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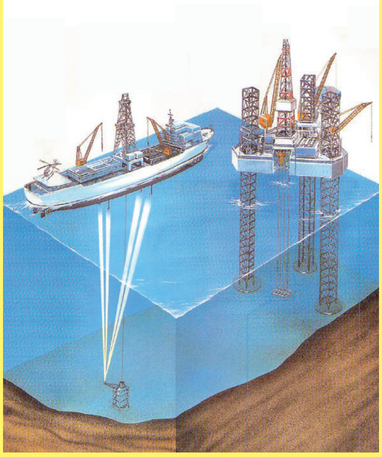

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Foreword

This is the latest issue of "Science and Technology Trends — Quarterly Review".

National Institute of Science and Technology Policy (NISTEP) established Science and Technology Foresight Center (STFC) in January 2001 to deepen analysis with inputting state-of-the-art science and technology trends. The mission of the center is to support national science and technology policy by providing policy makers with timely and comprehensive knowledge of important science and technology in Japan and in the world.

STFC has conducted regular surveys with support of around 2000 experts in the industrial, academic and public sectors who provide us with their information and opinions through STFC's expert network system. STFC has been publishing "Science and Technology Trends" (Japanese version) every month since April 2001. The first part of this monthly report introduces the latest topics in life science, ICT, environment, nanotechnology, materials science etc. that are collected through the expert network. The second part carries insight analysis by STFC researchers, which covers not only technological trends in specific areas but also other issues including government R&D budget and foreign countries' S&T policy. STFC also conducts foresight surveys periodically.

This quarterly review is the English version of insight analysis derived from recent three issues of "Science and Technology Trends" written in Japanese, and will be published every three month in principle. You can also see them on the NISTEP website.

We hope this could be useful to you and appreciate your comments and advices.

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Executive Summary

Life Sciences

1 Cognitive Robotics to Understand Human beings

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A long-standing mystery of the mind is that, although one's mind seems to be associated with one's physical body, its contents seem not to be expressed physically. As neuroscience advances, expectations are rising that many of the mental functions will be explained with brain activities. There is a need for research that creates brain algorithms through computational theory, combines knowledge of brain structure and functions obtained through external analysis with that acquired through psychophysical behavioral measurement, constructs models to represent phenomena that take place inside the brain, tests the validity and improves the accuracy of these algorithms, and explores the relationship between the brain and the mind.

Recently, comparisons of humans with computers and robots, detailed analyses of infant development and learning processes, and findings on the mechanisms for expressing emotions and understanding others' emotions have revealed that it is impossible to interpret human brain functions separately from the body, the existence of other individuals and interaction with environments and the world. Certain robotics researchers have launched constructions and reproductions of human functions on robots, which can be described as computers endowed with bodies that interact with the exterior world. Such attempts are becoming a powerful driving force for exploration of the mechanisms of the human mind and behaviour as well as human interaction with their conspecifics and the environment. To further promote such exploration and profound understanding of human beings, the new comprehensive field of "cognitive robotics" must be fostered, which unifies robotics, cognitive neuroscience, philosophy, the social sciences, and other diverse disciplines. In present Japan, human resources are scarce and research systems are weak in the theoretical and mathematical fields that link biology and the humanities with engineering. Since questions on the mind-body-environment relationships are the source of a wide range of disciplines across the humanities and natural sciences, they must be elucidated through cooperation of these disciplines.

Meanwhile, the initial phase of the development of humanoid robots for practical use has been completed, i.e. the structures and actuators that correspond to the body, and the computers to control them. The next major issue is the development of cognitive functions. Development of robots able to act autonomously in the real world requires a broad and systematic understanding of human beings and society. It is therefore very difficult for private firms and individual governmental departments, which pursue the realization of practical robots, to advance this fundamental and long-term research objective. Advances in fundamental cognitive robotics will largely contribute to the success of future development of practical robots. Government and industry should therefore jointly establish a research institute and boost research focused on the understanding of human beings, without asking researchers to contribute to the application.

The first issues studied in cognitive robotics are autonomous behaviour generated by unconscious cognitive processes, decision-making based on self-awareness, and the processes by which cooperative patterns of behaviour are generated through person-to-person interactions. These issues will have a significant impact on society. Scientific findings on the human mind and behavior are the common asset of humankind. This will spur even more serious debates than that when people argued "to whom does the human genome belong?" Japan should take leading roles in building a system to make all people worldwide share accurate knowledge. Particularly in the 21st century, applied technologies that utilize scientific findings on human cognitions or the control cognitive processes will no doubt bring advances to many fields, including economics, manufacturing, labor, entertainment, medicine, education, politics, and diplomacy. The spread of this sort of practical application must be preceded by a profound understanding of the mind as actually grasped by humans.

(Original Japanese version: published in March 2006)

Information and Communication Technologies

2 Technical Trends in Optical Interconnection Technology —Towards its Implementation in the "Keisoku" Supercomputer

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The race towards securing a competitive edge in supercomputing is gaining impetus, notably between the U.S. and Japan. The outcome will have significant ramifications for the progress of science and technology.The Japanese government is planning to launch a large-scale project to complete the development of a next generation "Keisoku" supercomputer, which will have a calculation capability of more than 10 PFLOPS, by FY2010.

One of the bottlenecks for this effort is the conventional hard-wired connection: implementation of hard-wired hardware for the next generation supercomputer is perceived as extremely difficult because of the enormous material resources required and the limited transmission rate that can be achieved. Optical interconnection is seen as the most powerful candidate qualified to resolve these difficulties. This technology can facilitate short-range communication (intra-chip, inter-chip, inter-board and inter-instrument) using opto-electronic devices and shows great promise in reducing the amount of hardware resources required and enhancing the achievable transmission rate.

Japan started a three-year optical interconnection project in 2005, aiming to develop elemental technologies in advance of the launch of the "Keisoku" supercomputer system project, the main target of which is the application of optical interconnection technology to resolve transmission bottlenecks in next generation computing, such as inter-node networks and CPU-memory connections.The U.S. has already commenced research on optical interconnection; a government initiative started in 2003. Japan has thus fallen behind in terms of device development.

The Japanese supercomputer project has hitherto lacked the continuity exemplified by the development history of the Earth Simulator. Such an isolated project cannot foster the continued development of elemental technologies. A long-rage strategy based on a well-laid roadmap is essential. The roadmap should be constructed in view of the major trends towards ubiquitous implementation of optical technologies in place of hard-wired circuitry. The grand strategy based on this roadmap naturally includes not only the supercomputer, but also ultra high-capacity routers since existing routers are facing the imminent need for a much higher transmission rate.

As is well evidenced by the fact that the level of supercomputer performance in past decades has already been incorporated in commercially available PCs, it is only a matter of time before hard-wired connections will be considered to be the bottleneck of these off-the-shelf products. It is fairly certain that, in the near future, optical interconnection will be an integral part of the CPU system. Intra/inter-chip connection requires a high level of elemental technologies that can give a long-standing, sustainable edge to the developer and may trigger a change in the market landscape. Thus, the enhancement of optical interconnection technology is a strategic move to maintain supremacy in the development of a next generation CPU and its peripheral devices, including memory.

