implemented a questionnaire on noteworthy research trends based on the analytical materials that we had prepared for respective field units of the Center for Research and Development Strategy (CRDS) for Japan Science and

Technology Agency (JST), for the program directors etc., of the Japan Agency for Medical Research and Development (AMED), and for the experts participating in the expert network operated by the Science and Technology Foresight Center of the National Institute of Science and Technology Policy (NISTEP). We then analyzed the responses to the questionnaire and identified “Innovation of the Informatics Technology by Stage Fusion” as a noteworthy research trend.

(Holding of workshops and preparation of Strategic Objectives)

We held a workshop to bring together experts from industry and academia involved in the “Innovation of the Informatics Technology by Stage Fusion,” which was identified as a noteworthy research trend. At the workshop, we focused on notable trends in Japan and overseas, social and economic impacts of progress in research and technological developments, visions of society arising from these advances, and the objectives to be met during the research period. We then prepared the Strategic Objectives based on the discussions in the workshop.

Relevant Matters in Cabinet Decisions, etc.

5th Science and Technology Basic Plan (approved by the Cabinet on January 22, 2016)

Chapter 2, (3), <1> It is necessary to further enforce the technology as a core of creating new value in which our country has advantage.

Chapter 2, (3), <2>, 2)

- The “material and nanotechnology” to lead to the differentiation of the system by the enhancement of various components such as innovative structural materials and new functional materials.

Chapter 3, (1), <3>

The creation of innovative functional materials, structural materials, etc. by making full use of computational science and data science is to be advanced, and, at the same time with this, an extreme reduction of their development period is to be realized.

General Innovation Strategies for Science and Technology 2016 (approved by the Cabinet on May 24, 2016)

Chapter 2, (1), 3, 2), [A]

In order to secure superiority against other countries, it is important that, not only the material informatics with a substance search as the main body, but also, by expanding the above-mentioned, all science technologies including theories, experiment, analyses, simulations, and databases are to be fused to construct a material development system capable of predicting the performance of materials (durability, safety, etc.). (Omitted) This system is capable of realizing the reduction of the periods of the creation of innovative substances and materials and of the research and development that anticipate needs, and thus is capable of realize the strengthening of the competitiveness of material industries. Furthermore, as new materials are early implemented in the society as energy-saving members, weight-reducing members, and so forth, they bring solutions to social problems such as energy and global environmental problems.

Japan Revitalization Strategy 2016—to the Fourth Industrial Revolution (approved by the Cabinet on June 2, 2016)

II, 3-1, (2)-2)-3

in the fields where Japan’s strengths can be utilized, such as nanotechnology and materials, the Government will establish a global research center that will enable strategic sharing, application and use of big data, and construct human and research networks.

Other

- Researchers from the fields of experimental measurement, theoretical calculation, and information and mathematics are acting in the “Construction of Platform Technology for Advanced Materials Informatics Linking and Fusing Theory, Experiment, Computational Science, and Data Science” (established in 2015) by the Japan Science and Technology Agency (JST) Presto. With this objective, fusion among the experiments of substance synthesis, organization control, etc., data science, and so forth is promoted, as is the use and development of informatics technology in material development.
- In Mi^2i, efforts for advancing material development by the fusion of the construction of databases and data science are

implemented, where the search for new substances using the construction of a data platform and informatics is conducted. Consortium activities, in which 40 corporations or more participate, have begun.
- As for SIP-Innovative Structural Material, the development of structural and functional materials has been implemented regarding aviation materials; in the field of materials integration, a study integrating materials and anticipation has been implemented. The construction of software to integrate results is also advancing.
- Between the desired substance found in research at each location and the actual developed materials, a large technological gap separates the virtual substance and the real substance. With this objective, the creation of research results that mend this gap is also expected. In other words, the research is expected to link the studies on both sides for each project; an efficient and effective material development platform can be realized by bridging this gap.

7.5 Advanced interaction technologies within networked intelligent information environment

Overview

A recent global goal is to realize a "super smart society" in which everyone has access to optimized high-quality services in natural forms through endeavors to fuse cyber space and society at a high level based on widespread use of artificial intelligence technologies, big data analysis technologies, and so forth. For this purpose, research and development in relation to "human to human" and "human to machine" interactions have been managed in a variety of ways as essential technologies; a great leap in the development of such research fields is expected to be made for the realization of a super smart society.

For this purpose, the research field of interaction is widely recognized as focusing on "mutual actions with the whole environment connected to a network." In this field, interactions in a variety of forms such as "human to human," "human to machine," and "human to the whole environment" are supported at a high level, and behaviors are understood and controlled to lead to the design of innovative systems that promote the optimization of social structures and human behaviors. Thus, interaction research aims to realize a highly optimized society in which everyone can enjoy the benefits of fast-growing artificial technologies.

Targets to Achieve

In these strategic objective, the purposes are to create new technologies for the enhancement of interactions and to attempt to further deepen the understanding of interactions for use in a variety of situations in society. Specifically, research engages in cooperation with other academic fields such as cognitive science, psychology, neuroscience, and primarily information science and technology to realize the following goals:
(1) The development of technology in relation to interfaces and the expansion of human abilities to support interactions.
(2) The solution of the principles and structures for understanding interactions and the development of the technology in relation to collection and analysis of the information to contribute to the above-mentioned goal.
(3) The development of technology to design the social structure and the environment that prompts the optimization of human behaviors using interactive technologies.

Future Vision of a Society to be looked at during the research promotion

Through the achievements of the items stated in paragraph 3, *Goals and Objectives,* contributions are made to the realization of the society described below.

- The society in which the enhancement of interaction contributes to realizing a super smart society and is spreading to various fields as a platform technology to support industrialization and a wide range of implementation of artificial intelligence technologies, big data analysis technologies, IoT technologies, and the like, the development of which has been advancing.
- The society in which mutual interaction data of "humans to humans," "humans to machines," and "humans to the whole

environment” is gathered in a variety of domains, and a variety of human, economic, and social resources including Cloud sourcing are maximized, and, thus, a large-scale change is caused in the ways in which the society wants and people work.

- The society optimized as a whole in which the advancement of personal fabrication based on the enhancement of interaction promotes natural alterations in behaviors along with a variety of individual ways of life and the like that are not understandable within the conventional societal models of mass production and mass consumption.

Specific Research Examples

(1) The development of technology in relation to the interfaces and the expansion of human abilities to support interactions.

The research aims to develop an intelligent agent to conduct continuous deep interactions with individuals and groups depending on place, situation, and past memory, and the research and development for high-level support of non-verbal communications that use wearable devices, etc. suitable to the human body.

(2) The solution of the principles and structures for understanding interactions and the development of the technology in relation to the collection and analysis of the information to contribute to the above-mentioned goal.

The collection and analysis of the data in relation to human behaviors in a specific domain such as life, medical care, nursing, fabrication, and infrastructure and of the data in relation to the processes of a variety of social symptoms, and research and development in relation to the modeling of human-to-human interactions.

(3) The development of technology to design social structures and environments that prompt the optimization of human behaviors by using interactive technologies.

This describes research and development for supporting creative activities enabling real-time and interactive designs, and research and development supporting the formation of groups and communities and high-level collaborative activities.

Domestic and Foreign Research Trends

(Trends in Japan)

- In addition to analytical research as a base for neuroscientific research or that of similar fields, “the cognitive interaction study of design (FY 2014 - FY 2018)” in the new academic field of the Grant-in-Aid for Scientific Research, is lively from the point of view of designing interactions.
- The research community working on multi-agent systems for analyzing and configuring group behaviors by recognizing humans and artificial objects as agents has been lively and has continued its activities since former days.
- As for agents that interact with humans, research not only on virtual agents that uses VR and/or voice communication technology, but also the development of communication robots that have their own bodies has been lively and active.

(Trends overseas)

- As for research on multi-modal interaction in the US, SimSensei, a mental palliative support system for depression, anxiety, PTSD, and the like (South California University), virtual agents that promote counseling and changes of behaviors to support nurses and patients (North Eastern University), and similar technologies have been continuously supported through funding bodies such as DARPA and NIH.
- In Europe, TARDIS (hosted by UPMC, France), which aims to strengthen the social skills necessary for finding a job, SSPNET, which aims to arrange and share a technological platform for the modeling, analysis, and use of social signals (hosted by University of Glasgow, UK), and similar projects are supported by the framework program. Besides practical research, cognitive science, developmental science, and endeavors to aim at a scientific outcome are lively.

Background of Consideration

The following surveys were conducted according to *Guideline for the Preparation of Strategic Objectives and the Like* (Resolution by Strategic Basic Research Subcommittee, Science and Technology Science Council, June 8, 2015)

(Preparation of analysis to examine domestic and overseas research trends with a scientometric method using the Grant-in-Aid for Scientific Research (KAKENHI) Database and similar information)

We prepared the analytic materials regarding research trends in Japan and overseas using a scientometric technique for analyzing research papers of co-citation relations or direct quotation relations in the Grant-in-Aid for Scientific Research Database, etc.

(Implementation of a questionnaire for specialists using analytical materials and preparation of notable research trends)

We implemented a questionnaire on noteworthy research trends based on the analytical materials that we had prepared for respective field units of the Center for Research and Development Strategy (CRDS) for the Japan Science and Technology Agency (JST), for the program directors etc., of the Japan Agency for Medical Research and Development (AMED) and for the experts participating in the expert network operated by the Science and Technology Foresight Center of the National Institute of Science and Technology Policy (NISTEP). We then analyzed responses to the questionnaire and identified "the enhancement of interaction with the environment that is connected to a network" as a noteworthy research trend.

(Holding of workshops and preparation of Strategic Objectives)

We held a workshop to bring together experts from industry and academia involved in "the enhancement of interaction with the environment that is connected to a network" which was identified as a noteworthy research trend. At the workshop, we focused on notable trends in Japan and overseas, the social and economic impacts of progress in research and technological developments, visions of society arising from these advances, and the objectives that should be met during the research period. We then prepared Strategic Objectives based on the discussions in the workshop.

Relevant Matters in Cabinet Decisions, etc.

Japan Revitalization Strategy 2016—to the Fourth Industrial Revolution (approved by the Cabinet on June 2, 2016)

II, 1-1, (2)-1), <2>, e)

The Government will push forward with technological development and demonstration for a wide range of fields, such as the transportation of people and goods including in an emergency, in response to a disaster, and in the management of infrastructure in order to realize a new robotic society in which multiple robots recognize their surroundings and work together autonomously.

5th Science and Technology Basic Plan (approved by the Cabinet on January 22, 2016)

Chapter 2, (2), 2

(Omitted) In order to realize a "super smart society," it is necessary for various "things" to connect over a network and for this to be systematized at a high level and, at the same time with this, to make a plurality of different systems link and collaborate. Accordingly, as it becomes possible to collect and analyze a variety of data and to make cross-sectional use of them among collaborative and cooperative systems, new values and services are generated one after another.

General Innovation Strategies for Science and Technology 2016 (approved by the Cabinet on May 24, 2016)

Chapter 1, (3), [A], 2)

Human interface technology: Besides virtual reality (VR), augmented reality (AR), *kansei* engineering, neuroscience, and the like, in consideration of the development of individual devices and technologies, research into the differences in social acceptability and the like, such as whether these technologies are equivalent to humans or are tools, is also important so that humans can cohabit with intelligent machines including robots, as typical examples.

Other

- In “the information environment in harmony with humans,” the strategic objective in FY 2009, and “intelligent information processing technology,” the strategic objective in FY 2014, the endeavors for the research and development of the technology to understand humans and groups at a high level were made.
- Furthermore, in *Asada Synergistic Intelligence*, ERATO, (FY 2005 - FY 2010) and *Center of Human-friendly Robotics Based on Cognitive Neuroscience,* COE, (FY 2009 - FY 2014), research to understand humans as a base for high-level interactions was performed.
- Moreover, research on hardware and robots in harmony with living bodies as a platform to support the above-mentioned goals was performed in the *Someya Bio-Harmonized Electronics Project,* ERATO (FY 2011 - FY 2016) and the *Ishiguro Symbiotic Human-Robot Interaction Project,* ERATO (FY 2014 - FY 2019).

In these strategic objective, while the achievements in these endeavors is used, it is expected that the endeavors for realizing continuous interactions among humans, groups, environments, and the whole society and changes in behaviors will be advanced through the enhancement and integration of interactions including endeavors for multi-modal applications and the integration of verbalism and non-verbalism.

7.6 Development of optical control technologies and elucidation of biological mechanisms

Overview

In recent years, technologies utilizing light properties have made rapid progress in controlling life functions. For example, optogenetics is a genetic engineering technique used to express photoreceptor proteins in a specific cell in order to manipulate the functions of the cell by irradiation with a specific wavelength of light at high temporal resolution. The use of this technique has rapidly increased in the field of neuroscience. The technique has enabled specific neural activities to be directly connected to behavior expression and has created a revolutionary paradigm shift in research of neuronal functions. Furthermore, optical control technologies are used in other fields in addition to neuroscience, including to manipulate enzymatic activity, intracellular signal transduction, gene expression, and even genome editing. The use of optical control technologies has increased from studies of neural activities to studies examining the general functions of the living body.

A Strategic Objective based on the background described above aim to develop new optical control technologies, improve existing technologies, and develop related control and measurement technologies. The development will be merged with technologies in other scientific fields for optical control technologies to evolve to universal techniques that can be used in life science research. In neuroscience, this Strategic Objective also aims to establish a seamless connection between cellular phenomena and the neural circuit, as well as the behavior of individuals in order to elucidate the principles of cerebral activities and the neural circuit involved in diseases and disorders. In the fields of developmental biology, regenerative medicine, immunology, metabolomics among others, this Strategic Objective aims to take advantage of the high spaciotemporal resolutions of optical control technologies in order to evaluate mechanisms of biological functions in various cells and tissues.

Targets to Achieve

The Strategic Objectives aim to use optical control technologies in order to understand life phenomena in various areas of life science as well as in neuroscience. The evolution of optical control technologies will enable the use of “universal technologies to elucidate underlying control of diverse functions of the living organisms” in collaboration with other scientific areas including physics, engineering, chemistry, and informatics. Specific objectives to be met include the following:

(1) To establish technologies underlying the control of life functions with light.
(2) To develop measurement and analytical technologies for functions emerging in optical control.

(3)　To use optical control technologies to determine mechanisms of life functions in diverse cells and tissues.

Future Vision of a Society to be looked at during the research promotion

To contribute to the research community by meeting the targets mentioned in "Targets to Achieve."

・Optical control technologies discovered by meeting the Strategic Objective will evolve to universal technologies for control various actual conditions regulating functions in the living organisms at will and are powerful for evaluating biological functions to improve innovation creation capabilities in life science research.

・Optical control technologies can be used to determine mechanisms of biological functions that cannot currently be evaluated and strengthen the intellectual basis of life science. Optical control technologies will contribute to the elucidation of mechanisms of various diseases including intractable disease; medical innovation through the development of diagnostic, therapeutic, and prophylactic methods; sustained progress in agricultural and livestock industries through the development of efficient production methods for crops and livestock; and the realization of life longevity of people and industrial development through advances in information processing and telecommunications infrastructure to be brought about by improved artificial intelligence.

Specific Research Examples

(1) To establish basic technologies for the control of biological functions at will by light

The research aims to promote the integration of newly developed optical control technologies and improve existing technologies by combining technologies in other scientific areas to overcome current limitations. For example, optical control technologies involving near infrared light, ultrasonic waves, or magnetic fields will be developed to noninvasively manipulate deep parts of the living body; technologies will be developed to expand the range of research subjects from small animals to primates; the structure of photosensitive molecules will be analyzed to underlie the development of these technologies; and the mechanism of photo signal transmission will be determined. Additionally, further improvements and new developments can be used to examine enzymatic activity, intracellular signal transduction, gene expression, genome edition, and physiological functions of cellular organelles among others.

(2) To develop measurement and analytical technologies for optical control

Optical control technologies will be used to develop observational and analytical technologies that are necessary for evaluating the mechanisms of biological functions. For example, technologies will be developed for noninvasive visualization of functions deep in the living organisms, simultaneous optical control and optical measurement, and live imaging by combining a number of different types of observation results.

(3) To elucidate mechanisms of biological functions in diverse cells and tissues using optical control technologies

Optical control technologies will be used to determine mechanisms of biological functions currently impossible to elucidate. For example, controlling mechanisms will be elucidated for memory formation, decision-making, and instinctive behavior (sleep, ingestion, and sexual behavior, among others); mechanisms will be elucidated for genesis, regeneration, immunity, and metabolism, among others; and biological phenomena will be modeled mathematically.

Domestic and Foreign Research Trends

(Trends in Japan)

A pioneering animal (mouse) study was reported in Japan around the time when optogenetics began to be used in neuroscience in the US. Initially, individual researchers in Japan developed and introduced optogenetics, and Japan was behind the US in research achievements. However, by the end of 2015, as researchers in related scientific areas formed study groups to popularize technologies in the neuroscience field, the number of pertinent papers from Japan increased to become third worldwide only after those in the US and Germany. Examples of research include not only technology development for selective gene introduction into a specific neural pathway using a retrograde viral vector and synaptic optogenetics in the neuroscience field, but also the development of the most advanced technologies represented by the world's fastest "photoswitch protein" and studies underlying the structural analysis of the channel rhodopsin. These high-level studies represent the strengths of Japan. However, Japan is somewhat behind the US in the integration of these individual studies to evaluate questions related to life science. In Japan, such research is only beginning to yield internationally respected results, such as the recent elucidation of the memory mechanism.

(Trends overseas)

Application of optogenetics in neurons was first reported in the US in 2005. The journal Nature Methods determined that the technique was the most impactful in all natural science areas and awarded this technique the Method of fiscal year in 2010. After the development of optogenetics and particularly after 2010, the number of papers related to neuroscience rapidly increased worldwide. Simultaneously, the US published more than half the research papers and continues to lead the world in optogenetic research. In Europe and the US, researchers in life science, physics, engineering, and chemistry form teams to rapidly integrate individual technologies and solve important issues related to life science.

Background of Consideration

The following surveys were conducted according to “Guideline for the Preparation of Strategic Objectives and the Like” (Resolution by Strategic Basic Research Subcommittee, Science and Technology Science Council, June 8, 2015).

(Preparation of analysis to examine domestic and overseas research trends by a scientometric method using the database of Grant-in-Aid for Scientific Research and similar information)

We prepared the analytic materials regarding research trends in Japan and overseas by using scientometric techniques for analyzing research paper co-citation relation or direct quotation relation in the databases of the Grant-in-Aid for Scientific Research, etc.

(Implementation of a questionnaire for specialists using analytical materials and preparation of notable research trends)

We implemented a questionnaire on noteworthy research trends based on the analytical materials that we had prepared for respective field units of the Center for Research and Development Strategy (CRDS) of the Japan Science and Technology Agency (JST), for the program directors, etc., of the Japan Agency for Medical Research and Development (AMED) and for the experts participating in the expert network operated by the Science and Technology Foresight Center of the National Institute of Science and Technology Policy (NISTEP). We then analyzed responses to the questionnaire and identified the “Photonic Research and Applications of Optical Control Technologies for the Innovation of Life Science including Neuroscience” as a noteworthy research trend.