Technological development of optical interconnection is still in its infancy. Timely investment in this area, based on a well-laid strategic roadmap, will amply reward the effort.

(Original Japanese version: published in January 2006)

Environmental Sciences

3 Prospects for Measures Against Pollinosis in Japan

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Pollinosis caused by cedar pollens was first reported more than 40 years ago at an academic conference held in 1963. The number of cedar pollinosis patients has increased ever since, and one in every five or six Japanese people is said to suffer from the allergy today. The total medical expenses directly or indirectly related to cedar pollinosis are estimated to reach 286 billion yen per year. Apparently, the most important factors responsible for the increase of cedar pollinosis are the increased pollen counts in the environment associated with the expansion of cedar and cypress forests, and the resulting increase in the strength and frequency of pollen exposure. The expansion of the area of cedar forests older than 30 years coincides with the increase in the number of cedar pollinosis patients since 1975.

At the end of the fiscal year 2004, the Council for Science and Technology Policy established a Research Committee on Measures Against Pollinosis comprising executives from relevant ministries and agencies (Ministry of Education, Culture, Sports, Science and Technology (MEXT), Ministry of Health, Labour and Welfare (MHLW), Ministry of Agriculture, Forestry and Fisheries (MAFF), Ministry of the Environment, and Japan Meteorological Agency), and experts on pollinosis to promote studies on measures against pollinosis. Among such efforts, those related to the measures against pollinosis can be broadly classified into pollen source control, exposure reduction, and prevention and treatment. The present article introduces the details of these measures, discusses effective pollen source control, and provides an evaluation of its validity as well as the problems concerning preventive and therapeutic measures against pollinosis.

For effective control of pollen sources, closer linkages must be established between pollen source control and the development of a pollen forecast system promoted by MAFF/ Forestry Agency and the Ministry of the Environment/ Japan Meteorological Agency, respectively. A map illustrating the degree of the contribution of cedar/ cypress forests in Japan to the pollen exposure of population groups needs to be produced, and the cedar/ cypress forests must be prioritized as targets for pollen source control. Moreover, the cost and the manpower required for the control must be estimated, and a road map for the entire policy must be produced. For exposure reduction, under existing conditions, it is difficult to predict the decrease in sensitization rate (pollen antibody prevalence) from the predicted decrease in pollen count as a result of pollen source control conducted in cedar/ cypress forests in a certain area. Thus, it is essential to promote studies on the relationship between pollen exposure and allergic reactions to pollens. Meanwhile, the results of high priority basic research on the new preventive and therapeutic methods currently in progress suggest that these methods have a high potential for practical application. In the future, they need to be tested in clinical trials in order to be approved as pharmaceutical drugs, which would require some research support. Joint development with pharmaceutical companies etc. will be essential for their practical application, and problems that may arise during such joint development should be clarified in advance.

Allergic diseases in general, including pollinosis, are showing a marked increase worldwide, although the increase in cedar pollinosis seems to have a unique background in Japan, i.e. the increase in the area of cedar/ cypress forests. Nevertheless, before starting individual research and development, first we must clearly define the position of the measures against cedar pollinosis in the prevention and treatment of allergic diseases in general.

(Original Japanese version: published in February 2006)

Nanotechnology and Materials

4 Trends in Materials Informatics in Research on Inorganic Materials

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A new data-driven development method called materials informatics is attracting attention in the field of inorganic materials science relating to ceramics, glass, and semiconductors. This method aims to accelerate materials development by organically combining information on synthetic processes for different materials and materials data.

Informatics is a method for building a new knowledge system by collecting and classifying information using information science. In the field of bioinformatics, developed earlier, automatic data analyzers have been used to process massive amounts of gene sequence data in order to compile genetic information databases and to carry out statistical analysis. Similarly, in the field of organic chemistry, it has been recognized that the use of combinatorial methods that allow the simultaneous synthesis of a large group of compounds by combination is an effective way to develop materials such as catalysts, and that informatics plays an important role in the analysis and utilization of the massive amounts of data produced for the development of new materials. In the field of inorganic materials research, however, materials informatics is still in the initial stages of development. One reason for this is that data in this field lack compatibility because the accumulated data formats used for such things as material characteristics and crystal structures are so diversified. Another reason is that each material has various aspects and characteristics that cannot always be simply represented digitally.

The different elements of materials informatics include: materials design using computer science and databases, preparation of synthetic experimental designs, automatic synthesis equipment for searching for new materials, high throughput screening, databases created from obtained data, sharing databases through the network, visualization of data, and data mining to predict future materials. Since so many different items need to be evaluated in materials research, it is sometimes difficult to share data that are obtained automatically by simple methods. To start with, it is necessary to share the information accumulated in databases between the servers of different research organizations so that the data are mutually complemented. This work cannot be done by a single organization and long-term domestic and international cooperation is required.

It is unfortunate that the importance of such work is not well recognized in Japan, compared with overseas countries. Since all manufacturing industries are based on the use of materials, we must recognize the importance of materials informatics in enabling innovative materials development and start the systematic accumulation of data, particularly that related to the research and development of inorganic materials.

(Original Japanese version: published in January 2006)

5 Dissemination of Nanosimulation Techniques to Promote the Development of Nanotechnology

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Materials and device design via computer simulations are now utilized across a wide range of industrial fields to facilitate efficient development of technology. However, simulation techniques for materials and devices on nanometer (a billionth of a meter) scales are still in the early stage. Since empirical data are difficult to obtain at such extremely minute scales, simulation techniques require modeling based on quantum mechanics, with a strong emphasis on accuracy. A promising method may be to take advantage of advanced nanosimulation techniques and codes being used in theoretical and computational science. However, there is a gap between researchers in nanoscience and engineers in nanotechnology development with respect to the scales they handle, leading to another gap in the way they view phenomena. Thus, technology transfer between the two fields cannot be implemented easily. It is therefore the objective of this report to discuss how to effectively promote the dissemination and transfer of nanosimulation techniques to development engineers and general users. This report analyzes trends in the dissemination of nanosimulation techniques in the U.S.A. and Europe and the present situation in Japan and recommends measures to be taken in Japan in the future.

In the U.S.A. under the National Nanotechnology Initiative, many public organizations are working on development, technology transfer, and dissemination of nanotechnology as well as the cultivation of human resources in the field. As part of this project, networks aimed at general users are being built, and supporting systems and internet and educational environments are being established to enable development engineers and students of nanotechnology to easily access a wide variety of nanosimulation software. In Europe, on the other hand, only the transfer of nanosimulation techniques to the engineering development of nanotechnology at individual project levels is being implemented. However, since European countries have sufficient awareness and experience both in the development of computation techniques and codes for nanosimulation and in educational activities such as seminars, they are potentially quite capable of developing nanosimulation techniques.

Japan is not necessarily behind the rest of the world in this field, because it has already started projects to develop software and disseminate techniques. However, it cannot be denied that Japan is somewhat behind with respect to support systems after the publication of software, quality of published software, and skill in the development of new calculation techniques. In order to address these problems, the following measures must be taken. (i) Introduction of long-term evaluation of activities including the support provided for published software, (ii) improvement of the status of technicians involved in the development and support of software, (iii) maintenance of linkages among researchers, technicians, and users, (iv) construction of hubs for nanosimulation software, and (v) enhancement of projects focused on the development of new calculation techniques. These measures are certain to contribute to the dissemination of nanosimulation techniques. The promotion of collaboration between nanoscience and nanotechnology through these measures can be expected to accelerate the development of nanotechnology in Japan.

(Original Japanese version: published in February 2006)

Energy

6 Trends in Technical Developments for the Exploration, Development, and Production of Petroleum and Natural Gas Resources

p.85

According to Japan's energy supply projections, 30 years from now oil and natural gas will account for the majority of the total energy supply. From confirmed and recoverable reserves, the reserve life index for crude oil is about 50 years. However, worldwide primary energy consumption is expected to increase. In particular, rapid economic growth in the populous countries of China and India requires enormous amounts of primary energy. In 2030, those two countries are expected to account for 1/4 of the world's energy consumption. Competition between them for fossil resources, especially oil and natural gas rights, is heating up. This is one of the causes of the sharp rise in oil prices.

Japan's basic policy is to reduce energy consumption and shift to renewable energy. However, during the time leading up to the transition period from fossil resources to renewable energy from 2030 through 2050, Japan must have an agile energy policy that will secure a sufficient supply of fossil resources. This report takes an overview of major technologies in the upstream sector of oil resources, examines the direction of technical development, positions of Japan in the international context, and discusses necessary policies.

Currently, as owners, the major oil companies and national oil companies from oil-producing countries carry out international resource development. An international hierarchy has also formed for the provision of technical services. Aerial topography surveys, geophysical exploration, and chemical exploration are all being carried out, in systematic manner. The most effective technology to survey geological formations and find those where oil and natural gas may exist continues to be seismic exploration, the analysis of reflected waves from artificial earthquakes in coming decades. Analysis of multiple waves, computer simulation, and imaging will continue to progress. Based on such explorations, development for production will be decided through analysis of test drilled rocks, and in some cases on the comprehensive analysis of data on subsurface structures and underground resources obtained directly from gas and oil reservoirs. Technology is now being developed so that once production begins, productivity can be maintained or improved by ascertaining, predicting, and resolving changes in the boundaries above and below ground in underground geological formations, gas and oil reservoirs, and products.

Policies to secure supplies of oil and natural gas resources must be multifaceted. A strategy is necessary so that in Japan, as in other countries, owner corporations can accumulate sufficient capital and project experience, technical service providers can obtain advanced technologies and establish a record of achievements. The adoption of advanced technologies based on industrial and technical strengths can be promoted in Japan. In the upstream sectors of exploration (mineral exploration), development, and production of these resources, policies are needed to ensure that Japan will have internationally competitive advanced technologies, powerful businesses, and the human resources to support them.

In the future, technologies to analyze, simulate, and feed back four-dimensional data that factors in changes in underground formations over time while using advanced sensors, information and communications, data analysis, advanced drills and materials, advanced three-dimensional control, and robot guidance for the acquisition of underground data will develop as fundamental upstream technologies. This will expand development in regions with harsh environments and in the deep ocean. Japan has a powerful technical base for leading parts of these upstream resource technologies. By further promoting this upstream cutting-edge technical development, Japan can secure a leading position. However, in order to do so, Japan must build a foundation of experience and success with each technology. Moreover, because development work takes place amidst ethnic conflict and international competition for rights acquisition, efforts must be made to train people who are not only knowledgeable and technically skilled, but also mentally tough and internationally common sensed.

(Original Japanese version: published in February 2006)

Science & Technology Policy

7 Technology Foresight surveys in China

p.101

In line with the setting of China's National Guidelines for Medium- and Long-term Plans for Science and Technology Development and the government's 11th Five-Year Plan, the Chinese Ministry of Science and Technology and the Chinese Academy of Sciences carried out foresight surveys looking at technology development through 2020. Both organizations relied mainly on the Delphi method (using repeat questionnaires to obtain a consensus of expert opinions).

The Ministry of Science and Technology survey covered six fields: information and communications; biotechnology and life science; new materials; energy; resources and environment; and advanced manufacturing technology. Analysis found that breakthrough technologies likely to be realized in China during the coming 10 years include next-generation mobile communications technology, technology for cultivating new crop varieties, and nanomaterials and nanotechnology. Furthermore, while China trails the leading countries by five years in most technologies, this self-assessment rates the country on a par with the leaders in the fields of TD-SCDMA, its own third-generation mobile telephone technology, technology for genetic engineering of plants, and nanocomposite materials.

The Chinese Academy of Sciences survey first examined the concept of "a little well-off (xiaokang) society in 2020, offering six visions: a globalized society, an industrialized society, an information society, an urbanized society, a recycling-oriented society, and a consumer society. The survey covered four fields: information, communications and electronics; energy; materials science; and biology and drugs. Another survey currently underway covers four more areas: manufacturing technology; resources and environment; chemistry and chemical engineering; and space. In a comparison of technical levels, the USA was seen as holding first place in most technologies, but Japan was number one in all-solid semiconductor white lighting technology; hybrid cars; high-quality, high-speed continuous-casting technology; urban waste disposal using microorganisms; and medical treatment using Chinese herbal medicines.

These foresight surveys were the first to be conducted in China with the clear intention of contributing to policymaking. The "8th Science and Technology Foresight Survey," carried out by the National Institute of Science and Technology Policy in Japan, was the first to be conducted in close cooperation with Japanese policymakers. Finding ways to provide policymakers with the information they need will become an ever more important goal for foresight researchers in both Japan and China. Those involved would benefit from exchanges of opinion.

(Original Japanese version: published in March 2006)

1

Cognitive Robotics to Understand Human Beings

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1 Introduction

The question of what human beings (self and others), the mind, and the world are has always been of great interest to humankind. Most academic disciplines originated to answer these questions. As neuroscience has advanced, the notion that brain function is closely related to the mind has become more widely accepted, increasing the expectation that unknown aspects of the mind could be explored by neuroscience. However, a long-standing question regarding the mind is that one's mind seems to be associated with oneself as a physical existence, yet its content seems not to be expressed physically. Simply accumulating knowledge acquired through external analysis and observation of the brain as a physical entity is not sufficient to elucidate the essential functions of the brain and the nature of the mind.

The brain has many parallel units (modules) that represent different parts of the body or participate in different functions. When neuroscientists study the properties of a module, they apply a controlled stimulus to the subject, so that it perturbs only the targeted module (or limited numbers of modules, including the target). When human beings engage in usual activities, however, many different modules work in an autonomous and distributed manner. Particular ideas or actions are generated either by the exchange of information between specific modules or the selective involvements of certain modules. Unless the algorithms for these information exchanges and selections can be elucidated, observation of the physical state of the brain at a given time cannot lead to an understanding of the information processing taking place at that time.