(Holding of workshops and preparation of Strategic Objectives)

We held a workshop to bring together experts from industry and academia involved in the “Photonic Research and Applications of Optical Control Technologies for the Innovation of Life Science including Neuroscience,” which was identified as a noteworthy research trend. At the workshop, we particularly discussed the notable trends in Japan and overseas, the social and economic impacts of progress in research and technological development, the visions of a society arising from these impacts, and the objectives that should be met during the research period. We then prepared Strategic Objectives based on the discussions in the workshop.

Relevant Matters in Cabinet Decisions etc.

“General Innovation Strategies for Science and Technology 2015” (Cabinet Decision, June 19, 2015)
Part 1, Chapter 1, 2.

It is also important to lead the promotion of common fundamental technologies, such as sensor technology, robot technology, advanced measurement technology, light and quantum technology, material technology, nanotechnology, and biotechnology, which may incubate business in a wide range of fields by using Japan’s advantages in the “Super Smart Society.”

Other

○ In existing research and development projects such as CREST "Advanced core technology for creation and practical utilization of innovative properties and functions based upon optics and photonics" (starting in fiscal year 2015) and PRESTO "Fully-controlled photons and their proactive usage for new era creation (FRONTIER)" (starting in fiscal year 2015) of Japan Science and Technology Agency, research aiming to develop technologies in light utilization and photonics has been performed in various areas. Furthermore, an optogenetic study focusing on the manipulation of the high-level circuits in the cerebral cortex of marmoset has been carried out as part of the "Elucidation of brain function network through innovative technologies" (fiscal years 2014–2023) of the Japan Agency for Medical Research and Development. Collaboration between the aforementioned research and the research performed as part of the Strategic Objectives is expected to accelerate the acquisition of results.

7.7 Integration of measurement technology and advanced information processing for cutting-edge R&D activities including materials science

Overview

Measurement technologies have been introduced and utilized effectively in various research fields such as material science and life science and are used in various facilities from large-scale research facilities (e.g., synchrotron radiation facilities) to general-purpose measuring instruments. However, obtaining significant information from measured data still depends on researchers' experience to a large degree. On the other hand, in the information science and mathematical science fields, the techniques for obtaining useful information from data to a maximum extent have been proceeding.

Therefore, this Strategic Objective is the creation of a new "information measurement" field, which is one of the activities for creating the "Super Smart Society" (Society 5.0) in the 5th Science and Technology Basic Plan by merging measurement technology, in which Japan has an advantage, with the information sciences, mathematical sciences, etc., that have been advanced in recent years. The information measurement technologies by which invisible physical quantities can be measured, invisible changes can be made visible, undetected changes can be made detectable, and other merits are provided will be established via bidirectional analysis using various measurement technologies (which use X-ray and neutron quantum beam facilities and general-purpose measurement instruments such as electron microscopes and nuclear magnetic resonators (NMR)) and information sciences, mathematical sciences, and other technologies (e.g., data assimilation, sparse modeling, image analysis, and signal analysis). This will promote novel scientific discoveries in all scientific and technological fields such as the substance and material field, the resource and energy field, and the medical care and drug discovery field.

Targets to Achieve

The Strategic Objective is aimed at establishing measurement–object feature analysis technologies and developing them into novel measurement and analysis technologies to facilitate the research agenda in which novel scientific development by improving measurement and analysis technologies in material science, life science, etc., is strongly expected. Specifically, we aim to achieve the following:

(1) Establishment of measurement–object feature analysis technologies

Examples of technologies to be established are feature extraction technologies for extracting feature values from spectra, images, etc., with low signal-to-noise ratios; information reconstruction technologies for obtaining useful information from lesser amounts of data, and syntactic analysis technologies for integrating different kinds of information.

(2) Establishment of novel measurement and analysis technologies that utilize the technologies described in (1)

Future Vision of a Society to be looked at during the research promotion

The achievements of the targets listed under "Targets to Achieve" contribute to realize a society with the following characteristics:

- A society in which the research and development cycle of general scientific and technological fields is accelerated
- A society in which the analysis applications for interpreting the maximum amount of information from measured or detected data are developed, various scientific and technological fields such as material science and life science fields are remarkably advanced, and a more rapid return of research results to society is realized
- A society in which the researchers who promote the research in fusion regions such as the measurement region, information and mathematical region, material science region, and life science region are nurtured and found

Specific Research Examples

(1) Establishment of measurement–object feature analysis technologies

Establish the technologies for quantitative analysis of feature values obtained from electron microscope images; the technologies for dynamically observing ultrashort time phenomena of reaction states on the material surfaces of catalysts, batteries, etc., under practical conditions; and the technologies of the nanoscale dynamic analysis method for analyzing the status such as the binding of substrates and signal molecules with biomolecules in the bioactivity occurrence state, as in the examples of the feature extraction technologies for extracting feature values from spectra, images, etc., with a low signal-to-noise ratio.

Establish the analysis technique for measuring a lower amount of photons without radiation-induced damage accompanied by increasing radiation luminance and the analysis technique for reconfiguring blood vessel images from less data (one-tenth or less of the conventional data amount), which enables cerebral blood flow to be analyzed in real time, as in the examples of the information reconstruction technology for obtaining information from a lower amount of data.

Establish the analysis technique for integrating various data obtained from different analysis means and for complexly analyzing these data, in the three-dimensional structural analysis, etc., of biomolecule complexes, as in the example of the syntactic analysis technologies for different types of data.

(2) Establishment of measurement techniques that utilize the technologies described in (1)

By utilizing the measurement–object feature analysis technologies, establish the measurement technique for feedback of optimized measurement conditions, establish the framework for quantitatively evaluating the measurement limits, and develop the advanced measurement technologies that provide a measurement result as high as that of the conventional large-scale measurement facilities using general-purpose measurement instruments.

Domestic and Foreign Research Trends

(Trends in Japan)

Advanced measurement technologies have been improved steadily using large-scale facilities (Spring-8, J-PARC, etc.), but the resources of large-scale research facilities usable by each researcher are limited, and interpreting significant information from such data largely depends on the researcher’s experience. However, the Grant-in-Aid for Scientific Research on Innovative Areas “Initiative for High-Dimensional Data-Driven Science through Deepening of Sparse Modeling” (2013–2017) has demonstrated that information science can be used for measurement result analysis in biology and geoscience, showing rapid advancement in recent years.

(Trends overseas)

The trends overseas related to effective utilization of data science and information science in other fields are represented by the “Materials Genome Initiative” (MGI, with an annual budget of approx. ten billion yen) in the USA, which aims to shorten the development period largely by merging the frontier information science techniques into substance and material research and is represented by the “Center for Hierarchical Materials Design,” which is financed by the National Institute of Standards and Technology (NIST) as a consortium for supporting MGI. Similar examinations have also been started in Europe and China.

Background of Consideration

The following surveys were conducted according to “Guideline for the Preparation of Strategic Objectives and the Like” (Resolution by Strategic Basic Research Subcommittee, Science and Technology Science Council, June 8, 2015).

(Preparation of analysis to examine domestic and overseas research trends by a scientometric method using the database of Grant-in-Aid for Scientific Research and similar information)

We prepared the analytic materials regarding research trends in Japan and overseas by using scientometric techniques for analyzing research paper co-citation relation or direct quotation relation in the databases of the Grant-in-Aid for Scientific Research, etc.

(Implementation of a questionnaire for specialists using analytical materials and preparation of notable research trends)

We implemented a questionnaire on noteworthy research trends based on the analytical materials that we had prepared for respective field units of the Center for Research and Development Strategy (CRDS) of the Japan Science and

Technology Agency (JST), for the program directors, etc., of the Japan Agency for Medical Research and Development (AMED) and for the experts participating in the expert network operated by the Science and Technology Foresight Center of the National Institute of Science and Technology Policy (NISTEP). We then analyzed responses to the questionnaire and identified the "Merging Measurement Technologies into Advanced Information Processing in Frontier Research such as Material Research" as a noteworthy research trend.

(Holding of workshops and preparation of Strategic Objectives)

We held a workshop to bring together experts from industry and academia involved in the "Merging Measurement Technologies into Advanced Information Processing in Frontier Research such as Material Research," which was identified as a noteworthy research trend. At the workshop, we particularly discussed the notable trends in Japan and overseas, the social and economic impacts of progress in research and technological development, the visions of a society arising from these impacts, and the objectives that should be met during the research period. We then prepared Strategic Objectives based on the discussions in the workshop.

Relevant Matters in Cabinet Decisions etc.

"Comprehensive Strategy on Science, Technology and Innovation 2015" (approved by the Cabinet on June 19, 2015)

Part 2, Chapter 1, 2.

It is also important to lead the promotion of common fundamental technologies, such as sensor technology, robot technology, advanced measurement technology, light and quantum technology, material technology, nanotechnology, and biotechnology, which may incubate business in a wide range of fields by using Japan's advantages in the "Super Smart Society."

Part2, Chapter 2 IV. iii) 2.

It is also important to develop Big Data collection and analysis systems that can anticipate needs. The final integration of these systems will (snip) accelerate production development by shortening the material development period and additionally will produce economic effects by creating new markets.

"5th Science and Technology Basic Plan" (approved by the Cabinet on January 22, 2016)

Chapter 2, (3) ② ii)

The Japanese government will especially enhance the following fundamental technologies as the core technologies for producing novel values and as the technologies acting in an actual world.

(Snip)

- "Material technology and nanotechnology," which differentiate systems by advancing various components such as innovative structural materials and new-function materials
- "Light and quantum technologies," which differentiate systems by advancing various components such as innovative measurement technologies, information and energy transmission technologies, and processing technologies

Other

○ Advanced measurement using large-scale facilities has been developed by the "Photon and Quantum Basic Research Coordinated Development Program" (2013–2017) and the "Major Strategy Promotion Program of SPring-8 Angstrom Compact free electron Laser (SPring-8)" (2012–2016), but these programs are not the projects specialized for data analysis, and their linkage with information science is insufficient.

○ Development of the recently advanced information sciences into other fields has been performed by fundamental research based on the Grant-in-Aid for Scientific Research and by the "Initiative for High-Dimensional Data-Driven Science through Deepening of Sparse Modeling" (2013–2017), which is the Grant-in-Aid for Scientific Research on Innovative Areas for geoscience and biology. (However, the Scientific Research on Innovative Areas "Initiative for High-Dimensional Data-Driven Science through Deepening of Sparse Modeling" does not include the substance and material research fields.) In addition, the development of data analysis techniques into material research fields has been the objective in part of the Grant-in-Aid for Scientific Research on Innovative Areas “Exploration of Nanostructure-Property Relationships for Materials Innovation” (2013–2017) and has resulted in momentum for developing information sciences into substance and material research fields.

○ Materials informatics is one of the new innovations in substance and material research and utilizes a large amount of data. In Japan, the “Materials Research by Information Integration” Initiative (MI2I) was started in the “Establishment of Fundamental Technologies for Advanced Materials Informatics by Merging Theoretical, Experimental, and Computation Science with Data Science” (launched in 2015 by the Japan Science and Technology Agency (JST) Strategic Basic Research Programs) and in the “Innovation Hub Construction Support Project” (2015–2019), thus adding to the momentum for utilizing data. A new, world-leading research development scheme and fundamental technologies can be established when data acquisition techniques are advanced by merging information sciences with substance and material research by this Strategic Objective.

7.8 Development of new material properties and frontier of information sciences based on the advanced control of quantum states

Overview

Advancement of quantum-theory-applied sciences and technologies such as semiconductors and lasers has made a great impact on industry and society. Physical elements that could be used in quantum information processing were developed in the 1990s, and quantum-status control technologies such as advanced laser technologies have been improved. We can see signs of the novel development of technological systems in which quantum theory is applied inclusively at a high level and application to industries is facilitated. In recent years, as western governments and global companies have increased investment in quantum sciences and technologies, it is important in Japan to merge the advantages of optical sciences and technologies, condensed matter physics, nanotechnologies, and other technologies into frontier quantum research to lead the pioneering in the quantum sciences from a medium- to long-term viewpoint and to create the first core quantum technologies in the world for generating novel industries and a technological basis to realize the Super Smart Society.

Therefore, this Strategic Objective is the creation of wide innovation sources (new technological ideas) through the development of novel quantum properties and quantum information systems by identifying the research field and direction in general consideration of technical feasibility, international advantages, innovative spirit, etc., and by focusing on the advancement of research and development. In addition, the Strategic Objective aims to realize the first quantum technologies and system implementation in the world as fundamentals in the society that will change in the future.

Targets to Achieve

The Strategic Objective is aimed at exploring unknown physical phenomena, substance function, and physical properties; pioneering the information sciences based on novel concepts; and creating novel technological ideas by realizing the advanced control of various types of quantum states from the quantum isolated system to the multibody system and macroscopic condensate. Specifically, we aim to achieve the following:

(1) Establishment of a basis for experimental analysis, abstraction, and clarification of complicated quantum systems by advanced quantum information processing and simulation. Realization of component technologies for large-scale, energy-saving information processing that cannot be achieved by conventional techniques

(2) Prompting the expansive merging and breakthrough of existing technological fields (photonics, electronics, etc.) by developing fundamental quantum technologies and systems that link with various physical and engineering systems

(3) Significant improvement of measurement and analysis technologies by applying macroscopic quantum effects, advanced quantum optics, etc., and acceleration of innovation of sensing imaging technologies that exceed the conventional accuracy and sensitivity limits

Future Vision of a Society to be looked at during the research promotion

The achievements of the targets listed under “Targets to Achieve” contribute to realize a society with the following characteristics:

- A super cyber society in which significantly advanced communication secrecy, ultrahigh-speed Big Data processing, and ultra-energy-saving, high-speed, and large-scale information processing can be performed, and a super smart society in which physical space is highly connected to cyberspace by using the information processing and communication basis described above
- A society in which global social challenges such as environmental energy, safety and security, and health and medical care are solved and relaxed; a society in which advantages are ensured in global value chains based on highly knowledge-intensive equipment, components, technology, industry, etc.; a society in which high quality of life is realized by establishing new-value-creating systems, etc., for satisfying people’s various types of needs
- A society in which the scientific and technological basis as the core of next-generation value creation and safety and security assurance is established by the innovation of a body of knowledge including understanding of

substances and life

Specific Research Examples

(1) Development of quantum-computer component technologies by advancing various quantum bit technologies for processing superconducting circuits, single spins, semiconductor quantum dots, etc.

To implement quantum calculation techniques into devices to exceed the calculation performance of classical computers, the development of various quantum bits (as the minimum units of quantum information) and their control technologies has been advanced in various national projects of Western countries, etc., and the strategic pioneering of their portfolio has been advanced. In this field, by advancing research and development that exploit Japan's advantage in optical sciences and technologies and quantum fundamental technologies, accelerate the development and system implementation of world-leading quantum cryptography communication technologies and component technologies such as quantum cryptography communication and quantum computing. For example, to establish highly confidential, long-distance broadband communication systems, it is important to validate control gate operations among many bits and to secure sufficient coherent time; therefore, develop and combine distinctive quantum bits and advance the quantum coherent control technologies for the purpose of the realization.

(2) Development of novel optical and electronic control devices and ultrasensitive measurement technologies using various types of degrees of quantum freedom

Advance the research and development for the improvement and practical use of spin control technologies (new functional material development, etc.) such as single-electron spin coherent control, etc., of quantum dots and for the improvement, etc., of quantum simulation technologies by developing opto-mechanical component technologies and by combining various quantum many-body system control technologies for cryogenic atomic gases, ions, solids, etc. Therefore, realize the fusion of mechanical systems with quantum optics and spin systems, and aim to establish novel quantum fundamental technologies such as the control technologies of weak interactions that are impossible in conventional technologies and the accurate measurement technologies exceeding the conventional accuracy. In addition, advance the fundamental research for developing new technologies such as ultrasensitive sensor technologies based on the new principle expected from the advanced large-scale first-principles calculation regarding electromagnetic responses of quantum many-body systems.

(3) Development of ultrasensitive sensors, etc., by accurate control of microscopic quantum status

Promote the advancement of cryogenic-status control technologies for quantum many-body systems such as molecules and clusters. In addition, promote the development of highly accurate quantum sensors, etc., using the microscopic quantum wave nature.

Specifically, promote the essential understanding of quantum-theory-specific phenomena in frontier atomic physics, quantum optics, superconducting, superfluidity, etc., by advancing the artificial manipulation and control technologies of Bose-Einstein condensation (BEC). In addition, promote the development, application, etc., of quantum-wave-characterized measurement means such as highly sensitive and highly accurate BEC atom interferometers (acceleration sensors, gravity gradiometers, and navigators), etc. In addition, for complex structural systems of living bodies, etc., that cannot be controlled sufficiently by conventional adaptive optics, high-resolution measurement with much less affected dispersion can be expected by using the interference effect of quantum entanglement; therefore, proceed with the technological development for their practical use and advancement.

Domestic and Foreign Research Trends

(Trends in Japan)

Research on superconducting quantum bits, quantum bits using electron spins, and their hybrid quantum systems has been performed in the "Quantum Information Processing Project" (2009–2013) (which is included in the "Funding Program for World-Leading Innovative R&D on Science and Technology (FIRST)"), the "Quantum Cybernetics" (2009–2013) (which is included in the "Grant-in-Aid for Scientific Research on Innovative Areas"), and other projects. In the

“Advanced Information Society Infrastructure Linking Quantum Artificial Brains in Quantum Network” (2014–2018) (which is included in the Impulsing Paradigm Change through Disruptive Technologies Program (ImPACT) obtained by advancing the above research results), the development of quantum artificial brains in which brain-type information processing is incorporated in quantum computers has been advanced.

(Trend overseas)

In the United Kingdom, the five-year project for quantum science research (budget: approx. 2.7 hundred million pounds sterling) was begun in 2014, and concrete enhancement measures such as research and development to establish the basis for installing quantum computers and quantum sensors, etc., in four base points as hubs have been implemented. In the quantum computing field, research and development including the activities in the industrial world have been promoted; “D-Wave 2,” developed by D-Wave Systems, Inc., a venture company in Canada, which was the world's first commercially available quantum computer, was purchased by Google Inc. and NASA in the US (2014). In addition to analog quantum computers based on quantum annealing techniques employed by D-Wave Systems, Inc., digital quantum computers (based on the logical gate system) using superconducting elements have been developed actively by University of California, Santa Barbara and Google Inc. in the USA and in Europe. In the Netherlands, the 10-year quantum science research (budget: approx. 1.4 hundred million Euro) was begun in 2015 by QuTech, which is a research institute that exclusively focuses on digital quantum computers, and research and development for realizing quantum computers have also been accelerated by support and collaboration by Microsoft Corp. and Intel, Inc.

Time standard research based on macro quantum control has been led by Japan and the USA in the past, but this research is active also in Europe, and China has closed in from behind in physical property research related to atomic ions. Thus, quantum simulation research based on these technologies have started throughout the world. Quantum-entanglement-based measurement and imaging technologies and substance control technologies, which support high sensitivity and resolution that cannot be obtained by conventional classical optics, have attracted attention. In the field of measurement technologies based on quantum sciences, research for realizing ideal complete measurement was proceeded conventionally, and future-practice-considered incomplete measurement and weak measurement technologies, which presuppose mathematical estimation processing, have recently become important.