In Japan, research on the computational theory of the brain[1] and research combining theory and physiological experiments[2] has been carried out. One of the major themes in Japanese brain science in the 1990s was "creating the brain" beside analytical experimental sciences ("understanding the brain") and research oriented to medical applications ("protecting the brain"). This theme was significant in that it not only expressed the concept of understanding brain functions through "cycles of creation of models of brain, computational theory and neural networks, their verification through experimental science, and improvement of theories and models," but also expressed the unconventional orientation of creating new systems inspired by the brain. Furthermore, computational neuroscience was defined as "to investigate information processing of the brain to the extent that artificial machines, either computer programs or robots, can solve the same computational problems as solved by the brain, essentially in the same principle" [3]. Based on this conceptual framework, innovative researchers, although still few in number, are engaging in studies to elucidate human brain functions through "cycles of creation of brain algorithms, their verification through robots, noninvasive measurements of brain activities, psychology, and experimental sciences, and further improvement of the algorithms."

From the perspective of ordinary Japanese sensibilities as well, the mind cannot be considered in isolation from the body, the environment, and the existence of other people. In other words, attempting to create the brain alone will not elucidate the essential functions of the brain itself or the mechanisms of the mind. Embodiment and context dependence are key concepts in cognitive science and neuroscience, and robots given bodies to interact with the environment are serving as effective simulation tools [4].

2 The Field of Cognitive Robotics

Since their beginning, robots have been constructed to imitate, replace, and supplement human beings or a part of human functions. Since 1960, the mainstream of robot development has been oriented to industrial applications - manufacturing robots. In recent years however, we have witnessed a rapid increase in the development of robots designed to serve ordinary people rather than experts [5-7]. Traditionally, robotics referred to a combination of science, engineering, psychology, sociology, and other disciplines necessary "for the development, construction, and dissemination of practical robots," with particular emphasis on the engineering aspects.

During the process of seeking the necessary conditions for robots to act as flexibly, smoothly, and autonomously as human beings in the real world, robotics researchers began to turn their attention to human cognitive mechanisms, learning, recognition of others, and social behaviors. In Japan, since around 1994, robotics researchers have organized research groups, such as the Keihanna Research Group for Sociointelligenesis, with the primary aim of elucidating human cognition, development, and behaviors by using robots. These researchers have adopted a "constructivist" approach, which aims to explain human cognitive mechanisms by creating and testing robots that can develop humanlike cognitive abilities to cope with the real world ("cognitive developmental robotics")[8]. These researchers have the advantage of having not only advanced knowledge and experiences in physics and engineering, which share a common basis in mathematics, but also a broad knowledge and understanding of biology, the humanities, and the social sciences, and of having a solid verification platform, such as robots.

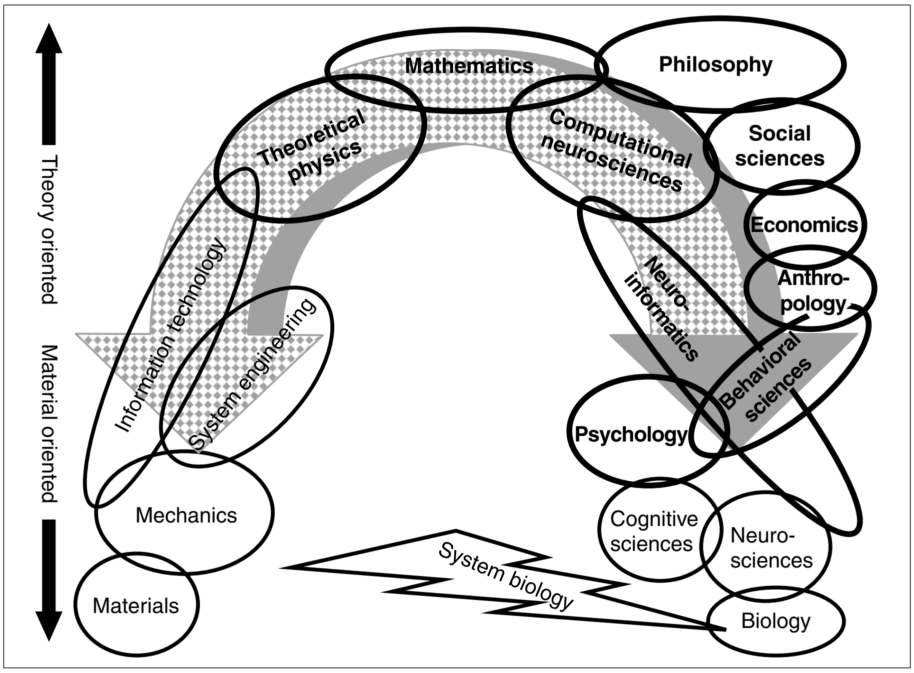
2-1 Cognitive robotics

"Cognitive robotics" in this report refers to an comprehensive science in which robotics, as described above, neurosciences (ranging from the experimental to the theoretical or mathematical variety and neuroinformatics), cognitive science, psychology (psychophysics and behavioral measurement) and behavioral sciences seamlessly collaborate in unity while keeping variations in perspective, closely connecting with fields such as philosophy, social sciences, anthropology, and economics; exchanging their knowledge and methodologies, and executing mutual verification. Robotics herein represents an expectation of interdisciplinary integration, rather than the simple collection of independent research fields, and will be realised by using robots as a common verification platform to highlight weaknesses and errors in research processes in individual disciplines and contradictions among different disciplines,

For the development of commercial robots, a demand-oriented perspective, based on future prospects and on a broad understanding of humans and society, is required. For humanoid robots (humanoids hereafter), the initial phase of development has been completed for structural modules and actuators, which correspond to their bodies, and the computers to control them. Currently, humanoid hardware developed in Japan is widely used, both in Japan and abroad as platforms for the development of software to serve as the cognitive mechanisms. Certainly, future success in the development of practical humanoids will depend on the improvement of their "cognitive functions."

Some research laboratories dedicated to the development of practical robots have taken up parallel research in cognitive robotics, which offers this fundamental knowledge. Even researchers specializing in the development of structural modules and actuators must take compatibility with next-generation cognitive functions into consideration. Energy consumption is another important future issue expected to accompany advances in robotic cognitive function. Research to solve this issue will become necessary.

Figure 1 : Cognitive robotics



Prepared by the STFC

Energy consumption problems associated with improvement in cognitive functions

Neural systems are enormous energy consumers in animals. Humans have remarkably large brains for their bodies (approximately 2.5% of body weight), and the brain consumes 20% of the body's total energy. The cerebral neocortex of primates increased exponentially in volume as their social behaviour became more complex (the social brain hypothesis, Reference 14). In order for robots to work in complex human society, improvement of their cognitive functions is indispensable. This raises the problem of energy consumption for information processing. Furthermore, because of size restrictions and mobility requirements for humanoid robots, it is critical to invent new materials and structures enabling flexible and efficient information processing within limited spaces. This means that humanoid robots can be most desirable test beds for the creation of new paradigms for computational theories and materials/structures.

Although noninvasive methods to measure brain activity have progressed, certain constraints remain. Currently, interpretation of results requires either (1) statistical analysis of data from multiple measurements or (2) training subjects for considerable hours to ensure reproducible responses prior to a single measurement and interpreting the result. In order to decipher spontaneous information processing in a subject's brain by each single measurement, algorithms of the information processing are a prerequisite. Currently, algorithms are being proposed by mathematical studies. Before they can become worthwhile for practical use however, the algorithms must be repeatedly verified and improved through simulations using robots. Such algorithms, if available, would serve as the foundation for the development of new computers and human-machine interfaces.