Background of Consideration

The following surveys were conducted according to “Guideline for the Preparation of Strategic Objectives and the Like” (Resolution by Strategic Basic Research Subcommittee, Science and Technology Science Council, June 8, 2015).

(Preparation of analysis to examine domestic and overseas research trends by a scientometric method using the database of Grant-in-Aid for Scientific Research and similar information)

We prepared the analytic materials regarding research trends in Japan and overseas by using scientometric techniques for analyzing research paper co-citation relation or direct quotation relation in the databases of the Grant-in-Aid for Scientific Research, etc.

(Implementation of a questionnaire for specialists using analytical materials and preparation of notable research trends)

We implemented a questionnaire on noteworthy research trends based on the analytical materials that we had prepared for respective field units of the Center for Research and Development Strategy (CRDS) of the Japan Science and Technology Agency (JST); for the program directors, etc., of the Japan Agency for Medical Research and Development (AMED); and for the experts participating in the expert network operated by the Science and Technology Foresight Center of the National Institute of Science and Technology Policy (NISTEP). We then analyzed the responses to the questionnaire and identified the “Pioneering Novel Condensed Matter Physics and Information Science Frontier by Advanced Control of Quantum Status” as a noteworthy research trend.

(Holding of workshops and preparation of Strategic Objectives)

We held a workshop to bring together experts from industry and academia involved in the “Pioneering Novel

Condensed Matter Physics and Information Science Frontier by Advanced Control of Quantum Status," which was identified as a noteworthy research trend. At the workshop, we particularly discussed the notable trends in Japan and overseas, the social and economic impacts by progress in research and technological development, the visions of a society arising from such impacts, and the objectives that should be met during the research period. We then prepared Strategic Objectives based on the discussions in the workshop.

Relevant Matters in Cabinet Decisions etc.

"5th Science and Technology Basic Plan" (approved by the Cabinet on January 22, 2016)

Chapter 2, (3) ② ii)

The Japanese government will especially enhance the following fundamental technologies as the core technologies for producing novel value in respective systems and as the technologies acting in the actual world.

(Snip)

- "Light and quantum technologies" which differentiate systems by advancing various components such as innovative measurement technologies, information and energy transmission technologies, and processing technologies

"Comprehensive Strategy on Science, Technology and Innovation 2015" (approved by the Cabinet on June 19, 2015)

Part 1, Chapter 1, 2.

It is also important to lead the promotion of common fundamental technologies, such as sensor technology, robot technology, advanced measurement technology, light and quantum technology, material technology, nanotechnology, and biotechnology, which may incubate business in a wide range of fields by using Japan's advantages in the "Super Smart Society."

Other

○ In the Strategic Objective in 2015, "Pioneering of Next-Generation Photonics by Discovering and Applying Novel Optical Functions and Properties," the artificial generation of novel optical functional materials, the development and application of innovative photonic technologies, the visualization of microstructures with high temporal and spatial resolution, the generation of complex optical infrastructure technologies and systems by merging with advanced mathematical sciences, and other challenges have been targeted by accelerating the advancement of new photonics fields for satisfying future social and industrial demands and by also attempting the resolution of fundamental principles for generating new technological ideas by accumulating and developing the conventional optical sciences and technologies in a cross-sectoral manner and in a multilayered way through the resolution, application, control, etc., of new optical functions and properties. It is important to accelerate the application of frontier light and quantum sciences and technologies by developing the generated superior research ideas synergistically through this Strategic Objective.

7.9 Creation of integration technology to enable utilizations of diverse and massive data using Artificial Intelligence core technologies rapidly growing in sophistication and complexity

Overview

Information technology has advanced worldwide and there is growing interest today in artificial intelligence, its recent advances, represented by deep learning, the greatest technological breakthrough in the last 50 years. These are being applied rapidly in various fields. The Ministry of Education, Culture, Sports, Science and Technology has launched the "AIP (Advanced Integrated Intelligence Platform) project" and set up an integrated R&D base within the RIKEN Institute pooling world-class research expertise and focusing on innovative Artificial Intelligence (hereinafter referred to as AI) technologies. Within this strategic objective framework, an integrated effort is to be implemented.

The 5th Science and Technology Basic Plan (approved by the Cabinet in January 2016) identifies the building of a world-leading super smart society as a critical target. Diverse and massive data are being produced and collected today in various scenes, among medical and health data as cohort data, data about materials and physical properties, and data for urban infrastructure and global environment.

It is necessary to analyze, process and control these data sets in intelligent and integrated manner in response to a varied set of situations and requirements, and yet such a technology platform has not been established. It will be necessary to rapidly build and install a secure information technology for future society to embrace and optimize such a platform technology.

The Strategic Objective aims at establishing such a platform technology capable of collecting, processing and controlling massive data in intelligent, integrated and secure manner, andwill seek to establish new technologies applicable to various fields in real society, from mobility, nursing and healthcare, to disaster prevention and mitigation, and robotics. This new platform will provide existing services with greater efficiency or contribute to the creation of new ones.

Goals and Objectives

The strategic objective seeks to advance the world's rapidly evolving innovative AI technologies and new algorithms being developed in R&D efforts, and to establish an information platform technology capable of analyzing, processing and controlling in intelligent and integrated manner diverse and massive data in various fields in society. Specifically, they include the following goals:

(1) Development of technologies to combine and analyze enormous quantities of various types of information to contribute to society and economy

(2) Development of technologies for systems that are optimized in accordance with circumstances, based on enormous quantities of various types of information

(3) Development of security technologies that can be adapted to complex systems made up of diverse elements

Future society to be aimed at research

Through the achievement of the goals identified in 3. Goals and Objectives, it is desired to contribute to the realization of such a society as follows:

- A society that has achieved an efficient utilization of data over the long term in various fields and that has widespread application of innovative AI technologies optimized for the qualitative and quantitative explosions in data utilization of the future
- A society that efficiently utilizes rapidly evolving information technology and environment, that provides people on the grid with optimized services and that is friendly with each and every one of its members. (For example, a society without traffic congestions under ordinary circumstances and offering healthcare services

in response to local and individual needs, but also capable, in rapid response to a disaster, of putting together and providing an emergency service, so as to shorten the information black out in the immediate aftermath.)

- A society that cuts down social costs dramatically or that is capable of creating new businesses and services, through a horizontally applicable information core technology and an optimization across industry barriers, in such areas as transportation and physical distribution directly affecting people's lives.
- A society that enjoys stress-free benefits from sophisticated and diverse services in different situations and in which all things are connected on the network, with a secure information environment properly embedded therein.

Specific Research Examples

(1) Develop technology capable of combining and analyzing diverse and massive data, to contribute to society and economy4

Research and develop technology to build and provide services that will, through an automatic processing and combination of diverse analytic data utilizing a new innovative AI core technology, cater to ever-changing environments and needs, and also promote R&D for an integration of elemental technologies.

Specific examples for promotion would include: a high-speed processing, in diagnostics, of massive medical image data acquired from capsule endoscopy and computed tomography; technologies to support optimized treatment planning and prescription based on advanced analysis of electronic charts or R&D of technologies to identify predictors of disorders through a processing and synthesis of analytical data acquired from such scope technologies; and R&D of software technology to integrate separate functionalities and services and a service platform-building technology based on the aforementioned technologies.

(2) Develop systems based on diverse and massive data and capable of optimization in response to varying situations

Carry out R&D for such technologies as: intelligent and self-optimizing data collection responsive to specific situations or environments; needs-driven control for resource allocation and structure in a multi-device environment; optimized control and high-speed processing of diverse and massive data based on cutting-edge machine-learning algorithms; and on-demand optimized processing in response to situational or environmental changes.

Specific R&D examples to be promoted would include: technology to dramatically minimize the computational load for streaming through a highly intelligent and selective processing of massive data produced continuously from cameras and millimetric wave sensors aboard self-driving vehicles; self-configurating network technology which, in the event of a disaster, can rapidly acquire specific on-site data sets from cameras, mobile devices, medical equipment and automotive vehicles that, otherwise under normal circumstances, serve other purposes; technology, including ontology, for disparate data integration that can understand the sense of a diversity of data; technology to utilize a range of machine learning for realtime analysis of time-series data; technology, in systems for nursing, to secure system integrity and minimize delays in processing massive and continuous biological and environmental data streams from care-receivers through a distribution of time-series data processing among the periphery of the main system or cloud servers.

(3) Develop security technology applicable to complex systems consisting of multiple, diverse elements

Carry out R&D for highly sophisticated but compact encryption technology for diverse devices and security technology responsive to complex and diverse situations

Specific R&D examples to be promoted would include: development and implementation of predictive security technology utilizing innovative AI and highly sophisticated lightweight cryptography algorithms; SBD(security by design) that can be installed on network systems handling diverse and massive data; and data reliability testing based on historical trail evidence (provenance) as profile data.

Research Trends domestic and international

(Domestic trends)

A whole set of R&D initiatives ranging from device hardware to middleware, such as AI (intelligent information processing) and big data (platform, application) has been promoted under such strategic objectives as the "Development of intelligent information processing technology to realize creative collaboration between human and machines" (FY2014) and the "Creation, advancement, and systematization of innovative information technologies and their underlying mathematical methodologies for obtaining new knowledge and insight from use of big data across different fields" (FY2013). At the New Energy and Industrial Technology Development Organization (NEDO), R&D in its "IT Integration-based New Social System Development and Demonstration Projects" (FY2012-FY2013) is envisioning service offerings for both computers and things. Furthermore, expectations are for R&D for on-demand platform services, with a view to social implementation, over an ever-amorphous diversity of data for computers, things and people.

In security area , the National Institute of Information and Communications Technology (NICT) is leading network security R&D focusing on real-world threats, while R&D for concealed computation on cloud is being promoted at the National Institute of Advanced Industrial Science and Technology (AIST) and elsewhere. Security for disparate systems without uniform specification or operation, a feature of information society of the future, is still very much at a preliminary stage. In 2014, the academia and industry joined hands to form the Connected Consumer Device Security Council (CCDS), marking a milestone for Japan by launching security-related R&D and personnel development.

(International trends)

In the United States, NSF(the National Science Foundation) has been continuously supporting R&D since 2006 that will provide a basis for diverse and massive data processing. New programs launched in 2015 have solicited proposals, ranging in USD size from hundreds of thousands through millions, for basic research (three years), interdisciplinary research (three-four years), and large-scale research (four-five years). In the private sector, also, General Electric has espoused the "Industrial Internet" concept, developing a variety of services in data integration and analysis for industrial equipment. In Europe, Horizon 2020 (since January 2012) is set to allocate some EUR 139 million for R&D programs in 2016 and 2017. Germany, in particular, is promoting Induestrie 4.0 aimed at strengthening the manufacturing sector’s competitiveness, investing in system-related R&D.

In security area, the EU raised security-related issues in “Secure societies” in Horizon 2020, allocating to them a total EUR 1.7 billion in research provisions. In the United States, too, the security-related R&D budget has been dramatically increased (some USD 800 million in FY2014).

History of the study

The following surveys were conducted according to “Guideline for the Preparation of Strategic Objectives and the Like” (Resolution by Strategic Basic Research Subcommittee, Science and Technology Science Council, June 8, 2015).

(Preparation of analysis to examine domestic and overseas research trends by a scientometric method using the database of Grant-in-Aid for Scientific Research and similar information)

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(Implementation of a questionnaire for specialists using analytical materials and preparation of notable research trends)

We implemented a questionnaire on noteworthy research trends based on the analytical materials that we had prepared for respective field units of the Center for Research and Development Strategy (CRDS) of the Japan

Science and Technology Agency (JST), for the program directors, etc., of the Japan Agency for Medical Research and Development (AMED) and for the experts participating in the expert network operated by the Science and Technology Foresight Center of the National Institute of Science and Technology Policy (NISTEP). We then analyzed responses to the questionnaire and identified the “Development of a Future Social System Technology Integrating AI, Big Data and IoT” and “R&D for a Secure Cybersociety Toward the Age of IoT” as a noteworthy research trend.

(Holding of workshops and preparation of Strategic Objectives)

We held a workshop to bring together experts from industry and academia involved in the “Development of a Future Social System Technology Integrating AI, Big Data and IoT” and “R&D for a Secure Cybersociety Toward the Age of IoT,” which was identified as a noteworthy research trend. At the workshop, we particularly discussed the notable trends in Japan and overseas, the social and economic impacts of progress in research and technological development, the visions of a society arising from these impacts, and the objectives that should be met during the research period. We then prepared Strategic Objectives based on the discussions in the workshop.

Relevant Matters in Cabinet Decisions etc.

Japan Revitalization Strategy (Growth Strategy) 2015: Realization of Revolution in productivity by investment in the future (approved by the Cabinet on June 30, 2015)

Section 2, I, 1, (3), v), [4]

…the Government will promote establishment and social implementation of core technologies to collect the world's most advanced technologies and knowledge into Japan such as artificial intelligence, information processing technology, smart device, networking technology, radiowave utilization technology, etc. In a similar fashion, regarding IoT, big data and artificial intelligence, the Government will carry out R&D and institutional reforms necessary to improve the next-generation platform to be integrated and utilized across various fields….

“General Innovation Strategies for Science and Technology 2015” (approved by the Cabinet on June 19, 2015)

Part 1, Chapter 1, 2.

In future, there will be a further systemization, collecting yet greater volume of data on realtime basis and processing it in a more sophisticated and larger scale. With this in mind, it is imperative to strengthen the leading basic research areas, such as IoT (Internet of Things), big data analysis, mathematical science, computational science and technology, AI (artificial intelligence), and cybersecurity.

Part 2, Chapter 2.

R&D will be promoted for such basic technologies as IoT supporting a comprehensive system, big data analysis, AI and cybersecurity, with a view to a horizontal utilization to resolve various policy issues.

“5th Science and Technology Basic Plan” (approved by the Cabinet on January 22, 2016)

Chapter 2. (2) ②

…a common platform will be built in stages that will allow for coordination and collaboration between multiple systems and that can be used in various services, including new services that have not yet been anticipated. […] based on the concept of security by design, it is important to promote these initiatives while incorporating security into the overall system from the planning and design stage. […] Japan, through collaborations between industry, academia, and government, as well as the relevant ministries, will promote the initiatives necessary to build a common platform (“super smart society service platform”) that effectively utilizes the IoT toward realizing a super smart society.

Chapter 2, (3) <2> 1

…Japan will speed up consolidation of the following fundamental technologies in Particular

- Cybersecurity: technology that supports safe information and communication, considering the characteristics of the IoT, such as the long life cycles from design to disposal
- Big data analytics: technology deriving knowledge and value from large amounts of a wide variety of data, including unstructured data
- AI: technology that supports IoT, big data analytics, and advanced communication
- Device technology: technology that enables the high-speed, real-time processing of large amounts of data with low power consumption
- Network technology: technology that distributes growing amounts of data at high capacity and high speed
- Edge computing: technology that enables increasing speed and diversification of real-time processing at the actual system location, which is necessary for increasing the functionality of IoT

In addition, since mathematical sciences are an inter-disciplinary scientific technology that supports all these fundamental technologies, we will promote it together with strengthening collaboration in R&D of each technology, and when fostering professional development.

Other

○ Currently, in the information domain, the strategic objectives envisaged are: “Development of intelligent information processing technology to realize creative collaboration between human and machines” (FY2014) and “Creation, advancement, and systematization of innovative information technologies and their underlying mathematical methodologies for obtaining new knowledge and insight from use of big data across different fields” (FY2013). It is critical to conduct R&D that, while coordinating with these initiatives and taking into full consideration the characteristics of technologies involved, envisions a real social utilization, such as the on-demand, realtime collection and processing of disparate data or its application to security in various scenes.

○ “CPS Integrated IT Platform (CPS-IIP) Project” (commenced FY2012) focuses on social CPS which organically link, and provide feedback between, real society and cyberspace at the scale of buildings, college campuses and local governments. This project is to be implemented in conjunction with the “AIP (Advanced Integrated Intelligence Platform) project” (commended FY2016) promoting integrated R&D on AI, IoT and security. Expectations are for an expedited program, in close coordination with other related domains, to attain the Strategic Objectives.

○ Under the Strategic Objectives, empirical basic research within the information security domain is expected to explore academic fundamentals, including methods of overall system design and build and software engineering. To promote such initiatives, it is critical to coordinate with other R&D efforts dealing with real-world threats in telecommunications and information processing. The academia will in particular play an important role when new security technologies are expected to spread horizontally, beyond industry domains, in a society where a diverse multitude of devices are connected.

7.10 Pioneering next-generation photonics through the discovery and application of novel optical functions and properties

Overview

Technologies making use of light have served not only as means for observing substances, but also as cross-disciplinary technologies covering a wide range of fields, including material processing, telecommunications, and medical care. Along with the recent rapid advances in lasers and precision control and high-sensitivity measurement methodologies, light-based technologies are now an essential part of the social infrastructure, pioneering new frontiers of knowledge, which include the creation of new materials, the discovery of new functions and the control of quantum states by serving as advanced sciences and technologies. On the other hand, many aspects related to the essence of light behavior remain unexplained, such as diverse nonlinear optical phenomena and elementary excitation properties in material-light interactions. Systematic acquisition of new knowledge is inevitable to gain a deeper understanding of this field and develop applications therein.

Therefore, this Strategic Objective is to accelerate progress in new fields of photonics that will meet future demands of society and industry through cross-disciplinary, multilayered integration and development of conventional optical sciences achieved by clarifying, applying, and controlling novel optical functions and properties. At the same time, by working to clarify the fundamental principles sustaining the creation of new technological ideas, we will strive to create basic technologies and systems for complex light through the synthesis of optical functional materials, development and application of innovative optical communication technology, visualization of microstructures with high temporal and spatial resolution, and integration with advanced mathematical sciences.

This cross-disciplinary and coordinated approach toward further supporting a broad range of fields that includes the environment, energy, manufacturing, telecommunications, and medical care will lead to the formation of a higher-order social and industrial infrastructure capable of meeting various aspects of social demands, including precision, sensitivity, capacity, and power consumption.

Targets to Achieve

The Strategic Objectives is aimed at developing fields for next-generation photonics that have the flexibility to support a broad range of social and industrial demands through the development of nano-devices achieved by elucidating properties related to crystal structures and dynamic behavior in elementary excitations, and the development of optimal light sources and photodetection systems suited to a wide variety of objectives, from the noninvasive observation of deep tissue to the recording of high-speed electron motion. Specifically, we aim to achieve the following.

(1) The invention of new optical functional materials and nanostructures and the development of high-performance optical devices through precision control of various photoresponse properties

(2) The improvement of noninvasive *in vivo* observation and imaging techniques within organisms and soft matter through applications of nonlinear, organic photonics

(3) The implementation of fundamental research on interactions between light and diverse elementary excitations in materials

(4) The pioneering of extreme photonics, including ultra-high-density strong EMF science, attosecond laser technology, and ultra-high-precision optical frequency comb technology

Future Vision of a Society to be looked at during the research promotion

The achievements of the targets listed under “3. Targets to achieve” contribute to realize a society with the following characteristics.

- A society in which photonics technologies employing unexploited optical functional materials and advanced light sources contribute to the resolution or mitigation of grave social issues, such as environmental and energy-related problems, and make it possible to reform the manufacturing industry and create new key industries, thereby strengthening Japan’s intellectual infrastructure and industrial competitiveness on the global stage.

- A society in which advances in photonics technology concerned with the use and control of light, such as new optical communication technologies or sensing technologies, redefine an "information society" and alter our perception of space by achieving a more sophisticated and secure telecommunications infrastructure and closer links between information technology and the real world through cyber-physical systems (CPS) and the Internet of Things (IoT).
- A society in which the development of light sources and photodetectors having a low impact on humans and the environment and the establishment of control technologies for these devices stimulates greater sophistication in life sciences and medical systems and promotes the development of advanced equipment, enabling more advanced healthcare and stress-free diagnostics that are quick and inexpensive and place little burden on the patient.

Specific Research Examples

(1) The invention of new optical functional materials and nanostructures and the development of high-performance optical devices through precision control of various photoresponse properties

Develop optical functional materials based on new principles not previously considered in conventional optical sciences and conduct R&D on their wide-ranging applications, as in the preceding example of metamaterials with controlled permittivity and magnetic permeability. Specifically, control light waves using structural features that are smaller than the wavelength of light and attain a resolution beyond the diffraction limit of light, develop nanoscale laser micromachining and measuring technologies, and conduct research on creating new materials. For clarifying basic principles identified as future challenges and establishing future technologies for high-volume manufacturing, conduct research on processes for discovering new functions and processes for creating new materials based on theoretical approaches involving simulations and on the elucidation of currently unknown physical properties, and develop techniques and the necessary equipment for freely designing and fabricating substances or materials possessing a specific refractive index, transparency, and permittivity.

(2) The improvement of noninvasive *in vivo* observation and imaging techniques within organisms and soft matter through applications of nonlinear, organic photonics

In order to develop applications for the broad range of advanced life sciences, develop optical imaging technologies that enable noninvasive observations in real-time for biological functions from the molecular to the whole-body level as far down as deep tissue, develop practical coherent light sources that are small and stable for use in this imaging technology, and conduct research aimed at elucidating mechanisms of interaction occurring under light irradiation between a biologically-relevant substance (the detection target) and a non-biological substance (the probe). This research will help develop a high-quality, high-resolution microscope enabling the direct observation and analysis of biomolecules and the interior of soft matter.

(3) The implementation of fundamental research on interactions between light and diverse elementary excitations in materials

With the aim of clarifying and deepening our understanding of the basic properties of solids required for an extensive range of basic research and industrial applications and of attaining next-generation high-performance optical devices, develop techniques for observing and controlling the dynamics of quasiparticles (collective excitations) in the interior and on the surface of solids and such ultra-fast dynamic processes as electrons emitted from a solid, and establish control technologies for various photoresponses and photochemical reactions, including a technology for controlling coherent light with an extremely short pulse duration. Specifically, conduct research on improving techniques for observing electron states at high resolutions in both temporal and spatial dimensions and techniques for controlling the oscillation and propagation of plasmons and phonons. In plasmonics, for example, a goal is to develop subwavelength photonic devices below the diffraction limit of light and nano-optical devices, such as surface plasmon-based circuits and interferometers.

(4) The pioneering of extreme photonics, including ultra-high-density strong EMF science, attosecond laser

technology, and ultra-high-precision optical frequency comb technology

Conduct research using relativistic high-density plasma generated through ultra-intense laser-matter interactions, and pioneer advanced optical sciences for use under extreme environments and conditions, such as a technique for generating and controlling attosecond pulses, terahertz polarization pulse shaping with arbitrary field control, an optical frequency comb for ultimate measurements of time and space, and a laser acceleration technology. These endeavors will help amass knowledge on advanced laser science to clarify basic principles and will contribute to a deeper understanding of atomic physics and material properties. These efforts will also lead to R&D on improved and commercially viable optical lattice clocks that are ultra-precise and ultra-stable, the recording of ultrahigh-speed electron motion during chemical reactions, and the development of technologies for manipulating electrons in matter with attosecond precision.

While the above targets share common technologies for controlling the conditions of light (phase, pulse, intensity, wavelength, etc.), we would like to radicalize photonics technology and expand its applications through multifaceted approaches that involve predictive techniques based on our knowledge of computational science and mathematics for complex systems that could help in development and verification for constructing and optimizing systems based on these technologies.

Domestic and Foreign Research Trends

(Trends in Japan)

In Japan research on applications relevant to optical sciences has unfolded in such projects as the Center of Innovation (COI) program and the Photon Frontier Network program. In particular, these programs are conducting new R&D on the establishment of element technologies for photonic crystals capable of producing revolutionary semiconductor lasers that transcend conventional operating principles and a laser acceleration system and to apply these technologies and system toward the development of an ultra-small X-ray free-electron laser.

(Trends overseas)

Following the 7th Framework Programme (FP7), Europe has launched Horizon 2020, the EU Framework Programme for Research and Innovation, in an effort to further develop optical sciences and technologies aimed at renovating its information and communcation networks and strengthening its industrial competitiveness. Germany has also promoted R&D at the Fraunhofer Society on optical sciences related to industrial technology as a national policy. In the U.S., the Fast-Track Action Committee on Optics and Photonics under the National Science and Technology Council (NSTC) outlined America’s future direction in its report “Building a Brighter Future with Optics and Photonics” in April 2014, declaring that the U.S. would focus on imaging and faint photonics.

Background of Consideration

The following study was conducted based on the Expert Panel Report on the Envisioned State of Strategic Basic Research (June 27, 2014).

(Preparation of analytic materials regarding research trends in Japan and overseas using the Science Map and Database of Grants-in-Aid for Scientific Research)

We prepared analytical materials on research trends in Japan and overseas using information in Science Maps 2010 and 2012 (July 31, 2014; National Institute of Science and Technology Policy (NISTEP)) and the database of Grants-in-Aid for Scientific Research.

(Implementation of a questionnaire for specialists using analytical materials and preparation of notable research trends)

We created a questionnaire on noteworthy research trends based on the analytical materials we had prepared and administered the questionnaire to the JST Center for Research and Development Strategy and to experts participating in the expert network operated by the Science and Technology Foresight Center of NISTEP. We then analyzed responses to the questionnaire and identified the “development of new fields in photonics based on ultra-precision control of light” as a noteworthy research trend.

(Holding of workshops and preparation of Strategic Objectives)

We held a workshop to bring together experts from industry and academia involved in the development of new fields in photonics based on ultra-precision control of light identified as a noteworthy research trend. At the workshop, we discussed particularly notable trends in Japan and overseas, the social and economic impacts of progress in research and technological development, visions of a society arising from such impacts, and objectives that should be met during the research period. We then prepared Strategic Objectives based on the discussions in the workshop.

Relevant Matters in Cabinet Decisions etc.

Comprehensive Strategy on Science, Technology and Innovation 2014 (approved by the Cabinet on June 24, 2014)

Chapter 2, Section 1, I.3 (4)1)

We will promote the research and development and systematization of ultra-low-loss power devices (SiC, GaN, etc.), which significantly reduce the power consumption of motors and information devices, ultra-low-power-consumption semiconductor devices (three-dimensional semiconductors, nonvolatile elements, etc.), and optical devices to advance technologies in efficient energy utilization, and will contribute to the significant reduction of energy consumption by expanding the applications of these technologies to devices in the transportion, industrial, and consumer sectors. … With this measure, we will realize a society possessing advanced technologies for efficient energy use and intended for international expansion.

Chapter 2, Section 2, 1. Basic Understanding

It is necessary to sufficiently utilize mathematical sciences, systems science, and photonics and quantum sciences, all of which support cross-cutting technologies.

Other

- Under the FY2008 Strategic Objective “Enhancing advanced materials science and life science toward innovations using new light sources, including state-of-the-art laser technology,” we have strived to merge research in the utilization of light developed in each individual field thus far, to conduct basic research on optical sciences related to the interaction of light and matter, and to produce technological ideas having a great rippling effect on other fields. It is necessary now to accelerate commercialization of advanced optical sciences by concentrating our efforts on expanding these excellent research ideas through research under the current Strategic Objectives.
- The goal of the Project to Develop Basic Technologies Aimed at Establishing Research Bases for Photonics and Quantum Sciences is to conduct R&D on state-of-the-art light sources, beam sources, beam control techniques, and measuring techniques that merge the technological ideas in fields of photonics and quantum sciences with the needs in priority areas and industry. The new light sources and element technologies developed through this project form the foundation for R&D conducted under the current Strategic Objectives.
- The program entitled the “Development of Systems and Technology for Advanced Measurement and Analysis” has promoted the development of element technologies and equipment for innovative and advanced measurement and analysis and their peripheral systems, resulting in the development of detectors and new light sources. Through coordination with research under the current Strategic Objectives, we can expect swift results in commercialization of advanced equipment, and particularly in optical sensing.

7.11 Elucidation of principles for innovative energy conversion functions, and generation of new substance creation, new device creation, and other core technologies, that will contribute to the high-efficiency conversion and advanced application of microenergy

Overview

There are many forms of untapped energy in the natural world and a significant volume of research is being undertaken on technologies for putting them to work by converting them to electric energy. Development of technology capable of converting microenergy to electric energy with output in the range of μW～mW has become the focus of attention in the U.S. and Europe, and growth is being seen in investments targeting two areas. One is sensors that, because of their ability to freely use energy in the environment, are anticipated to be applied in numbers ranging from the hundreds of millions to trillions. The other is independent power supplies for mobility devices, biodevices, and other applications in environments where drawing power from a power grid is impractical.

In contrast, amid the need for new principles for the highly efficient conversion of untapped microenergy from the natural world into electric energy and for the creation of new substances based on those principles, Japan has technological seeds for innovative research on new principles (e.g. the spin Seebeck effect) and the creation of new substances (e.g. high-ZT materials and multiferroics).

Under this Strategic Objective, therefore, attention will be focused on applying Japan’s strengths to the elucidation of principles for innovative energy conversion functions, and generation of new substance creation, new device creation, and other core technologies, that will contribute to the high-efficiency conversion, and advanced application, of microenergy, and in so doing accomplish two goals: 1) Acceleration of the adoption of sensors and other applications that do not have high energy requirements; and 2) Contribution to the realization of next-generation environmental protection and manufacturing applying cutting-edge Internet of Things (IoT) technologies and big data.

Targets to Achieve

The focus of this Strategic Objective is not only to elucidate basic principles, and create new materials and new structures and devices, but also to promote research strategically including fundamental analysis, design technology, and theoretical approaches, and, in so doing, create technology that converts microenergy to electrical energy, surpassing existing principles and conversion materials. In more specific terms, the following will be achieved:

(1) Elucidation of new principles contributing to the highly efficient conversion of, and advanced application technologies for, microenergy

(2) Development of theories, fundamental analysis, and design technologies for the highly efficient conversion of, and creation of advanced application technologies for, microenergy

Future Vision of a Society to be looked at during the research promotion

The achievements of the targets listed under “3. Targets to achieve” contribute to we realize a society with the following characteristics.

- A society in which the ability to create electrical energy from microenergy leads to the rapid adoption of sensors, mobility devices, biodevices, and other technology that are not suited for receiving power from an electrical grid and do not require large amounts of energy, and next-generation environmental protection and manufacturing applying IoT technology and big data are being realized.

5. Specific Research Examples

(1) Elucidation of new principles and generation of innovative substances and devices that will contribute to the high-efficiency conversion of, and advanced application technology for, microenergy

Develop core technologies for the high-efficiency conversion into electric energy, and advanced application, of heat, light, electromagnetic wave, biological body, phonon, spin, and other types of energy, and elucidate the underlying principles in creating new substances and devices with outstanding physical properties far surpassing the characteristics and functions of substances to date. More specifically, elucidate principles contributing to innovative energy conversion such as that taking the form of the interrelationship of spin and topology, and create new substances applying such innovative energy conversion, functional substances from inorganic compounds and/or organic compounds or inorganic / organic hybrid compounds, or new substances contributing to innovative energy conversion with an eye toward lowering environmental impact.

(2) Development of theories, fundamental analyses, and design technologies for the high-efficiency conversion of, and creation of advanced application technologies for, microenergy

Create analytical standards and analytical technologies for physical phenomena (physical properties of materials, interfaces, transport phenomena, etc.) that are associated with energy conversion and are required for elucidating new principles and creating innovative materials. More specifically, establish theoretical calculation and computer simulation methods contributing to new principles and new substance creation, and generate principles and design criteria for innovative devices based on new principles and substances. In addition, control interactions, for example, as in the independent control of two energy forms (e.g. phonon and spin current transfer), and perform an analysis based on electron-phonon and magnon-phonon separation.

Domestic and Foreign Research Trends

(Trends in Japan)

In Japan, large-scale projects focusing on applications of microenergy have not been implemented, and research investment is far behind that of other countries. Nevertheless, Japan has strengths in basic research and development in ferroelectrics and other branches of physics and thermoelectric conversion and other areas of conversion materials. Potential exists for the creation of innovative technologies through the combination of unrelated fields and combination of basic and applied fields.

(Trends Overseas)

In Europe, numerous projects on the application of microenergy are underway. In 2014, the U.K. made the decision to provide 50 million pounds (approx. 8.9 billion yen) in funding for work in seven emerging technologies over a four-year period. Energy harvesting is among the seven targeted fields of technology, and sights have been set on the commercialization of wireless sensors and autonomous power supplies. In the U.S., Fairchild Semiconductor, the University of California, Berkley, and other parties established the “Trillion Sensors Universe” in 2013, accelerating industry-academia collaboration with this project aimed at bringing about a society that puts one trillion sensors into use every year.

Background of Consideration

Based on the Expert Panel Report on the Envisioned State of Strategic Basic Research (June 27, 2014) an examination was carried out as described below.

(Preparation of analytic materials regarding research trends in Japan and overseas using the Science Map and Database of Grants-in-Aid for Scientific Research)

Materials for the analysis of domestic and overseas research directions were prepared using information from the Science Map 2012 & 2010 (National Institute of Science and Technology Policy, July 31, 2014) and information from the Database of Grants-in-Aid for Scientific Research.

(Implementation of a questionnaire for specialists using analytical materials and preparation of notable research trends)

Experts associated with the JST Center for Research and Development Strategy and experts participating in the expert network of the Science & Technology Foresight Center of the Japan Science and Technology Agency were asked to respond to a survey on notable research directions. This survey was constructed using prepared analysis materials. Survey results were analyzed and “creation of core technologies related to high-efficiency energy conversion for the construction of small, distributed power supplies and applications for such power supplies" was identified as the most notable research direction.

(Holding of workshops and preparation of Strategic Objectives)

Workshops bringing together experts from industry and academia to discuss the "creation of core technologies related to high-efficiency energy conversion for the construction of small, distributed power supplies and applications for such power supplies" were held. Discussions focused on notable domestic and overseas research directions, the potential social and economic impacts of research and technology development advances and visions of the future society that could emerge as a result, and objectives that should be achieved during research periods. Strategic Objectives were prepared based on workshop discussions.

Relevant Matters in Cabinet Decisions etc.

Fourth Science and Technology Basic Plan (approved by the Cabinet on August 19, 2011) (August 19, 2011 Cabinet Decision)

III. 2. (2) ⅰ)

Promote research and development of, and advance strategies for appropriate open access to, core technologies required for development and application of advanced materials and components for which high rates of added value, high market share, and future growth are expected and for which Japan has a wealth of technologies with international competitive advantage, core technologies supporting the use and application of high-performance electronic devices and information communication, and other innovative common core technologies.

Comprehensive Strategy on Science, Technology and Innovation (Cabinet Decision June 24, 2014)

Chapter 2, Section 1, I. 3. (7) 1)

In order to further improve energy usage efficiency, work to advance technology for the application of cogeneration, which produces both heat and electricity, and technology for the application of low temperature heat emission and other forms of energy that have not been used to date.

Other

- It is imperative that the creation of core technologies contributing to the high-efficiency conversion and advanced application of microenergy and commercialization of results be pursued while also carrying out the following related R&D and research under the Strategic Objectives described herein.
  - Through a portion of the research being conducted under the fiscal 2011 Strategic Objective, "Realization of breakthroughs in phase-interface phenomena and creation of basic technologies for high-functionality interfaces that will result in dramatic advancements in highly-efficient energy utilization," the fiscal 2012 Strategic Objective, "Establishment of molecular technology, which is the free control of molecules to bring innovation to environmental and energy materials, electronic materials, and health and medical materials," and the fiscal 2013 Strategic Objective, "Creation of new functional materials by means of technology for controlling spaces and gaps in advanced materials in order to realize selective material storage, transport, chemical separation, and conversion, etc.," efforts are being made to create basic science and technology related to the conversion and transport of energy. In research being conducted under the fiscal 2014 Strategic Objective, "Development of innovative materials and devices based on atomic or molecular two-dimensional functional films, and their applications to practical uses," work is being pursued to create device design technology using topological insulators. In addition, in research moving forward under the fiscal 2013 Strategic Objective, "Creation of innovative core technologies by merging material technology, device technology, and nano-system optimization technology toward the realization of information devices with ultra-low power consumption and multiple functions," efforts are being made to link and merge new functional materials, electronic devices, and system optimization.

- At the New Energy and Industrial Technology Development Organization (NEDO), the "Project to Advance the Implementation of Clean Devices in Society" (two-year project beginning in 2014) is underway. The purpose of this project is to widen the definition of clean devices that contribute to energy saving (environmental power devices and other innovative devices contributing to energy saving) from those devices traditionally imagined, to include devices used for new applications in the form of products and services, thereby maximizing energy-saving impacts. This project is targeting the development of directions for device installation and testing, reliability and safety, and standards and standardization.
- At the Center of Innovation (COI), efforts are being made to develop and apply nano sensing devices in projects such as "the center of innovation for creation of platform on big life data from unconscious sensing to support human and social well-being."

7.12 Creation of innovative catalysts using diverse natural carbon resources

Overview

The worldwide chemical industry which depends on oil is undergoing a rapid transformation. In the U.S., as a result of the shale revolution, ethylene, manufactured using ethane with cheap natural gas as a feedstock, is beginning to gain a strong competitive edge. In China, methanol is being synthesized using coal. In the meanwhile,, it is very difficult to create innovative catalysts that efficiently activate methane and lower alkanes which are found abundantly in natural gas, but if it can be achieved, it will have a major impact internationally. In particular, there are growing expectations for manufacturing technologies with low carbon dioxide emissions and energy input, and it is a matter of urgency to develop these very advanced technologies.

For this reason, this Strategic Objective aims to create innovative catalysts that use various resources such as methane (CH_4) and lower alkanes (CnHx: n = 2, 3) as chemical feedstocks and energy, leveraging Japan's highly competitive catalyst research capabilities. The target is to establish a common platform for material research using advanced substance synthesis, measurement and calculation technologies and data science, strategically promoting the discovery of catalytic principles and the creation of catalysts, enabling a society that uses diverse natural carbon resources with high efficiency.

In recent years, calculation and measurement technologies have been making advances. If we can leverage them to design and invent innovative catalysts, we will be able to establish a platform for new catalyst research. Beyond this, we also expect to develop new methodologies in nanotechnology and materials research, further reinforcing the competitiveness of Japan.