2-2 Global progress of robotics

In October 2005, the European Commission published a report on the growth of global robot markets [15].

A) Since the European Commission's report focuses on robot markets, it deals with major areas of robotics without a category for cognitive robotics. In Japan, a market for humanoid robots, such as personal and home robots, and service robots has already started. Although cognitive robotics can be regarded as a research area in basic science, not necessarily oriented to applications, it is also recognized as a fundamental necessity for development targeted toward commercial robots.

B) In Europe, because of the cultural backgrounds of monotheism and the belief that "God created human beings in his own image," researchers feel guilty and reluctant to create humanoid robots (artificial humans)[16]. Therefore, there is little expectation for the commercialization of humanoid robots. However, for the purpose of basic research in cognitive science, neuroscience, and certain medical fields, since 2004, the European Commission has promoted projects similar to the cognitive developmental robotics projects of the Keihanna Research Group for Sociointelligenesis. European researchers also conduct questionnaires and other surveys, before and after robot demonstrations, to evaluate how contact with actual robots can decrease public aversion to

Table 1 : Examples of research areas in cognitive robotics

Knowledge to be obtained	Research area	Subject of analysis
Properties of elementary functions of unconscious and autonomous congnition / behaviours	Experiment combining experimental animals and robots	Based on the neural activities in an experimental animal's brain, a behaviour predicted from the neural activities is reproduced simultaneously in a robot.
	Physiological and psychological experiments on conscious experimental animals	Relationships between temporal profile, properties, intensity of neural activities and the manifestation of cognition and behaviour (cause-effect relationship).
	Primatology, anthropology	Development, learning and social behavior of monkeys and humans.
	Cognitive archaeology, anthropology, history	Changes in human cognitions associated with evolution and environmental and social diversification.
	Cognitive developmental robotics	A robot that has a cognitive framework and can achieve route-finding through physical interaction with the environment.
	Psychophysics, behavioral measurement	Time sequence, correlation and regularity of unconscious perception/behaviour. Control of behavior and cognition as a result of perturbation of perceptions and behavioral patterns.
Mechanisms of development in intelligence for interaction with others and society; Mechanism of developmental disorders of social abilities, e.g. autism	Genetics, evolution, anatomy, physiology	Motivation; selective attention; recognition of the novelty and regularity of stimuli; imitation.
	Fetology, baby science	Spontaneous motion; response to a caregiver's cyclic repeated actions.
	Theory-of-mind	Pointing, joint attention, false belief task (estimation of others' expectations and predictions).
	Mirror neurons-, analysis of perception-behavior relationship	Common neural information processing in perceiving others' actions and expression of emotions and in evoking/performing/expressing the same actions and emotions in the self.
	Noninvasive brain activity measurement	Location, strength and temporal changes of brain activities during cognition and behaviour associated with others or self.
	Computational neuroscience	Close forward/reverse relationship between brain algorithms for perception and behavior and perceptive and behavioral models.
	Cognitive developmental robotics	Development of cognitive patterns through physical interactions with others and the environment.
	Philosophy	Relationship of neuroscientific functions and physiological meanings of emotion and sensation with actual feelings and senses or "the experience of reality."
Mechanism of the formation of norms of social conduct; Mechanism of the expression of impulsive acts and depression	Neuropharmacology, psychoneurology	Perturbation of parameter molecules that control brain activities and the mechanism of deficits in social behaviour.
	Cognitive developmental robotics	Simulation of perturbation of parameter molecule and changes in individual/cooperative behaviour.
	Economics	Effect of prediction/evaluation of advantages and disadvantages on human behaviour; the role of values, motivation and emotion in decision-making.
	Social sciences, social psychology	Tools for human interaction: objects, gestures, languages, technologies and regimes that have accumulated through history and are shared in society; Caregivers treat their children as more mature and older than their actual states in order to involve them in a communication game.

Prepared by the STFC based on References [9-13] and other material them.

C) European industries are currently developing home robots but carefully refrain from giving them a hint of resemblance to human beings [15].

D) In the U.S, NASA announced in December 2005 that it would promote the development of humanoid robots that could aid construction of a lunar base as a step toward manned Mars exploration. NASA explains why construction robots need to be humanoid as follows. Humanoids can use the same tools and equipments as human crews. Furthermore, since programming all tasks is impossible, robots must learn their work, and humanlike shape will make it easier for human crews to teach and remotely control them. Based on the concept that "it may not be the human capability to learn, but to teach, that has contributed most to our progress," NASA cites the following as the basic concepts of its robotics research[17]. (1) Robots need to be fostered/taught rather than to learn; (2) robots need to be able to "teach" other robots rather than to simply transfer data to them; (3) robots' ability to "teach" is proof that "learning took place"; and (4) research must be practical.

The U.S. has been systematically applying cognitive science to human education for many years. It is difficult to objectively evaluate how much and when learning of a child has been completed. In the U.S, sound accumulation of experiments and observation in human education enable criteria to be set as (1) - (3) above. In addition, the ability to "teach" is a concrete indication of the ability to recognize self action. To achieve practical purposes as mentioned in (4), the contribution of broad basic research is, in fact, indispensable. The U.S. can establish such a policy because it has such a large pool of researchers in social science, anthropology, psychology, and philosophy, who can contribute for applied research while carrying out basic research.

Table 2 : Comparison of developing robot markets

Area of activity	Degree or level of activity			
	Japan	Korea	Europe	U.S.
Manufacturing robotics	++++	±	+++	±
Humanoids A)	++++	+++	± B)	±
Personal/home robotics A)	++++	+++	± C)	±
Service robotics A)	++	+++	++	++
Biological & medical applications	±	±	+++	+++
Security and space robotics	±	–	++	++++ D)

++++: Excellent; +++: Very Good; ++: Good;
± : Fairly Good; -: No Remarks
A~D : see text.

Prepared by the STFC from Reference [15]

3 Comparison between Humans and Robots as Systems

3-1 Beyond differences in materials and structure

Many people believe that robots can never have the "same kind" of mind as human beings, because although the mind is not physical in principle, it is an attribute of human beings that consists of biological materials and structures. It is not known, however, how and to what extent mental functions are dependent on biological material and structure, and in what way. On the other hand, those who try to develop anthropomorphic robots are aware of the limits of existing mathematical computations and materials/structures and are exploring new materials and structures inspired by biological systems. The basic principle in robotics as a science for understanding human beings is, while understanding fundamental differences, to study human information processing and behavior with simulation on robots and to seek better conditions and principles of simulation.

3-2 Changes in human-robot comparison

Robots are basically described as machines with computers for information processing and with input and output devices, which are auto-regulated by the computer. Human beings can also be considered as systems, with the brain that processes information and auto-regulates sensory inputs and motor outputs. Comparisons between humans and robots as systems have been changing, as described below.

(1) The age of artificial intelligence

In the early age of robot studies, intelligence alone was emphasized among human characteristics and it was compared with symbol processing by artificial intelligence, which corresponds to the brain in robots. The brain was regarded as responsible for the entire process of perception, recognition, planning, and decision-making (top-down approach), while the body was merely a device for inputs and outputs. Robots based on this concept were incapable of adapting to unpredictable changes in their environments.