Targets to Achieve

This Strategic Objective aims to create innovative catalysts that use various resources as chemical feedstocks and energy, such as methane (CH_4), which accounts for the majority of the content of natural gas, and lower alkanes (CnHx: n = 2, 3). Specifically, we aim to achieve the following;

(1) The invention of catalysts that realize C1 chemistry in order to convert methane into chemical feedstocks and energy

(2) The invention of catalysts that efficiently convert lower alkanes into chemical feedstocks and energy

(3) The establishment of a common platform for identifying the guiding principles of catalytic reactions through collaboration in materials research leveraging material creation, measurement, analysis, theoretical calculation, and test and calculation data,.

Future Vision of a Society to be looked at during the research promotion

The achievements of the targets listed under "3. Targets to achieve" will contribute to realize a society with the following characteristics.

- A society in which a key industry supporting the foundation of Japan has been formed through the ability to use diverse carbon resources other than oil such as the methane contained abundantly in natural gas and lower alkanes, converted into chemicals and fuel..
- A society in which a future path to resource-rich nation status has been opened if that is somewhat freed from resource risk by establishing diverse feedstock and energy sources that do not rely on oil and the exploitation of methane hydrate is achieved.

Specific Research Examples

(1) The invention of catalysts that realize C1 chemistry in order to convert methane into chemical feedstocks and energy

Using methane as a reactant, develop highly active, highly selective catalysts that achieve direct synthetic reactions to produce methanol and other chemicals with high added value.

(2) The invention of catalysts that efficiently convert lower alkanes into chemical feedstocks and energy

Using ethane or propane as a reactant, develop innovative, highly active, highly selective catalysts that react to produce ethylene glycol, acetic acid, propanol, acrylic acid and other chemicals with high added value.

(3) Through collaboration in material research leveraging material creation, measurement, analysis, theoretical calculation, and test and calculation data, build a common platform for identifying the guiding principles of catalytic reactions.

Realize onsite dynamic surface measurement of the actual operating conditions of the catalytic reaction. Realize multiscale, multiphysics analysis of catalytic reactions using large scale theoretical calculation. Realize material research leveraging test and calculation data through the use of materials informatics.

Domestic and Foreign Research Trends

(Trends in Japan)

Catalyst research in Japan is highly competitive in relation to other countries. Japan is diligently pursuing research and development into the solubilization and conversion of biomass to sugar, chemical catalysis, water splitting and hydrogen generation using sunlight, artificial photosynthesis to convert carbon dioxide into fuel and feedstocks and other similar areas. However, research into the use of methane and lower alkanes for chemical feedstocks and energy is an unexplored field. Recently, new concepts have emerged in catalyst research, such as research into electride catalysts that enable synthesis of ammonia at room temperature (Hosono et al., 2012). There is increasingly active research that promises to contribute to the conversion of methane and lower alkanes to feedstocks and energy. It is necessary to incorporate the knowledge from these peripheral research areas, as well as from the rapid progress in measurement, calculation and data science, and quickly build a framework for addressing the conversion of methane and lower alkanes to feedstocks and energy.

(Trends Overseas)

In response to the shale revolution, the development of technologies for utilizing methane and lower alkanes is having a direct impact on the industrial competitiveness of each country, with research and development being undertaken in Europe, America and other countries.

For example, Russia researchers reported that they have achieved successful results in selective synthesis of methanol from methane using nitrous oxide at 160 °C with maximum yields of 96%. In America, since 2003, the Department of Energy’s ARPA-E funding program for innovative advanced research has provided support for a project to develop small scale processes for converting methane to liquid fuel using methane assimilating microorganisms. In addition, venture companies are working on manufacturing chemicals from methane using microorganisms.

Background of Consideration

The following study was conducted based on the Expert Panel Report on the Envisioned State of Strategic Basic Research (June 27, 2014).

(Preparation of analytic materials regarding research trends in Japan and overseas using the Science Map and Database of Grants-in-Aid for Scientific Research)

Analytic materials regarding research trends in Japan and overseas using information in the Science Map 2012 & 2010 (July 31, 2014 National Institute of Science and Technology Policy) and the Database of Grants-in-Aid for Scientific Research were prepared.

(Implementation of a questionnaire for specialists using analytical materials and preparation of notable research trends)

A questionnaire concerning future notable research trends was conducted for the specialists participating in the expert network of the Japan Science and Technology Agency Center for Research and Development Strategy and the National Institute of Science and Technology Policy Science and Technology Foresight Center, using the analytical materials prepared. The results of the questionnaire were then analyzed and then the creation of innovative catalysts for efficient conversion of energy was identified as a noteworthy research trend.

(Holding of workshops and preparation of Strategic Objectives)

A workshop gathering experts from industry and academia related to the noteworthy research trend towards the invention of innovative catalysts for efficient conversion of energy was held. Particularly notable trends in Japan and overseas, the social and economic impacts of research and technology development and the future society to which they may give rise, and the targets that should be achieved during the research period were discussed. The Strategic Objectives were prepared based on the discussions in the workshop.

Relevant Matters in Cabinet Decisions etc.

Comprehensive Strategy on Science, Technology and Innovation 2014 (approved by the Cabinet on June 24, 2014) Chapter 2, Section 1, I. 3. (3) 1)

Conduct research and development into innovative catalyst technologies for efficient production of energy and chemicals from diverse feedstocks such as shale gas, unconventional crude oil, and carbon dioxide, as well as energy resources from microorganisms and biomass

Other

- The research areas covered by catalysts are broad, and the areas targeted by each project are different. The main targets of major projects are as follows.
  - The main research fields targeted under the 2012 Strategic Objective of the creation of advanced catalytic-transformation technology to solve various challenges related to the environment, energy and drug design are chemical catalysts for conversion of carbon dioxide and water splitting and hydrogen generation using sunlight.
  - The Japan Science and Technology Agency Advanced Low Carbon Technology Research and Development Program (ALCA) targets solubilization and conversion of biomass to sugar, and chemical catalysts.
  - The Ministry of Economy, Trade and Industry's Japan Technological Research Association of Artificial Photosynthetic Chemical Process (ARPChem) is working on artificial photosynthesis for converting carbon dioxide into feedstock using hydrogen generated by a water splitting reaction using sunlight and photocatalysts.
  - Some of the research conducted under the FY2012 Strategic Objective "The establishment of molecular technology, using the free control of molecules to bring innovation to environmental and energy materials, electronic materials, and health and medical materials", and the FY2013 Strategic Objective "Creation of new functional materials by means of technology for controlling spaces and gaps in advanced materials in order to realize selective material storage, transport, chemical separation, and conversion, etc.", targeted solubilization and conversion of biomass to sugar, and chemical catalysts.
- As indicated, despite the importance of this Strategic Objective of converting methane and lower alkanes to chemical feedstock and energy, it is a hitherto unexplored field with no projects to address it, and it is anticipated that an organization will be built with other institutes to conduct research under this Strategic Objective.

7.13 Establishment of environmentally-adaptive-plant design systems for stable food supply in the age of climate change

Overview

To resolve the global food problems faced by Japan and other countries around the world, technologies for the development and the cultivation of agricultural crops that can adapt to climate change and other environmental changes must be established. In order to achieve these technologies, the knowledge in the area of basic plant science that is gained through model plant research in Japan must be linked to crop development and cultivation, and various biological data in plant science must be gathered and analyzed from new perspectives including technologies in engineering, information science and other different fields.

To this end, the Strategic Objective is focused on an information science approach to conduct an integrated analysis of genome, transcriptome, metabolome and other omics data accumulated in plant science, phoneme and other quantitative data obtained using state-of-the-art measurement technologies, and environmental factors and the like that have been quantified in numerical terms, in order to build prediction models for plant growth and environmental response. Subsequently, plants with the improved environmental adaptability that have been designed by using these prediction models will be developed, and demonstration cultivation in actual environments will be conducted, in order to achieve "environmentally-adaptive-plant design systems" which are based on "growth and environmental response prediction models"

This will make it possible to design, manufacture and cultivate crops able to grow under a variety of environmental conditions, thus ensuring a stable food supply.

Targets to Achieve

The Strategic Objective is to establish "environmentally-adaptive-plant design systems" which will make it possible to predict growth and environmental response of plants based on environmental conditions, various plant-related factors and other quantitative data, and to design, manufacture and cultivate plants with improved environmental adaptability. Specifically, we aim to achieve the following:

(1) Development of quantitative measurement technologies that can make a detailed characterization of growth, physiological state and environmental response of plants

(2) Identification of biological markers (biomarkers) for each target plant that can respond to fluctuations in phenotypic character

(3) Establishment of "growth and environmental response prediction models" that work by means of bioinformatics, integrating technologies in plant science and different fields such as engineering

(4) Design, manufacture and verification of plants with improved environmental adaptability based on the "growth and environmental response prediction models"

Future Vision of a Society to be looked at during the research promotion

The achievements of the targets listed under "3. Targets to achieve" contribute to we realize a society with the following characteristics..

- A society in which crop and plant varieties developed based on the predictions made using the "growth and environmental response prediction model" will make it possible to ensure stable food production even in areas unsuitable for the cultivation of existing crops, under increasing concern that rapid climate change may convert regions that are conducive to the cultivation of existing crops into regions that are unsuitable for the cultivation of those crops.
- A society in which it contributes to resolve food shortages due to population increase and environmental degradation that the "environmentally adaptive plant design system" based on the "growth and environmental response prediction model" and the crop improvement technologies, environmental monitoring technologies and integrated omics analysis technologies and the like developed by Japan will be provided to other countries in the form of a comprehensive agricultural technology package, andthat will enable stable crop cultivation even in

countries in which most of the land area is unsuitable for the cultivation of existing crops, and countries with reduced yields due to the effects of climate change.

Specific Research Examples

(1) Development of quantitative measurement technologies capable of detailed determination of plant growth, physiological state and environmental response

Improve phoneme analysis technologies that are capable of making quantitative determinations of plant phenotypes.. Also improve advanced sensing technologies and imaging technologies that can determine the precise physiological state of plants.

(2) Identification of biomarkers for individual plants that can respond to fluctuations in phenotypic character

Conduct research on the Identification of biological markers (biomarkers) that can respond to fluctuations in phenotypic character. Also conduct research on the accumulation of data on gene expression and metabolic changes that are linked to the phenotypic character of plants under various environmental conditions, such as outdoor settings and controlled environments.

(3) Establishment of a "plant growth and environmental response prediction model" through bioinformatics that integrates plant science with engineering and other technologies in different fields

Conduct research on the prediction of phenotypic character such as plant growth, flowering and so on in presumed environments will be conducted. Also conduct research on the prediction of responsiveness to environmental stress, genes that can improve tolerance, and prediction of related traits.

(4) Design, manufacture and verification of plants with improved environmental adaptability based on the "growth and environmental response prediction model."

Development and advance plant engineering technologies for the manufacture of plants that are designed to have improved environmental responsiveness based on the "growth and environmental response prediction model." The cultivation in outdoor settings and controlled environments of the plants designed and manufactured based on the "growth and environmental response prediction model" will be verified, and data on phenotypic character during the period of cultivation and changes in physiological state will be prepared and provided as feedback to the "plant growth and environmental response prediction model."

Domestic and Foreign Research Trends

(Trends in Japan)

Progress has been made in Japan in recent years in numerical analysis based on genome, transcriptome, metabolite and other types of "big data" in the field of plant science, and expression analysis that incorporates climate change, individual differences at the ecological level and so on is now the trend (Overview Report (of the specialist biology study team), FY 2013 Study of Trends in Academic Research, Japan Society for the Promotion of Science). But although the level of research in Japan in the field of plant science is extremely high and (as can be seen in the achievements in the International Rice Genome Sequencing Project) ranks with that being conducted in the United States and Europe, it has been reported that Japan lags behind the West in the application of such achievements, in terms of both the level of technical development and industrial technology capabilities (2009 International Comparison of Science and Technology Research and Development, Life Science Field, Center for Research and Development Strategy, Japan Science and Technology Agency).

(Trends Overseas)

In the United States, genetic analysis of the Arabidopsis (thaliana) has been pursued as part of the Plant Genome Initiative, and genetic analysis research of crops and vegetables has also been pursued in recent years. In Europe, the achievement of an integrated understanding through systems biology is being pursued based on certain specific systems, and in recent years research and development aimed at developing crops and vegetables has been conducted in the form of crop performance and improvement ("Environmental Response Mechanism and Breeding Technologies for Plants in the Field" 2009 Workshop Report, Center for Research and Development Strategy, Japan Science and Technology

Agency). Overseas, there has been a notable trend in which major biotechnology companies, which can develop its own unique DNA marker technologies and genetic analysis technologies, have absorbed midlevel seed and seedling manufacturers and expanded into the area of vegetable seed and seedling development. Furthermore, due to the widespread use of next-generation sequencers, the genome sequencing of non-model crops has been progressing rapidly in Europe, the United States and China (Panoramic View of the Life Science and Clinical Research Field (2013) 2nd Edition, Center for Research and Development Strategy, Japan Science and Technology Agency).

Background of Consideration

The following study was conducted based on the Expert Panel Report on the Envisioned State of Strategic Basic Research (June 27, 2014).

(Preparation of analytic materials regarding research trends in Japan and overseas using the Science Map and Database of Grants-in-Aid for Scientific Research)

We prepared analytic materials regarding research trends in Japan and overseas using information in the Science Map 2012 & 2010 (July 31, 2014 National Institute of Science and Technology Policy) and the Database of Grants-in-Aid for Scientific Research.

(Implementation of a questionnaire for specialists using analytical materials and preparation of notable research trends)

We conducted an opinion survey concerning future notable research trends for the specialists of the Center for Research and Development Strategy (Japan Science and Technology Agency) and experts participating in the S&T Experts Network operated by the Science and Technology Foresight Center (National Institute of Science and Technology Policy), using the analytical materials we had prepared. Then we analyzed the survey results and identified the "development of a system for the design of in silico plants to accelerate the elucidation of plant life phenomena" as a noteworthy research trend.

(Holding of workshops and preparation of Strategic Objectives)

We held a workshop to gather experts from industry and academia related to the noteworthy research trend of "development of a system for the design of in silico plants to accelerate the elucidation of plant life phenomena." We discussed particularly notable trends in Japan and overseas, the social and economic impacts of research and technology development and the future society to which they may give rise, and the targets that should be achieved during the research period. Then we prepared Strategic Objectives based on the discussions in the workshop.

Relevant Matters in Cabinet Decisions, etc.

The 4th Science and Technology Basic Plan (approved by the Cabinet on August 19, 2011)

III. 2. (1) ii)

To improve the food self-sufficiency rate, enhance food safety, and ensure a stable supply of water, the government will promote R&D concerning the production, distribution, and consumption of safe and quality food materials and products, and R&D concerning stable supplies of food and water, which will include the utilization of advanced technologies such as genetically modified organisms (GMO) and the adoption of industrial viewpoints.

III. 2. (5) i)

The government will promote R&D into nanotechnology and optical / quantum technologies that will lead to the development of advanced techniques for measurement and analysis, advanced information & communication technologies such as simulation and e-science, S&T that is cross-sectionally available in multiple areas such as mathematical science and system science technologies, and S&T for integrated areas.

Comprehensive Strategy on Science, Technology and Innovation 2014 (approved by the Cabinet on June 24, 2014)

Chapter 2, Section 1, IV. 3. (1) 1)

Considering such factors as the target market and technology competition in the world, while bridging between fundamental research and research for commercialization to achieve their mutual collaboration, this measure is aimed at strategically promoting the development of new breeding technology, etc., that realizes the provision of revolutionary products in the following fields: analysis of genomes and metabolites, development of an information base such as database creation; identification of useful genes, development of DNA markers, bioinformatics and engineering technology, and utilization of genome editing techniques.

Other

- For this Strategic Objective, the active participation of researchers in fields other than basic plant science — such as information science, engineering and agriculture — will be needed, and efforts to achieve substantive collaboration will be essential. It will be particularly important to ensure the participation and training of researchers in the field of bioinformatics, in which the lack of researchers has been pointed out as a problem. Moreover, in order to ensure the efficient use of research data and achievements in the life science field in Japan, maximum use must be made of the Japan Science and Technology Agency National Bioscience Database Center (JST-NBDC) and other resources.

In order to design projects that involve verification, we are hoping for the participation of institutions that are equipped with environments in which plants can be cultivated and managed under the same conditions as in actual crop cultivation environments. In addition, we also hope there will be organic collaboration with the Strategic Innovation Program (SIP) “Next-generation Agriculture, Forestry and Fisheries Industry Creation Technologies” and other exit strategies, and that the achievements of research conducted for this Strategic Objective will be deployed effectively.

7.14 Development of mathematical sciences to describe and analyze social issues in which basic principle is unclear

Targets to Achieve:

Among various phenomena in our society, for the phenomena whose controlling principles/laws are unclear at present, a profound impact to society can be expected if their mathematical models can be developed. The Strategic Objective aims to achieve the followings by utilizing the nature of the mathematics of universality and abstractness and by finding out the *essence* of complex structures that lurk behind the phenomena through interdisciplinary cooperation among the researchers of mathematics, mathematical science and the researchers of application fields.

○ Derivation of a model that mathematically describes a phenomenon
○ Building of mathematical theory for demonstration, verification, and evaluation of the derived mathematical model

Vision for Reaching Achievable Important Goals in the Future:

By carrying out this Strategic Objective and obtaining the research results described in section 2 "Targets to Achieve," mathematical models can be derived for the phenomena whose controlling principles/laws are unclear at present.

New mathematical theory for the demonstration, verification, and evaluation of the mathematical models will also be built. Furthermore, it is expected that the verified mathematical models will be usable under various situations due to their universality of being free from changes in targets and the times.

For example, assumed target phenomena and application fields are as follows.

- Social phenomena (economic changes, propagation of infection, traffic flow, changes in power/communication network, resident behavior in disasters, aging of various social infrastructures, etc.)
- Natural phenomena (climate change, accidental natural phenomena such as torrential rain, land slide, tornado, tsunami, etc.)
- Life phenomena (interaction mechanism between genes, perceptual recognition/information processing mechanism in the brain, etc.)

By deriving mathematical models for the phenomena as stated above, it is expected that, for example, the following will be achieved in the future.

○ Extraction of the part of the essence of complex structures lurk behind the phenomena and streamlining of processing backed by mathematics

In order to avoid various difficulties when modeling the phenomena of complex structures (growing complexity of model, etc.), works with a large amount of information and high computer processing load can be streamlined substantially by mathematically finding out the part of the essence and describing it in a simplified manner according to mathematical grounds. For example, it is expected to achieve the creation of a new material with a relatively simple and stable structure, which is expected to manifest new functions by mathematically finding out the part of the essence of its structure and controlling the part precisely, a substantial reduction in the processing time for image analysis, and a substantial reduction in the time required for data analysis.

○ Clarification of signs before manifestation of a risk, smart preventive responses, and effective control

By modeling a phenomenon mathematically by considering it as a change of its network structure, as for a power supply system, economic system, manufacturing system, various information system, etc., with a network structure, for example, it is expected that a sign of becoming unstable can be detected and this will lead to prior measures and effective control. It is also expected that it becomes possible to detect the sign of a phenomenon that has not occurred yet and cannot be assumed with an empirical model using limited information only.

Specific Content:

(Background)

In recent years, with the informatization and the growing complexity of society, the development of measuring equipment, dramatic improvement in computer performance, etc., it has become possible to obtain information related to life phenomena, natural phenomena, and social phenomena and to understand the complexity of these phenomena well. However, the models of these phenomena cannot be created because their controlling principles and laws are not clear. Therefore, many of them are understood based on the accumulation of empirical knowledge that applies well without knowing the reasons why they occur. Additionally, even though some sort of models are already used in the fields, such as economy, energy, and disaster prevention, there is a growing number of phenomena that cannot be described by models based only on a theoretical framework that is unique to a specific field. Thus, cooperation with the researchers of mathematics and mathematical science, which is indispensable to understanding the essence of phenomena, is not necessarily sufficient. Furthermore, due to the development of mathematics in recent years, there is a possibility remaining that the theories of modern mathematics, which have not been applied, will provide a clue to understanding the essence of these phenomena and deliver a revolutionary result.

In such a situation, Japan set a Strategic Objective of "***Search for Breakthrough by Mathematical / Mathematical Sciences Researches toward the Resolution of Issues with High Social Needs (Focusing on Collaboration with Wide Research Fields in Science and Technology)"*** in 2007 to promote cooperation between the researchers of mathematics and mathematical science and the researchers of other scientific fields. From this project, it was reported that the notable results of the cooperation include the application of the methods of pure mathematics developed into the resolution of problems and, in particular, building of mathematical models to describe various phenomena.

With this situation in mind, this Strategic Objective addresses social problems that are difficult to resolve as an extension of the conventional science and technology, expects the researchers of pure mathematics to take up mathematical problems among problems in the real world, and to participate in the realization of a breakthrough, as well as focuses on the mathematical modeling of phenomena, which can exert the power of mathematics and mathematical science. Additionally, since it is also necessary to integrate the techniques from different mathematical fields and create a completely new formulation beyond the framework of existing models, cooperation among researchers from various fields within mathematics and cooperation among theoretical researchers related to different mathematical modeling is also indispensable.

(Research Theme)

1) Derivation of a model that mathematically describes a phenomenon

By integrating the existing modeling technologies in social phenomena and the engineering field and the knowledge and logics of mathematics and mathematical science, find out the part of the essence of complex structures that lurk behind various phenomena, and derive mathematical models for phenomena with enough data as well as phenomena without sufficient data.

The target phenomena and application fields may include, for example, economic changes, propagation of infection, traffic flow, changes in power/communication network, resident behavior in disasters, aging of various social infrastructures, etc., for the social phenomena; in addition, climate change, accidental natural phenomena, such as torrential rain, land slide, tornado, tsunami, etc., for the natural phenomena; and interaction mechanism between genes, perceptual recognition/information processing mechanism in the brain, etc., for life phenomena.

Examples of the frameworks of mathematical models describing these phenomena are as follows.

1: Network models representing the structure and dynamics of complex network in the real world such as power network, communication network, nerve system network and human contact relation
2: Multi-scale models for integrated handling of systems consisted of hierarchies by subsystems with different spatial-temporal scales and mesoscopic models positioned between micro models and macro models
3: Hybrid models and multi-physics models to describe systems in which heterogeneous systems interact, such as electronic circuits, including continuous variables and discrete variables, and tissue formation of organisms, including physical actions and chemical actions

By utilizing the universality of the derived mathematical model and applying the model to phenomena other than the initial target phenomena, the additional aim is to develop a modeling technique into one that can be applied to various fields in a cross-sectoral manner.

2) Building of mathematical theory for demonstration, verification, and evaluation of a mathematical model

For the mathematical models derived in 1) above and existing mathematical models, the aims are to demonstrate and verify that the models describe the actual problems and phenomena and to build mathematical theories and techniques for model evaluation.

Policy Positioning (positioning within the policy system and necessity/urgency in terms of policy etc.):

The 4th Science and Technology Basic Plan (endorsed by the Cabinet on August 19, 2011) clearly states, in "(5) Enhancement & strengthening of common bases of science and technology" of "III. Response to key problems which Japan is facing," "mathematical science" is positioned as "scientific technology that can be utilized over multiple fields in a cross-sectoral manner" and the research and development related to it shall be promoted.

Additionally, in the Mathematics Innovation Strategy (Interim report) (Issued on August 2012 by Advanced Research Base Division, Science and Technology/Science Council), problems that lead to "Clarification of structure complex phenomenon, system, etc.," "risk management," "forecast of future changes," etc. are organized and listed as problems that are expected to be resolved through the use of mathematics and mathematical science.

Coordination with Related Policies, Division of Roles, and Differences in Policy Effects:

In the research area for "**Alliance for Breakthrough between Mathematics and Sciences (ABMS)"** of the Japan Science and Technology Agency (JST), an independent administrative agency, which was inaugurated based on the Strategic Objective for "***Search for Breakthrough by Mathematical / Mathematical Sciences Researches toward the Resolution of Issues with High Social Needs (Focusing on Collaboration with Wide Research Fields in Science and Technology)"*** (set in FY 2007), excellent results, such as new mathematical models, are beginning to be obtained through cooperation with the researchers from a wide range of fields, such as pure mathematics. This Strategic Objective will accelerate the efforts to resolve social problems through cooperation between mathematics and various fields while cooperating with the research area and incorporating the researchers from a wide range of fields, such as pure mathematics.

Additionally, in the workshop for cooperative research of mathematics and mathematical science and various sciences/industries (57 times in FY 2011 and 2012 in total; total number of participants: 3,211) which has been co-hosted by the Ministry of Education, Culture, Sports, Science and Technology (MEXT) with universities and other organizations since 2011 and the research promotion program for creating innovation through cooperation between mathematics and mathematical science and various sciences/industries (started in FY 2012), a project sponsored by the MEXT, activities to actively find problems which are expected to be resolved by utilizing the knowledge of mathematics and mathematical science in the various sciences/industries, to concretize research themes by cooperation with the various sciences/industries to lead them to concrete research. It is expected that the problems and research themes with deeper discussions through these activities develop into the research in this Strategic Objective.

Background to Deliberations:

According to the report *1 by JST's Center for Research and Development Strategy (CRDS), research of modeling and analysis technology in Japan are conducted at mathematics and engineering department and complexity science and engineering department of universities, in the most advanced mathematical model project of the Funding Program for World-Leading Innovative R&D on Science and Technology by the Cabinet Office, etc. and it can be thought that the level of basic research is high. Today it becomes possible to obtain a large amount of data in various fields such as accumulation of high-throughput data like genome information in biomedical science, acquisition of multi-measurement electroencephalographic data in brain science and measurement of real-time traffic/transport information data in geographic-information science, therefore the problem in the future is to establish the technology for extracting the essence of an actual system from these data and creating a mathematical model.

The report also states that the five-year project on the ecology and evolution of infection was initiated jointly by the NSF, NIH, and USDA of the United States and the BBSR of Britain from 2012 by investing about 1.5 billion yen and that mathematical modeling of ecological, evolutionary and socio-ecological principle for infection inhibition is set forth as a part of the targets and, in the guideline of the framework for project orchestration in the field of applied mathematics, how the DOE of the United States will distribute its funds to what sort of mathematical modeling research and algorithm research in the future.

By setting this Strategic Objective that places mathematical modeling as its core, it is necessary to gather the researchers of various application fields, researchers of mathematical science and researchers of mathematics to let them focus on mathematical modeling research to further improve international competitiveness.

*1 "Survey report of research and development: System science and technology field (2013)," Center for Research and Development Strategy, Japan Science and Technology Agency

Background of Consideration

In the survey sponsored by the MEXT in FY 2009 (commissioned to Kyusyu University), the survey results based on a questionnaire survey of university mathematics and mathematical science research organizations (175 organizations), researchers of other fields (5,000 researchers), and companies (1,000 companies) and the interview survey of domestic and foreign experts (65 experts) were reported and evolutionary continuation of the research area for "**Alliance for Breakthrough between Mathematics andSciences (ABMS)"**, which is underway in the JST Strategic Basic Research Programs was proposed.

In the Mathematics Innovation Strategy (Interim report), problems that lead to the clarification of structure complex phenomenon, system, etc., risk management, forecast of future changes, etc., are considered problems that are expected to be resolved through the use of mathematics and mathematical science.

In the report of the CRDS released in 2013, the most advanced mathematical modeling was taken up as one of the five research and development areas. In this report it was pointed out that mathematical modeling is a cross-sectoral academic area covering the modeling process of phenomena and behaviors itself and, since adequate modeling of the target is the premise for the control of the phenomenon, future forecasts, and scientific decision making, many academic or social problems can be achieved through constrained optimization of model elements such as parameters. This Strategic Objective was prepared based on the results of these considerations.

Other

When implementing the research based on the Strategic Objective, it is also important to hold places where the researchers of this area related to mathematical modeling, the domestic and foreign researchers of related application fields and others can gather for a certain period to discuss topics such as phenomena for which mathematical modeling in the real world should be achieved and mathematical approaches intensively and to grasp social key problems and research trends in the world, in order to lead this research to a new development.

7.15 Creation of innovative core technologies by merging material technology, device technology, and nano-system optimization technology toward the realization of information devices with ultra-low power consumption and multiple functions

Targets to Achieve:

Faced with the limits to further miniaturization and integration of conventional silicon devices, this program, with the common objective of developing information devices with at least double-digit improvements in total performance(consumption power and speed) , aims to create technologies necessary for establishing a foundation of the future electronics industry, including the creation of material technology pursuing the applicability of new functional materials (core technology necessary for developing and using advanced materials and components), the development of device technology by verifying the operation of logic and memory devices employing new materials, new principles, and new structures, and the creation of nano-system* optimization technology for implementing advanced nanotechnologies, etc., and then the fusion of these various technologies. The program aims to achieve the following targets to these ends.

○ Creation of new functional materials supporting innovative devices and creation of material technologies in pursuit of their applicability

○ Creation of innovative device technologies based on logic and memory devices, etc., employing new materials, new principles, and new structures to enable ultra-low power consumption, ultra-high speed, ultra-large capacity, etc.

○ Creation of core technologies for optimal design of nano-systems by accumulation, integration, and fusion of element technologies from various fields

*In this Strategic Objective nano-systems are defined as parts, equipment, or systems that accumulate, integrate, and fuse element technologies from other fields based on nanotechnology so that taken as a whole they are able to provide advanced functions that contribute to the solution of important issues, as well as being recognized by society.

Vision for Reaching Achievable Important Goals in the Future:

In this Strategic Objective, the research achievements noted in the Section"Targets to Achieve," will be linked to practical application research at private sector companies, etc. to enable the development of innovative devices that use these technologies to achieve information and telecommunications devices and system components that offer ultra-low power consumption, advanced functions and multiple functions. More specifically, they will lead to the creation of the type of society described below and help to achieve objectives such as "Highly efficient and smart use of energy" "Strengthening common infrastructure for the enhancement of industrial competitiveness" "Enhancement of cross-sectional science & technology" etc. as noted in the 4th Science and Technology Basic Plan (approved by the Cabinet on August 19, 2011).

1) Creation of various ultra-low power consumption information and communication terminals, information devices etc., making a major contribution to the formation of a sustainable advanced information and telecommunications network in keeping with the age of energy conservation

2) Fusion of devices based on new operating principles to enable multifaceted applications that include touch panels, flexible displays, solar batteries and biosensors, achieving a true "Ubiquitous Society"

3) Development of end products with social added value that are in keeping with the knowledge-based society, low-carbon society, advanced information society and so on, in order to maintain Japan's international competitiveness and nurture key industries that open the way to a new industrial structure

Specific Content:

The semiconductor industry is currently facing fierce competition worldwide. In recent projections,*[1] the scale of the market in 2012 was USD 289.9 billion, just slightly down from the previous (record-setting) year. However, gradual growth is expected to continue, and this sector serves as a foundation for industrial competitiveness. For example, it is introduced in the following manner: "The semiconductor industry has a profound impact on Japanese society, economy

and environment through both its 'visible impact' and 'invisible impact.'"*[2] In addition, with the full-fledged introduction of information and telecommunications technologies in the future, the quantity of information in Japan is expected to experience explosive growth (the "information explosion"). It is estimated that in 2025, 100 to 200 times the current amount of information will be exchanged over the Internet. It has been pointed out that, in order to deal with this information explosion, the number of IT units to process this information must be greatly increased, and the information throughput of each unit will increase dramatically, and the rapid increase in the power consumption of IT units in the future will become a serious problem.*[3] In addition, according to estimates by a private research institute,*[4] by 2020 the quantity of global information is expected to grow to approximately 40 zettabytes (approximately 50 times the quantity in FY 2010), and in order to process this ever-increasing information, integration and miniaturization of existing silicon devices will also become a vital trend in the future. With existing silicon devices, however, the increased power consumption of devices due to integration, the physical limits to miniaturization, the increased variations in characteristics and so on is becoming an urgent problem. The search for measures to overcome these restrictions has taken two approaches. One approach is to improve performance by employing nanoelectronics technologies, which have seen remarkable progress worldwide in recent years, in an effort to add materials and devices with new functions that are in line with existing complementary metal-oxide semiconductor (CMOS) technologies. The other approach is to achieve devices and systems based on new operating principles that go beyond conventional CMOS technologies.
Under these circumstances, rather than independent efforts to achieve miniaturization, increase speed, reduce power consumption or provide multiple functions, state-of-the-art nanotechnologies and other basic technologies are being mobilized in this Strategic Objective to create innovative "seeds" with the aim of establishing the foundation for the electronics industry of the future. The specific research projects that are being conducted are shown below. In this Strategic Objective, an organization must be established to enable specialists in each field (materials, devices, systems etc.) to coordinate and collaborate from the earliest stages of the project, in order to conduct strategic and agile research toward the achievement of the common goals of developing information devices that offer a double-digit or greater reduction in power consumption and a double-digit or greater increase in speed as compared to existing devices.

1) Creation of new functional materials that provide underlying support for innovative devices and development of basic technologies through the pursuit of possible applications

Examples
- Creation of measurement, analysis and processing technologies relating to the structure and physical properties of new functional materials
- Research into crystal growth, determination of functions and construction of scientific theory relating to graphene and other atomic thin films that are expected to find applications in innovative devices

2) Creation of innovative devices by means of new materials, new principles, logic devices of new structures, memory devices etc. that enable ultra-low power consumption, ultra-high speed, ultra-large integration, etc.

Examples
- Research into technologies for applying new materials and new functional materials with outstanding properties to devices
- Proposals for devices provided with new functions through integration of heterogeneous materials, etc. and proof of concepts
- Invention of innovative device architecture technologies that enable miniaturization and large integration

3) Integration, convergence and fusion of basic technologies such as those in 1) and 2) in order to create core technologies for achieving optimal nanosystem design

Examples

- Design of material structures and device structures to produce and optimize device functions and creation of computer simulation technologies
- Creation of ultra-low power consumption technologies through linkage and coordination of materials, circuits etc. at various technology layers

*1 World Semiconductor Trade Statistics (WSTS), "WSTS Semiconductor Market Forecast Autumn 2012," November 2012.
*2 Semiconductor Industry Research Institute Japan, "Social Science Analysis of the Impact of the Semiconductor Industry on Society, Economy and the Environment in Japan (Final Report)," July 2009.
*3 Ministry of Economy, Trade and Industry, "Workshop on Energy Conservation and Increased Competitiveness for Information and Telecommunications Equipment."
*4 International Data Corporation (IDC), "Big Data, Bigger Digital Shadows, and Biggest Growth in the Far East," December 2012.

Policy Positioning (positioning within the policy system and necessity/urgency in terms of policy etc.):
The 4th Science and Technology Basic Plan states that "...since information and telecommunication technologies are basic technologies in promoting energy supply, energy use, and low carbon generation from social infrastructure, R&D will be advanced with regard to next-generation information and telecommunication networks, further energy-savings for information and telecommunication equipment and system components, and technical development for optimized control of entire network systems." Moreover, under "Strengthening common infrastructure for the enhancement of industrial competitiveness," the Plan states that "R&D will be promoted into innovative common basic technologies, including basic technologies required for the development and utilization of advanced materials and components of high added-value, large market share or future growth potential. Japan has many technologies of high global competitiveness, and many basic technologies that support the utilization of high-performance electronic devices, information and telecommunications. Therefore, a strategy for appropriately opening up those technologies will be promoted."
Moreover, the "Action Plan for the Implementation of Important Science and Technology Policy Measures" (July 19, 2012, Special Subcommittee for the Promotion of Science and Technology Innovation Policy, Council for Science and Technology Policy (CTSP), Cabinet Office) lists "Innovation of energy use" aimed at achieving large-scale reductions in energy consumption as a policy issue, and establishes "Dramatic reduction in energy consumption through technical innovation" as a priority effort. In addition, the Key Issues and Efforts in the FY 2013 Priority Policy Package" (same as above) states that Japan should become the first country in the world to apply carbon nanotubes (first discovered by Japan) and graphene and other new nanocarbon materials to a variety of components and products (heat exchangers, batteries, electronic devices, composite materials etc.) to increase the industrial competitiveness of components, parts and products in a wide variety of industries and create new growth industries, and that for these and other reasons, "the application of carbon nanotubes (CNT), graphene and other new nanocarbon materials to a variety of fields and the development of technologies for commercial use" should be a priority effort aimed at increasing Japan's industrial competitiveness.
For these reasons, developing low energy consumption devices through the use of innovative materials is needed from a policy standpoint as well, in order to achieve the objectives of "Promotion of green innovation" and "Strengthening the industrial competitiveness of Japan."

Coordination with Related Policies, Division of Roles, and Differences in Policy Effects:
The achievements of efforts conducted up to now at universities and the like and existing Strategic Basic Research Programs, etc. should be actively utilized, and close coordination with related projects should be secured, in order to ensure that achievements are quickly turned into practical applications. Specifically, from the standpoint of establishing an industrial infrastructure for the electronics of the future, intellectual property relating to achievements produced in this Strategic Objective should be appropriately secured, even during the period of research, and then quickly deployed in industrial-academic collaboration projects and the like as well as private sector company projects whose aim is to

develop practical applications for research achievements. The framework of the Tsukuba Innovation Arena (TIA), which gathers together a wide range of researchers from industry, academia and government, and other research and development centers in particular, should be used to maximum advantage, in order to build an organization that can link basic research achievements in this Strategic Objective directly to increased industrial competitiveness for Japan.

Scientific Justification for the Research and Development Goals (need, urgency, achievability etc. based on domestic and international research trends):

"A Strategy for American Innovation" which was revised in February 2011 includes the expression "acceleration of nanotechnology" among its priority items and states that there is a need for investment in nano-electronics in particular. In addition, the EU has established Joint Technology Initiatives (JTI) to provide priority support for high-risk research that requires large quantities of funds on a long-term basis, in research domains for which there is clear support from the industrial world, and this Initiative includes "nano-electronics." In China, nanotechnology research is included as a key scientific research topic for basic research sectors in the National Outline for Medium and Long Term Science and Technology Development Planning (2005 - 2020), and "Notional and principle-oriented nanodevices, nano-electronics, nano-biology and nano-medicine" are listed among the specific priority issues.