As tasks became more related to the real world, weaknesses of computers and robots emerged, one after another[18]. The fact that what human beings do naturally is in fact very intricate functions thus came to be recognized for the first time as a topic of scientific research. For researchers in modern philosophy and cognitive science, a new set of subjects were presented by robotics research [19].

(2) The age of neural network

Robots were designed according to the concept of neural networks. Circuits of information processing were formed and reinforced according to experiences and their frequency. These robots were no longer dependent on symbol processing that assumed mental representations. In contrast to (1), these systems were formed in a bottom-up manner, triggered by inputs of stimuli. Although these systems were appropriate for modeling insects and other creatures without central nervous systems and were robust against environmental changes, they were unable to elaborate higher-order functions, such as those seen for vertebrates.

(3) The age of combining top-down and bottom-up approaches

In recent years, embodiment, interaction with the environment, and development have become key concepts in cognitive science and philosophy. From their viewpoints, both human beings and robots have bodies that move and have diverse interactions with environments. Unlike computers, they must be able to find solutions within a limited time to complex problems occurring incidentally. The solutions must be valid in the real, physical world feasible under constraints imposed by the physical and functional properties of their own bodies.

As human beings mature over a period of years, they formulate "self" algorithms to integrate the outside world, input processing, and output production by repeated information processing in the neural system and physical interaction with the environment. Likewise, robots for understanding human beings must have the ability to autonomously change their own

Examples of human functions that seem ordinary but are actually remarkable

[Problem setting ability] Machines can process symbols quickly but cannot set problems by themselves.

[Domain-specific knowledge] The more closely related a problem is to the real world, the more human beings utilize their wide repertoires of domain-specific knowledge to solve them. Most of this is implicit knowledge that is held unconsciously or recruited according to physical or environmental cues.

[Heuristic knowledge] To solve problems in the actual world, human beings quickly select a finite number of information items required at a given moment. Machines cannot do this (the frame problem). Although heuristic solutions may be difficult, even for humans in novel complex situations, humans can avoid being brought to a standstill by acting as if the frame problem did not exist.

[Symbol grounding problem] Machines cannot associate symbols used for language processing or computation with actual objects and phenomena in the world.

[Binding problem] Humans can process multiple characteristics of an object in a parallel and distributed manner and finally bind them all together as the characteristics of the object (e.g. processing elementary information of an apple: "redness, brightness, size, roundness, hardness, smell, taste, etc.," and rebinding them as "an apple").

information processing methods (algorithms) and to develop intelligence through their physical interaction with the environment. In order to behave adaptively, they must also selectively perceive the world according to their genetic traits (initial conditions), experience, and memory, and according to predictions, motivation, and purpose. In other words, both top-down and bottom-up approaches of research are indispensable.

4 Ways of Understanding the Mind

Many people vaguely hold the agnostic view that the nature of the mind is hard to understand and will therefore never be elucidated scientifically. One opinion is that “The very moment a mental function is programmed, people stop considering it as an essential element of ‘true thinking.’ An indispensable core of knowledge always resides in the next thing to be programmed” [20].

Even natural scientists sometimes hold the implicit bias that “the mind, biological systems, and humanity are something special.” This may hinder the elucidation of the mind. When analyzing the brain, neuroscientists with little knowledge of psychology, behavioral science, and philosophy may derive mental processes from “naive psychology,” a set of commonplace theories without scientific bases. Efforts to recreate human cognitive functions in non-biological robots can be a means of escaping such biases.

Questions such as “in the end, can robots have minds?” or “do we want robots to have minds?” are not necessarily common interests of robotics researchers. The basic principle of cognitive robotics for understanding humanity is that even if researchers personally predict that the human mind cannot be completely recreated in robots, they should attempt to understand humans through the process of creating homologues of the human mind.

4-1 Substantialistic attempts to create a mind

From substantialistic viewpoints, researchers “postulate” that components of the mind are basically intrinsic in individual humans, and “assume” that robots can (be created to) have similar intrinsic components. Inquiry into what kind of principles should be used to create close homologues of the human mind’s components and attempts to configure robots based on such principles will further improve understanding of the nature of the human mind. In psychology and neuroscience, where it is said that consciousness is only the tip of the mind’s iceberg, verification that most mental processes occur unconsciously has begun. Since unconscious cognitive and behavioral processes are known to be relatively “mechanical” and closely related to physical states and the environment [11], they are appropriate to be built into robots.

As neuroscience revealed most macro structures and functional localization in the brain, it was disclosed that each function unit is working in an autonomous, distributed, and recurrent manner. Engineering attempts to reproduce conscious/unconscious systems to integrate autonomous, distributed, and recurrent processing are now carried out [12].

4-2 Relation Theory to validate the “substantial” mind

Now that the human mind is far from being elucidated completely and the robot “mind”

Turing Test

The Turing test was proposed in 1950 by mathematician Alan Turing as an answer to the question “Can machines think?” Instead of directly answering the question, he invented a verification method that uses an imitation game to distinguish humans from computers. A human inspector, a test subject (a machine), and a control subject (a human) go into separate rooms and communicate with each other through teletyped text. The inspector asks various questions to determine which subject is the human. If the machine can make the inspector judge it as a human, it is acknowledged that the machine has demonstrated the ability to think.

consists of materials and principles differing to those of the human mind, methods based on the Relation Theory are used to evaluate the "mind" of robots constructed in the manner described in 4-1. The mind of robots will be ameliorated by repeated cycles of construction from a substantialist perspective, evaluation with Relational methods and modification with the substantialist approaches.

5 Robots as Social Members

5-1 Humans interpret the world intentionally

When a computer creates a combination of characters and words that meets the requirements of a haiku (i.e., meets its substantial requirements) by chance during random symbol manipulation, one who reads it without knowledge of the process might assume the presence of an author and recognize the author's intentions, implications, and metaphors in the "haiku" [20]. This may occur because humans have a propensity to try to find meanings of any subject encountered [21]. For the time being, when human beings find intentions, feelings, and other mental properties in robots, this can be attributed to human empathy and projection of emotions.

(1) Projection of emotions

Human beings can empathize with or project emotions, even onto non-human creatures, natural structures, artificial tools, and vehicles. Young children often see faces, expressions, and emotions on objects. This is a normal phenomenon for infants, who are still developing the ability to promptly identify the faces and voices of fellow humans from among diverse stimuli from the outside world and to infer other people's intentions ("theory of mind"). This tendency disappears as children grow. In certain societies, where empathy with dolls and toys is an implicit taboo for adults, resistance or rejection may be encountered when these objects are used for psychotherapy [22].

(2) Animism

In anthropology and archaeology, it is known that in hunter-gatherer societies and traditional societies preserving close relationships with nature, people, including adults, tend to recognize spirits in many subjects (animism). Traces of animism can be seen even in some modernized countries, such as Japan, where indigenous beliefs have survived or have not been suppressed by ideas imported from abroad (i.e., Buddhism, Confucianism, and Taoism). For example, some Japanese perform rituals for worn-out tools and captured animals and fish (e.g. bonito burial mounds ["Katsuozuka"] and the Ainu bear ritual ["Kumaokuri"]) to cordially send their spirits into another world. Such traditions may be the basis for the Japanese tendency to not resist finding emotion in robots, which are mere machines [23, 24].