The status of Japan, based on an international comparison with various foreign countries, has been assessed as follows. "In terms of nano-electronics, Japan maintains a high level overall, but based on a comparison of activity worldwide, optimism is not necessarily warranted. Particularly in the area of nano-CMOS technology which drives the field of nano-electronics, there has been a significant drop in research and development activity on the part of Japanese manufacturers — this at a time when the establishment of research and development centers and alliances is progressing worldwide. The fact that basic research and development on the part of academia has lagged as compared to other countries is particularly serious. Unless human resources development measures and systems for industry-academia cooperation are established from a long-term perspective, ultimately Japan will be unavoidably overtaken by South Korea or China." *[1]

In the light of this situation, progress in nanoelectronics research and development in this Strategic Objective that results in the achievement of more compact devices with greatly reduced power consumption and new functions will be needed in order to achieve the low power consumption systems that will be indispensable for the age of "Big Data," as well as increased competitiveness for the electronics industry and other sectors.

*[1] JST Center for Research and Development Strategy, "International Comparison of Science and Technology & Research and Development 2009, Nanotechnology and Materials Field, 2011 Edition," 2011.

Background to Deliberations:

The Future Strategies for Science and Technology Workshop sponsored in March 2009 by JST/CRDS entitled "Nano-electronics, Opening up the Next Generation: Looking Beyond 2030" reconfirmed the importance of (1) research and development of nano-electronics core technologies to get around or break through the boundaries to miniaturization and integration, and (2) the search for new materials for nano-electronics devices and demonstration of the potential for application in devices. Based on the discussions at this workshop as well, a JST/CRDS Strategic Proposal entitled "Construction of Fundamental Technologies for Nanoelectronics: Towards a technological breakthrough overcoming limitations in scaling, integration and power consumption reduction" (July 2009) was formulated, calling for the need for long-term efforts to search for new principles, structures and materials and conduct research and development of devices for their use. With graphene and other two-dimensional thin films attracting a great deal of attention, a JST/CRDS Future Strategies for Science and Technology Workshop entitled "Creation and Development of Atomically Thin Functional Films and Molecular Thin Films" was held in February 2012, at which it was pointed out that the ideal way to minimize energy loss during electronic motion was through the use of thinnest-possible films — in other words, atomically thin films and molecular thin films. Based on the discussion at this workshop, a JST/CRDS Strategic Proposal entitled "Development of New Materials and Innovative Devices Using Atomically Thin 2D Functional Films" was formulated, recommending that the "creation of innovative device core technologies through atomically thin functional films that meet application needs" and the "creation of functional research and scientific principles for device design for atomically thin films with new structures to help radicalize 'seeds' technologies" as specific research and development issues.

Based on these discussions, the "Research and Development Policy for Nanotechnology and Material Science Technologies (Interim Report)" (July 2011) prepared by the Nanotechnology/Material Committee under the Research Program and Evaluation Subcommittee of the Council for Science and Technology established "Reducing energy consumption and achieving multifunctional capabilities for electronics" as a priority research and development issue in order to resolve problems, and indicated that it was important to improve energy-saving performance and accelerate research and development efforts with a view to the global competitive environment. In addition, the interim report entitled "Policy for Promoting Research and Development in the Field of Information Science Technologies" (September 2011) compiled by the Committee on Scientific and Technical Information (CSTI) listed "Ultra-low power consumption (greening) of IT systems" as an approach that would be needed in the future for information science technologies. Subsequently, ongoing discussions have been held by the two committees.

The objectives for this Strategic Objective will be prepared based on the results of these studies.

Other:

With countries around the world currently engaged in fierce competition, it is essential for Japan to use its accumulated academic, technical and human resources to maximum advantage, working in cooperation with the Tsukuba Innovation Arena (TIA) and other global centers for concentrated industrial, academic and government collaboration, to build organizations that can link the achievements of basic research in this Strategic Objective directly to the strengthening of Japan's industrial competitiveness. To this end, the achievements of efforts at universities, etc. up to now and existing Strategic Basic Research Programs must be actively used, and close cooperation among related projects must be maintained, in order to quickly turn these achievements into practical applications.

7.16 Development of intelligent information processing technology to realize creative collaboration between human and machines

Targets to Achieve:

This program builds a new research area based mainly on information science and technology (related to intelligent information processing technology) in collaboration with disciplines of cognitive science and robotics (intelligence/control system), and aims to achieve the following targets in order to develop comprehensive intelligent information processing technologies that realize creative collaboration between human and machines.

○ Development of intelligent information processing technologies for realization of interaction in response to situation and conversation context
○ Clarification of the mechanisms of interaction, work, etc., and development of technologies for development of intelligent information processing system which realizes creative collaboration between human and machines

Vision for Reaching Achievable Important Goals in the Future:

Under this strategic objective, obtaining the research results described in "Targets to Achieve" above enables clarification and technology development regarding followings that have not been clarified by the current intelligent information processing technologies, and by integrating developed technologies, a new intelligent information processing technology will be created.

- Intelligent information processing technology for realization of interaction in response to situation and conversation context
- Clarification of the mechanisms of interaction, work, etc., and development of technologies for development of intelligent information processing system which realizes creative collaboration between human and machines

After the completion of this project, by deploying and advancing the research outcome in a demonstrative manner, the following intelligent information processing systems will be developed by around 2025.

- Advanced question answering/advisory system (for support of the elderly, individualized education, diagnosis support for doctors, etc.)
- Advanced decision-making support system (for support of discussion for experts, support of policy/system design, etc.)
- Autonomous robot (emulation of human works, disaster relief, support of caregivers, etc.)

The intelligent information processing systems, such as listed above will lead to building of an ambient information society and contribute to realization of safe, affluent and high-quality life which is one of the key issues in Japan, creation of new knowledge, generation of new industries and services through innovations.

Specific Content:

(Background)

In the complicated society, humans perform a variety of intelligent activities, such as adequate problem solving, creative activities, etc. based on various information and value judgment. In the field of cognitive science, clarification of the principle of human intelligent processing is underway and in the field of robotics development and practical use of task achievement type robots are being carried out.

In the development of intelligent information processing technology at present, research and development are underway by individual tasks, such as voice recognition, natural language processing, voice interaction, etc. By adding the approaches of cognitive science and robotics (intelligence/control system) to the current approach, a collaborative research system that produces synergistic effects can be created. Additionally, integration of research studies from different fields raises the expectation for creation of innovation.

(Research Theme)

In order to achieve "Targets to Achieve" as described above, this strategic objective aims to build a collaborative research system which consists of the researchers of information science and technology (related to intelligent information processing technology) as its core and the researchers from cognitive science and robotics (intelligence/control system) to develop an comprehensive intelligent information processing technology to realize creative collaboration between human and machines. Specifically, the following research studies are supposed.

1) Development of intelligent information processing technologies for realization of interaction in response to situation and conversation context

- Technologies for understanding the situation of human by nonverbal information, such as peripheral

environment of a specific person, the behaviors of a person during interaction (attitude, voice inflection, wording, etc.)
- Technologies for understanding the words from human by generating various meanings and interpretations and adding deductions based on situation and conversation context
- Technologies of information representation generation and timing control for realizing adequate interaction based on the characteristics of a person (character, habit, etc.)

2) Clarification of the mechanisms of interaction, work, etc., and development of technologies for development of intelligent information processing system which realizes creative collaboration between human and machines
- Technologies for reducing ambiguity and defining problems to be solved through interaction
- Technologies for effectively providing humans with solutions, such as answer, proposal, and advice etc. based on the information machine obtained through interaction and/or on the Web
- Information system that behaves adaptively at a semantic level, including the interaction process between human and machines

Note that, as for the development of comprehensive intelligent information processing technology, it is required to incorporate advices and proposals from researchers of the related fields of humanity and sociology at the research and development phase to consider ethical, legal, and social issues.

Policy Positioning (positioning within the policy system and necessity/urgency in terms of policy etc.):

The 4th Science and Technology Basic Plan (Cabinet Decision on August 19, 2011) states, as "Improvements in affluence of citizens' life" in "Realization of a safe, affluent and high-quality life," that 'Toward the realization of true affluence in citizens' life, efforts shall be promoted that contribute to the improvement of quality and affluence of life through science and technology, such as improvement/enrichment of public/private services and enrichment/deepening of people-to-people links etc. using science and technology of the latest information and communications technology.' Also, it states, as "Enrichment and enhancement of common bases for science and technology infrastructures," that 'Research and development shall be promoted for science and technology that can be utilized over multiple fields in a cross-sectional manner and science and technology of interdisciplinary areas.'

The Comprehensive Strategy on Science, Technology and Innovation (Cabinet Decision on June 7, 2013) states, as "Realizing the base for next-generation infrastructures" in "Development of next generation infrastructures as a top-runner in the world," that 'Various infrastructures will be organically and efficiently interlinked, allowing smooth distribution and circulation of data and information. By taking account of the latent needs by the general public and companies, it is anticipated that the QOL of the general public will be improved and the economic activities of companies will be promoted. As a result, a society will be materialized where people can sense safety, security, and affluence in their life.'

The Japan Revitalization Strategy – JAPAN is BACK – (Cabinet Decision on June 14, 2013) states, in "Realizing safe/convenient life environment through IT utilization," that 'In order to realize society where people can live safely/conveniently by utilizing big data, etc., the government will make efforts to solve important cross-sectional issues by utilizing IT through collaboration among relevant ministries.'

The Declaration to be the World's Most Advanced IT Nation – New IT Strategy under the Second Abe Administration (Cabinet Decision on June 14, 2013) states, in "Encouraging research and development and collaboration among the results of research and development," that 'It will be necessary to conduct research and development while monitoring developments in the telecommunications-based society and to promptly and accurately link the results of research with IT strategies so that cutting-edge technologies that lead to innovations.'

Coordination with Related Policies, Division of Roles, and Differences in Policy Effects:

Japan Science and Technology Agency (JST), CREST "Creation of Human-Harmonized Information Technology for Convivial Society" (started in FY 2009) aims to build the basic technologies to realize "harmonious interaction of human and information environments" through fusion and integration of elementary technologies, such as real-space communication, human interface and media processing. Additionally, JST PRESTO "Information Environment and Humans" (started in FY 2009) aims at ubiquitous computing, evaluation research on intelligent functions for users such as usability testing and statistical analysis, and networking research on intelligent functions. Meanwhile, this strategic objective aims at not only human-machine interfaces, but also improvement of the quality of human intelligent activities, realization of creative collaboration between human and machines, and building of support tools and common fundamental technologies for human intelligent activities by extracting "knowledge" from information. Therefore, synergetic effects are expected from this effort through collaboration with other related policies.

Scientific Justification for the Research and Development Goals (need, urgency, achievability etc. based on domestic and international research trends)

In Europe, the EU's Seventh Framework Programme for Research and Technological Development (FP7) took up the natural language analysis technology as one of the Work Programs and an annual budget of 50 million euro (approx. 6.5 billion yen) has been allocated to projects, such as interoperation of language analysis tools and machine translation as related efforts.

Also, in the United States, the DARPA has set natural language processing and technology for understanding of deep meaning of image as its key targets and huge amounts of budget are allocated for programs, such as the Machine Reading Program (20 million dollar or approx. 2 billion yen per year). Additionally, giant IT companies, such as Google, Amazon, Apple and IBM are not only overwhelming the world by the IT business, but also leading the world in the information and communications technologies through the most advanced research and development. In particular, as for the fields related to the intelligent information processing technology, IBM developed its question answering system "Watson" and beat the world chess champion at the time in 1997. In 2011, Watson produced results, such as overall victory over human in a quiz program "Jeopardy!" Furthermore, IBM announced in January 2014 it would invest one billion dollar to make "Watson" as a full-fledged business. Now it plans to apply the business not only to diagnosis support system for doctors, but also to a wide range of businesses, such as finance, retailing, and public offices.

In Japan, as an interdisciplinary effort for the realization of intelligent ICT, there is the "Can a Robot Get into the University of Tokyo?" project by the National Institute of Informatics. This is an attempt to realize a comprehensive AI that can pass the entrance examination at a level of the University of Tokyo without the help of human. In the development of intelligent information processing technology at present in Japan, research and development are underway by individual tasks, such as voice recognition and natural language processing to realize human intelligent activities. Therefore, in order to apply intelligent ICT to the society, research and development efforts in a human-participation-type framework in which creative collaboration between human and machines is realized becomes important in the future.

If we continue to allow a huge lead of the United States and Europe as they are in the research and development of intelligent information processing technology, we will fall behind in the speed of research and development in all the academic and technological fields and this will affect the national strength of Japan. Therefore, we should not waste a minute in the research and development.

Background to Deliberations:

In an overview activity over the information science and technology field by JST's Center for Research and Development Strategy (CRDS), intelligent information processing technology, cyber-physical system, and big data were selected as three key items of the research and development emerging to create new social values. Then, for the intelligent information processing technology, a core member meeting by expert was held (in April 2013) and the contents to be addressed in this strategic objective were discussed.

In July 2013, the CRDS held the Workshop for Future Strategy of Science and Technology with domestic and foreign expert attendees. The contents of the effort were refined, and interdisciplinary collaboration and the community of researchers were strengthened there. In this workshop, several proposals were made, such as the creation of intelligent information processing system, collaboration of human and machines, and building of a knowledge system to stimulate human in order to increase people related to, intelligent activities.

This strategic objective was prepared based on the results through these considerations.

Other

When implementing this research and development, it is necessary to form a comprehensive research system so that each research team will not only develop its independent elementary technology throughout the project.

Additionally, since this project aims to create a new intelligent information processing technology by integrating the developed technologies and to develop intelligent information processing systems after the completion of the project, it is important to promote the research areas so that the services of specific fields can be demonstrated as the results of research and development.

7.17 Creation, advancement, and systematization of innovative information technologies and their underlying mathematical methodologies for obtaining new knowledge and insight from use of big data across different fields

Targets to Achieve:

This program, by carrying out research in collaboration between the information science/mathematical science fields and various research fields (application fields) that are having a major impact on society by utilization of big data, aims to create and advance next-generation application technologies that, by solving issues in the application fields, can obtain new knowledge and insight from big data; and it further aims to build common core technologies enabling integrated analysis of big data from a variety of fields. To these ends the program aims to achieve the following targets.

○ Creation and advancement of next-generation core application technology that, while promoting use of big data in individual application fields, assumes expansion to a variety of fields

○ Creation, advancement, and systematization of next-generation core technology for integrated analysis of big data from a variety of fields

Vision for Reaching Achievable Important Goals in the Future:

By achieving the research results stated in the Section "Targets to Achieve" for this Strategic Objective, it is possible to construct common core technologies for integrated analysis of big data from a variety of fields and realizes the use of big data across fields. Using the constructed technology would enable the high-degree application of academic paper data in research fields where use of big data is effective, experimental/simulation data, and observation data; this in turn would enable acceleration of generation of innovation in integrated fields combining multiple different areas, including social sciences and humanities.

Following completion of this project, the aim is to realize the following, for example, through the promotion of research and development and practical application using common core technologies enabling integrated analysis of big data in various fields by academia and industry.

- In the field of life science, establish order-made medical care, early diagnosis, and effective treatment methods using efficient techniques for seeking disease-associated genes utilizing whole-genome data for 100,000 people (3 billion base pairs) linked to treatment information.
- In the global environment field, establish basic information technology that connects the relationships between different data—such as global warming; natural environment issues such as forest and water cycles, ecosystems, and geographical space—at a high level in order to contribute to the resolution of global-scale issues in which various factors are complexly intertwined and create a sustainable society.
- In the field of disaster prevention, promote strengthening of exhaustive disaster prediction and disaster prevention functions as well as optimal planning methods for cities using technology that accumulates and structures meteorological data obtained from disasters and accidents as well as geospatial data in a form that can be easily analyzed.

The aim of this Strategic Objective is to, by realizing the above, create new industries and markets through innovation and promote the strengthening of Japan's international competitiveness, as well as contribute to the achievement of "strengthening the industrial competitiveness of Japan" and "development of research information infrastructure" as prescribed in the 4th Science and Technology Basic Plan (approved by the Cabinet on August 19, 2011).

Specific Content:

With the progression of the advanced information society, we have arrived in the era of big data (information explosion) in which digital data is increasing explosively. According to statistics compiled by a private-sector survey institution, [*1] the amount of digital data worldwide is expected to grow to approximately 35 zettabytes in 2020 (approximately 35 times the amount in FY2010). Furthermore, according to a survey conducted by the Institute for Information and Communication Policy,[*2] the amount of data distributed in Japan in FY 2009 was 7.61E21 bits (equivalent to approximately 290 million DVDs per day) (for example, E18 bits indicates that a bit is 10 to the power of

18), but the amount of data consumed was 2.87E17 bits (equivalent to approximately 11,000 DVDs per day), and so it is said that the amount of information consumed is only 0.004% of the amount distributed.

While this qualitative and quantitative flood of data (big data) enables the acquisition of new knowledge and insight, when attempting to combine various data (a diversity of data ranging from natural science data such as bio and astronomical observations to social science data on human observations) and process it on a large scale, in many cases there is a large amount of unanticipated data and data that cannot be analyzed correctly, and so the current situation is that much of this data is not organized or structured and cannot be utilized effectively.

For this reason, there is growing international awareness of the importance of effectively and efficiently collecting and consolidating this data as well as discovering new knowledge and creating new value through innovative scientific methods. Alongside the first scientific method of empirical science (experiments), second scientific method of theoretical science, and third scientific method of computational science (simulations), data centric science (=e-science) is said to be the fourth scientific method,[*3] and is gaining attention as a method for opening up new scientific frontiers in the big data era.

This Strategic Objective aims to realize two objectives to be achieved in order to conduct research and development of innovative methodologies for smoothly carrying out big data analysis. Specifically, the following research is being pursued.

(1) Creation and advancement of next-generation core application technology that, while promoting use of big data in individual application fields, anticipates expansion to a variety of fields

In addition to resolving issues in individual application fields, strengthening of the expansion of individual technologies into other fields and the introduction of new core elements are being promoted. For this reason, it is expected that systems of cooperative research teams comprising researchers in the fields of information science/mathematical sciences and application will be created. Specifically, the following research is being promoted.

- Research and development aimed at easy realization of the transfer, compression, and storage of a large amount of diverse data (health/medicine data, earth observation data, disaster prevention-related data, social data, etc.)
- Research and development aimed at extracting significant information by searching, comparing, and analyzing image data, three-dimensional data, and various other data
- Research and development aimed at more accurately discovering and gaining insight into new topics from application data (clarification of disease factors, forecasting climatic changes, disaster mitigation using real time analysis, forecasting people's needs, etc.)
- Establishment of research and development infrastructure for promoting a heuristic search-style research approach that provides new knowledge or expertise by constructing a diversity of mathematical models related to living organisms and natural phenomena, etc., from quantitative data and combining this with actual measurement data.

(2) Creation, advancement, and systematization of next-generation core technology for integrated analysis of big data from a variety of fields

Development of new and original core elemental technologies and of new elemental technologies that spread across multiple application fields by researchers in the fields of information science, mathematical sciences, and humanities is carried out. Specifically, the following research is being pursued.

- Data cleansing technology (noise removal, data normalization, absorption of unnecessary data changes, etc.) and technology that automatically creates annotations of meaning or content of data
- Advanced compression technology, technology enabling searches to be made for data while still compressed, technology enabling data mining without losing confidentiality or anonymity
- Upgrading of data mining technology and machine learning (technology for modeling from large amounts of diverse data, technology for searching for relationships between different types of data)
- Visualization technology for gaining insights from the correlations and relationships between various application data
- System technology for sharing and distributing big data (data processing, metadata management, traceability, creating anonymity, charging, security, etc.)