On the other hand, there are areas where new or imported religions repressed indigenous animism as taboo or heresy. In such areas, especially those where a monotheistic religion believing that humans were created in the image of an omnipotent Creator and all other creatures were created for the use of humans prevailed, people tend to think that "creation of humanoid machines is disobedience to God," "humanoid machines are harmful and dangerous to human beings," and "robots can never have a soul because they are not created by God" [16].

5-2 Appropriate distance between humans and robots

(1) The Uncanny Valley

According to psychological studies, people in general unconsciously feel affection towards an artificial object if it reminds them of a human or living creature. Robots with nuts-and-bolts appearances are treated relatively roughly, while those with relatively humanlike appearances evoke the kind of attitudes and responses akin to those seen among humans [25].

However, as early as 1970, a Japanese robotics researcher suggested the possibility that excessive similarity to a human might elicit repulsion [26]. His hypothesis was as follows: (1) As robots become more humanlike in appearance, human beings feel friendlier towards them; (2) however, when the resemblance to human beings exceeds a certain level, people become uncomfortable, falling into the so-called Uncanny Valley; and (3) as the resemblance further increases, friendly feelings increase again.

It was suggested that every human has his or her own comfortable physical distance from others (any other human's conspecifics) that varies according to social relationships and degree of intimacy. People feel anxiety or repulsion when someone approaches too closely[27]. This suggests that there may be critical distances or conditions of cohabitation between robots and humans that divide the reactions of the latter, as to whether they feel comfortable or not.

The development of robots is advanced in Japan, Europe, and the U.S. for the moment People's attitudes toward humanoids vary among these areas. The Europeans and Americans are skeptical or passive towards the development itself or the releasing of robots into the public. In Japan, on the other hand, so-called pet robots and communicating robots are already commercially available and have been accepted favourably to date. The Japanese in general tend to avoid precautions against the possible risks of humanoids and discussing countermeasures against them. However, as humanoids become more widespread and more humanlike, even the Japanese public's favourable attitudes toward robots could sour. Another possibility is that Japan may find an original way to develop robots, based on the traditional Japanese emphasis on cooperation and refrain from encountering problems of their uncontrollability, even in a complex real environment, and that such robots could be applied in usual social lives. If this could be realised, it would develop as a unique area of research.

(2) Humans can adapt even to inappropriate science and technology

When emerging sciences or technologies are discussed in terms of human adaptability, invasiveness, and usefulness, their promoters often claim that children can adapt themselves to them easily, although adults may have troubles, and that problems will disappear once those who have adapted themselves in childhood become the majority of the population.

In principle, the brain develops in accordance with its genetic frameworks. However, if a newborn organism is exposed to certain artificial stimuli from birth and before a certain developmental stage (critical period), it comes to recognize the given condition as natural. If the stimulus is removed early enough before the critical period, the organism may recognize the world as intact siblings do. The phenomenon is known as plasticity. If a stimulus persists until after the critical period, its influences are fixed for the rest of life. Because of plasticity, organisms may adapt, even to an entity that is meaningless or harmful to their survival. The fact that an immature organism can adapt to a given stimulus or environment does not necessarily warrant the harmlessness or usefulness of that stimulus or environment.

> **A classic experiment well known in neuroscience**
>
> When a kitten is raised from birth through a critical period in a visual environment in which it is exposed to unique visual stimuli, vertical or horizontal stripes for example, it becomes unable to recognize any visual stimuli other than those presented in the experimental environments, vertical or horizontal patterns, respectively.

Long-term prediction and careful analysis are essential for resolving the difficult questions of whether people adapting to the new stimulus of robots from infancy would benefit from them throughout their lives, and whether allowing many people over several generations to grow up with such a stimulus as a present environmental factor would work to the benefit of human society and humanity as a living species. There is a need to embark on broad follow-up surveys (cohort studies) while many members of society are still from generations that do not accept robots as a pre-existing environmental factor.

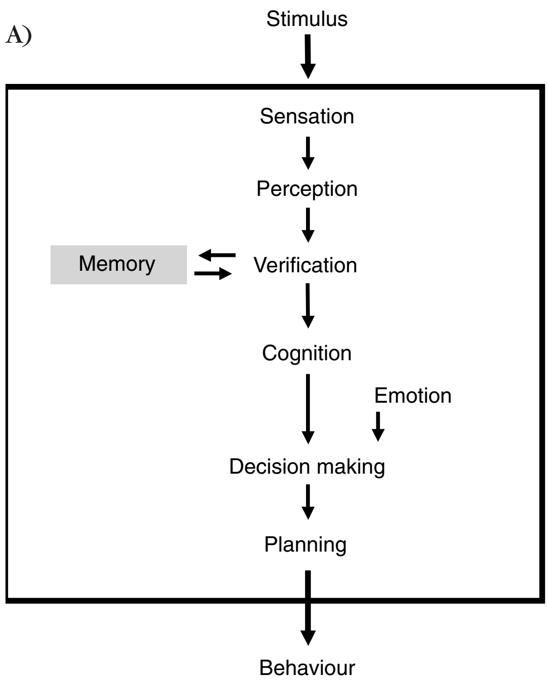
6 Examples of Projected Future Cognitive Robotics Research

6-1 Mechanisms of unconscious/conscious autonomous behavior

Most information processing in the brain and behaviour takes place in an unconscious manner. When people walk along a familiar path or engage in a skilled task, or when sleepwalkers return to their beds after wandering around, they are behaving and perceiving unconsciously and autonomously. If robots that can act autonomously are to be manufactured, those in the first stage will perceive and behave unconsciously.

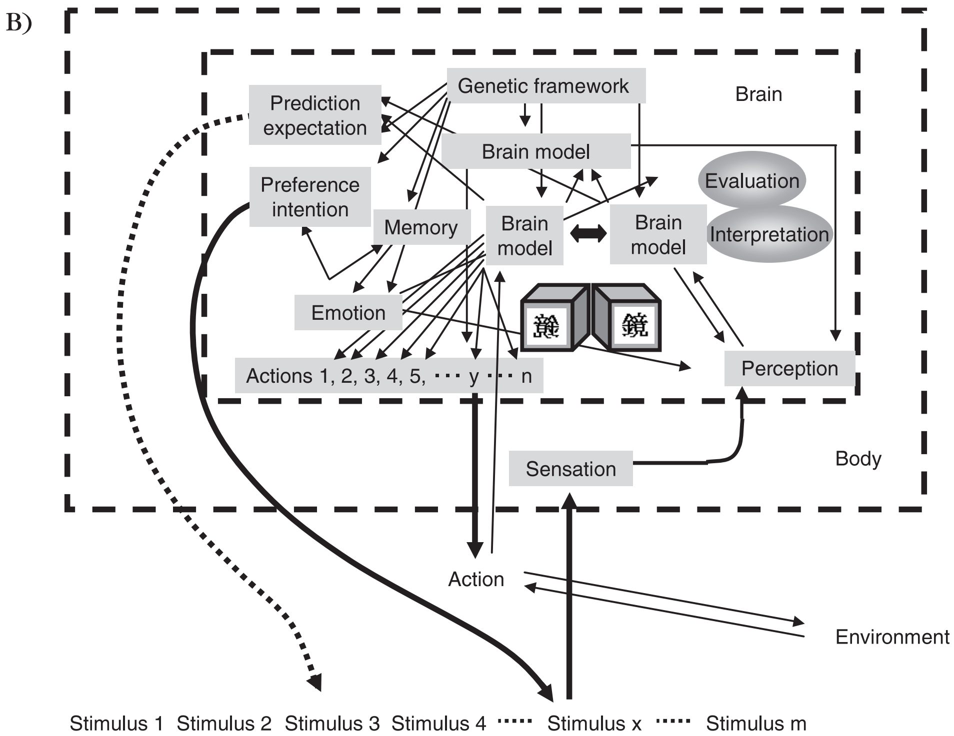
Recent improvements in neuropsychological and psychophysical methodology and behavioral measurement methods, combined with the development of noninvasive brain activity measurements, have promoted rapid advances in the elucidation of unconscious cognitive and behavioral processes [9-11]. As a result, the linear model proposed for processing from stimulation to action (Figure 2, A) based on