- Mathematical and computational methods for discovering the essence of issues and structure of big data

In addition, in (1) creating and advancing next-generation core application technology, it is effective to proceed while also incorporating next-generation core technology obtained through the research conducted in (2); moreover, in (2) creating, advancing, and systematizing next-generation core technology, it is effective to proceed while also sharing and utilizing next-generation application technology obtained through the research conducted in (1). For this reason, the research conducted in (1) and (2) needs to be mutually coordinated.

*1 IDC, "Big Data, Bigger Digital Shadows, and Biggest Growth in the Far East", December 2012

*2 Institute for Information and Communication Policy Survey Division, "Results of Survey Research on the State of Japan's Information and Telecommunications Market and Measurement of Information Distribution Amounts (FY2009): Measurement of Information Indexes", August 2011

*3 Tony Hey, Stewart Tansley, and Kristin Tolle. *The Fourth Paradigm: Data-intensive Scientific Discovery* (Microsoft Research 2009)

Policy Positioning (positioning within the policy system and necessity/urgency in terms of policy etc.)

Under the section "Responses to Essential Issues Facing Japan" in the 4th Science and Technology Basic Plan, promoting research and development of innovative common core technologies such as core technologies for supporting the utilization and application of electronic devices and information-telecommunications, as well as promoting strategies for appropriately opening up these technologies are given as means of "strengthening the industrial competitiveness of Japan". Furthermore, promoting research and development related to advanced information and communication technologies such as simulation and e-science, science and technology that can be applied across multiple fields such as mathematical science, and science and technology for integrated fields is given as a means of "improvement and reinforcement of common infrastructure for Science and Technology". In addition, under the section "Enhancement of Basic Research and Human Resource Development", constructing and expanding "knowledge infrastructure" systems that enable integrated searching of and data extraction from all research information in order to promote efforts to strengthen research information infrastructure is given as a means of "development of research information infrastructure".

In order to promote the necessary discussion and consideration of "academic clouds", which enable researchers at universities and other institutions nationwide to easily access online and utilize data, information, and research materials from many fields that can be applied to scientific research and use the latest "data science" methods to obtain scientifically or socially significant research results, the Ministry of Education, Culture, Sports, Science and Technology established the "Conference for Reviewing Academic Clouds" under the Director-General of the Research Promotion Bureau. From April through June 2012, three topics for consideration were discussed—"Coordination of databases", "Construction of system environments", and "Research and development contributing to the enhancement of data science"; proposed in July, the "Challenges for Academia in the Era of Big Data" summarized the direction that research and development of core technologies is important at each stage of big data processing (data collection, accumulation/structuring, analysis/processing, and visualization) as research and development of common core technologies related to big data.

Coordination with Related Policies, Division of Roles, and Differences in Policy Effects

In October 2012, the Minister of State for Science and Technology Policy and executive members of the Council for Science and Technology Policy selected "FY2013 Science and Technology Budget Priority Policy Packages" and the "Improvement of infrastructure aimed at generating new industries and innovation using big data" proposal made jointly by three ministries—the Ministry of Internal Affairs and Communications; Ministry of Education, Culture, Sports, Science and Technology; and Ministry of Economy, Trade and Industry—was identified as a priority policy package that should be prioritized for resource allocation. Under this priority policy package, the three ministries will collaborate to promote in an integrated manner human resources training as well as research and development of core technologies related to the collection, transfer, processing, usage/application, and analysis of big data in certain fields aimed at realizing these technologies by around 2016.

Of these three ministries, the Ministry of Education, Culture, Sports, Science and Technology has positioned one of its Research and Development for Next-generation Information Technology programs, "Research on Systems for Utilizing and Applying Big Data" as an individual priority within the priority policy package. In addition to promoting human resources training of data scientists and other specialists through international cooperation using research centers integrating different scientific fields, this program conducts investigations of issues concerning the development of technologies such as data-related technologies and the ways academic cloud environments (environments for coordinating and sharing cloud bases between universities) are constructed. Furthermore, in order to construct models for utilizing big data, the Japan Science and Technology Agency is endeavoring to dig up enormous amounts of data that is lying idle and improving rules in order to promote database coordination amongst research organizations and usage of databases by the privates sector, etc. In addition to the above policies, research and development aimed at the advancement and systemization of common core technologies aimed towards the resolution of next-generation issues from a medium- to long-term perspective is undertaken under this Strategic Objective to enable the usage and application of big data across fields.

Furthermore, in May 2012, the ICT Basic Strategy Board of Information and Communications Council, Ministry of Internal Affairs and Communications, summarized "Usage of Big Data", remarking that, since construction of information/communication infrastructure is underway, this infrastructure test bed (JGN-X) constructed and operated by the National Institute of Information and Communications Technology (NICT), may also be used as necessary when promoting research in this Strategic Objective.

Scientific Justification for the Research and Development Goals (need, urgency, achievability etc. based on domestic and international research trends)

In the United States, the President's Committee of Advisors on Science and Technology (PCAST) determined in 2011 that the Federal Government's investment in big data technology was insufficient, and in response, the Office of Science and Technology Policy (OSTP) announced a Big Data Research and Development Initiative on March 29, 2012. This initiative aims to improve and strengthen technology for accessing and organizing data and gleaning discoveries through a total investment of 200 million US dollars by 6 Federal departments and agencies (NSF, NIH, DOD, DARPA, DOE, and USGS). In Europe and Asia, too, investment is being made in big data research, and intense international competition is expected in the future. Specifically, in Europe public expenditure for ICT research and development is being doubled from 5.5 billion euros to 11 billion euros by 2020 and large-scale pilot projects are being carried out as part of endeavors to develop innovative and interoperable solutions in fields that are of public interest (ICT for conserving energy and resources, sustainable healthcare, electronic government, and intelligent transportation systems, etc.). Furthermore, in China centers have been established for sharing information resources, and technology is being developed for creating metadata and automatic classification in order to establish mutual relationships between collected data. In addition, South Korea is to commence construction in 2013 of a National Scientific Data Center for promoting sharing of research data, including big data, and data science. Consequently, there is an urgent need for research and development advancing the use and application of big data across fields with the aim of promoting innovation in the science and technology field through collaboration that transcends the division of roles between the public and private sectors as well as ministerial and agency frameworks.

In Japan, various types of sensor information are evolving and there are related research fields where the standard of research is world-class, such as high-performance computing and natural language processing; efforts are also being undertaken in fields that handle large-scale data requiring research in regional units, such as genetic information. For these reasons, expanding these strengths into a broad range of fields and areas when utilizing large-scale data creates an environment in which common core technologies in science and technology as well as industrial competitiveness can be strengthened.

Background to Deliberations:

The "Conference for Reviewing Academic Clouds" established under the Director-General of the Research Promotion Bureau of the Ministry of Education, Culture, Sports, Science and Technology summarized the "Challenges for

Academia in the Era of Big Data", proposed on July 4, 2012, as well as specific research and development items and the direction that research and development of core technologies is necessary at each stage of big data processing (data collection, accumulation/structuring, analysis/processing, and visualization) for research and development of common core technologies related to big data.

Based on this, the Committee on Information Science and Technology, operated under the Subdivision on R&D Planning and Evaluation, Council for Science and Technology (77^{th} and 78^{th} sessions) (July 5 and August 2, 2012) also expressed the opinion that research and development of common core technologies for utilizing and applying big data is necessary based on shared awareness of the importance of "data science" that creates new intellectual value through the efficient and effective gathering and accumulation of large quantities of data generated as the results of intellectual activity in various fields and processing of information using innovative scientific methods.

Furthermore, the "Mathematical Innovation Strategies (Interim Report)", which was compiled by the Advanced Research Base Working Group of the Council for Science and Technology (5th session) (August 7, 2012), states that, in order to develop innovative methods and technologies for effectively utilizing big data, it is important that not only do mathematical researchers proactively collaborate with researchers in information science fields and various areas of application but also that the diverse knowledge and potential of mathematical researchers themselves is fully utilized and efforts are made to create common core technologies for identifying essence and structure for efficiently utilizing big data.

This Strategic Objective was formulated based on consideration of the above factors.

Other:

In promoting this Strategic Objective, it is expected that the creation of flexible networks for researchers in big data-related fields and the construction of new human resource training schemes and innovation-generating cycles (environments in which innovation is constantly being created) will also be pursued through the fusion of information/mathematical science fields and various research fields in which big data is effectively utilized.

7.18 Establishment of molecular technology, which is the free control of molecules to bring innovation to environmental and energy materials, electronic materials, and health and medical materials

Targets to Achieve:

Establishment of molecular technology is to be achieved, which is a series of techniques to exploit fully features of molecules to create the desired functions by designing, synthesizing, operating, controlling, and integrating molecules on the basis of scientific findings in fields of physics, chemistry, biology, mathematics, etc. For this, the following technology systems are established, which are basic technologies to realize super-low-power consuming and ultra-light devices utilizing molecules for battery device, organic thin-film solar cells, and etc. and to establish innovative methods of treatment such as drug delivery systems, functional medical materials, etc.

- Establishment of technology systems of *molecular technology for designing and creating molecules*, which freely design and create new functional materials in cooperation with precision synthesizing technology and the theory-computational science.
- Establishment of technology systems of *molecular technology for shapes and structure control*, which leads to creation of new functions through accurately control molecular shape and structure.

Vision Reaching Achievable Important Goals in Future:

As represented by organic EL displays, various parts and devices are already shifting to soft materials, which are molecular materials. This trend implicates that soft materials gives fundamental solutions to issues that the entire human society faces, such as the reduction of environmental burdens, responses to restricted resources, and high biocompatibility; in other words, molecular technologies that realize soft materials give solutions to such problems.

Under this Strategic Objective, obtaining research outcomes described in section "Targets to Achieve" enables the designs of functions as molecular materials, which consequently enables the application of the outcomes to solving a variety of problems associated with social needs. Green innovation and life innovation described in the 4th Science and Technology Basic Plan are to be promoted by building a cooperative structure between research of relevant academic fields and industries. For example, efforts will be made to achieve the following outcomes within about five years after the completion of projects.

- **Electronic devices build with soft materials**

  Organic materials with conductivity control capability are used as components of electronic devices in place of the conventional semiconductors and metals, and computers with low environmental burden and ultra-low energy consumption and ultra-light portable information terminals are created.
- **Resource-recycling solar cell films with ultra-low energy consumption**

  Solar cells that are ultra low cost and produce low environmental burdens are created with components that use molecular materials and conversion of manufacturing processes.
- **Medical treatments using drug delivery system, etc.**

  Safe and effective medical treatments are realized through the development of sophisticated drug delivery system equipped with detection functions and functions to regulate the discharge of active ingredients and three-dimensional structuring of functional medical materials needed for regeneration of tissues and organs.

Besides these aspects, practical applications in fields such as reduced use of fossil resources, high-density secondary cells, advanced environmental monitoring, low-cost water production, and purification are possible.

Specific Content:

(Background) From molecular science to molecular *technology*!

In the recent years, for instance, the use of thin membrane, n-type semiconductor made with molecular called fullerene is resulting in rapid progress in the development of organic solar cells that are receiving attention as power generation technologies with low environmental burdens. Meanwhile, in the field of pharmaceutical development, designing molecular structures and shapes with computers has drastically reduced side effects and enabled the production of molecularly targeted agents that specifically work on lesions.

Basic science called molecular science exists in the background of such achievements. Conventional molecular science has discovered and analyzed various molecules by observing and exploring in nature and obtained similar functions as natural molecules by artificially mimicking their features. With the rapid progress in computer performances and drastic progress of measurement and analytical technologies in the recent trends, however, research and development that design intended functions and obtain suitable materials without seeking models in nature have emerged.

Given these circumstances, this Strategic Objective aims to deliver a radical breakthrough to the series of material development technologies that support environmental and energy technologies, information communication technologies, and medical material technologies by developing molecular technology.

(Contents of study) For the establishment of basic technologies shared by life innovation and green innovation!

In order to produce innovative outcomes involved with green innovation and life innovation, this Strategic Objective aims to accelerate research and development of individual policies and fusion of different fields by building a solid foundation of molecular technologies that can be applied to a various fields separately from research and development in individual tasks of application. Research and development of molecular technologies cannot be easily implemented only by using the knowledge of independent academic fields, such as conventional chemistry, physics, biology, and mathematics. Thus, it is important to recognize the bottleneck in the tasks of application as a common problem and establish a system that overcomes this problem through the approach which integrates different fields. This Strategic Objective perceives molecular technologies as the technology consisting of the following six elemental technologies. 1) Molecular technology for design and creation, 2) molecular technology for controlling shapes and structures and 3) molecular technology for conversion and processes, which are trans-boundary technologies. Then, 4) molecular technology for controlling electronic state, 5) molecular technology for controlling aggregations and compounds and 6) molecular technology for controlling transportation and transfer, which are intended for the use in a specific field of application. This Strategic Objective specifically puts emphasis on *molecular technology for design and creation* and *molecular technology for controlling shapes and structures*, which are the most basic of all these technologies. Examples of specific topics of research and development are described below.

- **Molecular technology for design and creation**

  Molecular technology for design and creation is the technology that aims to freely design and create new functional materials. In other words, in addition to the conventional method that largely depends on instincts and experiences, this technology gives governing principles to freely design and synthesize materials which have the target functions through tight cooperation between syntheses and theoretical analyses.

  (Examples of topics of research and development)

- Production of theories for creating molecules from functions and development of simulation technologies
- Cultivation of molecular design methods which enables forecasting of molecular structures
- Development of methods for precision syntheses based on functional designs and forecasting
- Development of high-purity purification method of molecular substances

- **Molecular technology for controlling shapes and structures**

  Molecular technology for controlling shapes and structures freely creates one-dimensional, two-dimensional, and three-dimensional macro structures for building practical materials based on molecular-level nano structures produced from molecular sequences, molecular assemblies, and self-organization. This technology also leads to the production of new functions by tightly controlling molecular shapes and structures.

  (Examples of topics of research and development)

- Technologies to create spatial and pore structures through build-up and top-down methods including self-organization
- Technologies to expand sizes from nano to macro structures
- Observation and analytical technologies of physical phenomena in materials consisting of macro structures
- Designs and analyses of macro-level structures and functions using computer simulations

Policy Positioning (positioning within the policy system and necessity/urgency in terms of policy etc.):

Soft materials produced by molecular technologies have various capabilities that satisfy various tasks of the 21st century, such as low environmental burden, energy and resource efficiency, low cost, and compatibility with the people and the society. The greatest goal of this Strategic Objective is to solidify the position of molecular technologies that realize these aspects as the basic technology of Japan. Industries with added values that molecular technologies produce will support the economic growth of Japan and make great contributions to solving problems such as global environmental and energy issues, safety and security issues, and medical and health issues.

The 4th Science and Technology Basic Plan (Cabinet decision on August 19, 2011) states, "Research and development concerning innovative common basic technologies with high rate of added values and market share, high possibility of future growth, and international competitiveness that favors Japan such as basic technologies needed for the development and use of cutting edge materials and basic technologies that support the use and utilization of advanced electronic devices and information and communication shall be promoted while promoting proper strategies to make these technologies open to others" in order to solidify common grounds for the reinforcement of industrial competitiveness. It also states, "Research and development shall be promoted on scientific technologies that can be horizontally used in multiple fields and science and technology of integrated fields such as nano-technology and photo quantum science which lead to development of advanced measurement and analysis technologies, advanced information communication technologies such as simulation and e-science, mathematical science, and system science technology" in order to strengthen cross-boundary scientific technologies. In addition, "Policies on research and development of nano-technology and material science technologies <interim summary>" (July 2011, Nano-Technology and Material Science and Technology Committee, the Subcommittee of Research Plan and Evaluation, the Council for Science and Technology) stipulates, "Development of innovative technologies is essential for remaining internationally competitive; thus, efforts such as research and development toward the production of potential possibilities should also be promoted based on the mid- to long-term perspectives rather than emphasizing on technologies which are available when setting up social issues." Molecular technology is listed as one of "technologies for designing and controlling substances and materials," which is a focused research and development task for solving problems.

Coordination with related policies, Division of Roles, and Differences in Policy Effects:

Policies that try to solve problems in individual application themes, such as solar battery, storage battery, and pharmaceutical development have been the mainstream. This Strategic Objective, however, is intended to reevaluate technical problems that have become bottlenecks in various fields using a cross-boundary technical concept called "molecular technology" and to promote joint studies by researchers from different fields. Molecular technology constructively reorganizes the achievements of basic sciences that Japan has been accumulated over many years and constructs an unprecedented and new technical structure. Contributions from basic sciences, such as physics, chemistry, biology, and mathematics as well as engineering fields such as nano-technology, information technology, and bio-technology are essential in the process of implementing and structuring molecular technology. These academic fields need to be integrated, and various technologies must be utilized as an integrated unit; therefore, these fields must be integrated at technological levels such as material design technologies and process technologies.

The Strategic Objective to be established in fiscal year 2012, "Advanced Catalytic Transformaiton program for Carbon utilization" plans to start a development of new catalyst for material conversion. This technology can supplement molecular technology for conversion and processes, which is an important elemental technology for establishing molecular technology and thus is expected to arrange necessary coordination.

Scientific Justification for the Research and Development Goals (need, urgency, achievability etc. based on domestic and international research trends):

This Strategic Objective is a new material technology strategy for Japan to take initiatives in contributing to solving problems such as environmental and energy problems and problems on medicine and health. Japan has strong material industries grounded on nano-technology and material science and is especially competitive in molecular technology as a part of this Strategic Objective. For example, Japan's market share for many molecular materials used in display products is overwhelmingly high in the global market. Neither Japan nor other countries has implemented strategic and comprehensive investment in research to academically explore fundamental aspects of this new technological field and improve its innovativeness. There is a possibility that Japan can lead the world if we worked on this field ahead of other countries.

Background to Deliberations:

The Center for Research and Development Strategy (CRDS) of Japan Science and Technology Agency held the Substance and Material Field Overview Workshop in July 2008 in which participants discussed outcomes of nano-technology, effects of integration, and future issues and proposed the establishment of the concept of molecular technology. The Science and Technology Future Strategy Workshop "Molecular Technology" was held in December 2009. This workshop aimed to discuss whether molecular technology could become an important key technology through intensive discussions of specialists and find future directions and specific research and development topics. Based on discussions in the workshop, participants further examined research domains and themes to be intensively promoted in the future and summarized the strategic initiative, "Molecular technology, production of new functions from the molecular level - Contribution to sustainable societies with the integration of different fields" in March 2010.

Based on above discussions, Nano-Technology and Material Science and Technology Committee, the Subcommittee of Research Plan and Evaluation, the Council for Science and Technology of Ministry of Education, Culture, Sports, Science and Technology listed molecular technology as one of "technologies for designing and controlling substances and materials," a focused research and development task for solving problems, in "Policies on research and development of nano-technology and material science technologies" prepared as an interim summary in July 2011.

This Strategic Objective was prepared based on the outcomes of these examinations.

Other:

The development of molecular technology requires the environment for researchers from different fields to actively participate and effectively work together. It is also important to perceive molecular technology as a common basic technology in precompetitive domains for expanding the outcomes of this Strategic Objective toward the establishment of molecular technology and to actively use places such as Tsukuba Innovation Arena for the cooperation among the industry, the academia, and the government.