Figure 2 : Models of cognitive pathways



A) Classic linear model

B) Conceptual diagram of the cognitive pathways based on the latest knowledge
Human perception of stimuli is not neutral or mechanical (like visual processing in robots), but involves the selection of a subset of stimuli to perceive that dependent on each person. Interpretation of, evaluation of, and response to the stimuli also depend intricately on personal genetic traits, experiences, and memories.



Prepared by the STFC

conscious behavior has been proven invalid. Research, although still in rapid development, has suggested that multiple diverse pathways of information expression and processing take place simultaneously and concurrently (Figure 2, B). During development, physical interactions with others and the environment lead to the construction of strongly interconnected perception and behavior models in the brain, formulating algorithms for information processing.

Humans acquire the ability to unconsciously and autonomously act and perceive, partly because their motor and neural systems are endowed with structures that enable functions profitable for survival. These structures are being analyzed via molecular-biological analyses in neurobiology and neuropathology. Another reason is that they formulate perception and behavior models and algorithms in the brain through interaction with the environment. Such models and algorithms have been proposed from studies in computational neuroscience and are being refined by testing on robots. According to a hypothesis "certain orders of unconsciousness are self-organized in a bottom up manner, despite being a system that works automatically and purposelessly, because recurrent cycles of information processing are embedded" [12].

It is supposed that unconscious cognitive processes can be analyzed scientifically, rather more easily than conscious ones are, because the former are more directly linked to physical state and environmental conditions, and they function passively and mechanically according to type of stimuli and the states of subjects and environments [11]. An effective means of analysis is to reproduce perception and motion models of the human brain and recurrent information processing cycles in robots, and to evaluate the generation of autonomous actions. Robots for practical use are also expected to act autonomously, without depending exclusively on human-made programs.

A major challenge of Japanese society is to enable elderly and disabled people to live as independently as possible in an ordinary environment. It is thus meaningful to seek out prerequisites for the autonomous actions of humans and to develop supporting technologies.

According to a theory, it is only when people face external changes, which prevent them from continuing with their ongoing unconscious behaviour, that the information processing in the brain changes and hence the state known as consciousness is generated.

It has emerged that even when people take an action intentionally or focus on a single stimulus from several available, the result of their decision is already "determined" in term of neural activities in the brain areas that modulate behaviour a few hundred milliseconds before they become aware of the decision or in terms of the manifestation of elementary actions. Experimental modification of subjects' neural activities or behavioral patterns can change

Examples of definitions of consciousness and unconsciousness:

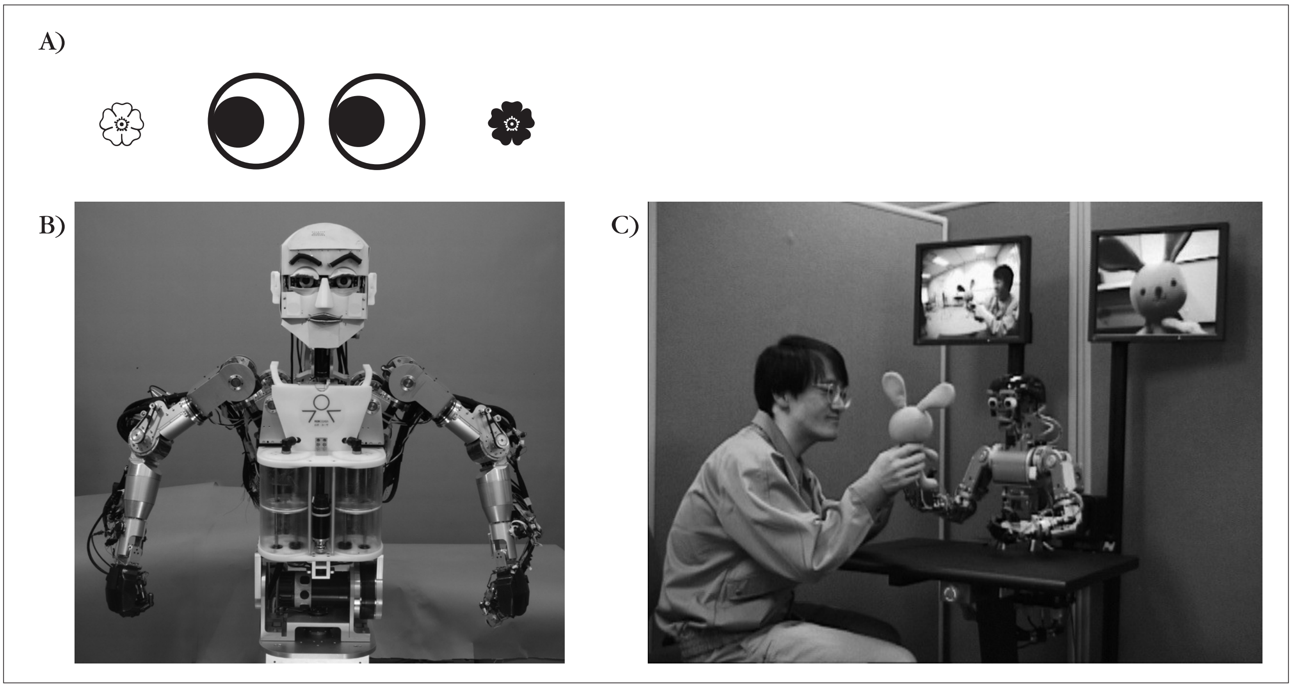
(1) Consciousness probably refers to a loose set of many interrelated, heterogeneous things rather than to a specific state or function. Consciousness can only be shaped against a "background" of unconsciousness. Unconsciousness precedes consciousness; either ontogenetically (developmentally) or phylogenetically (evolutionally) [11].

(2) Consciousness is a process of becoming aware of any inhibition against thinking or introspection, and a process of introspection, in which such awareness elicits past inhibitions against behavior (physical and mental) [30].

(3) Consciousness is defined as making approximations by performing a highly simplified fictitious series of computations to solve unconsciously generated improper configurations, associated with massive and parallel sensori-motor integration [3].

(4) Consciousness is not the cause of cognition, but only a result. Consciousness is a specific state of working memory and is meant to model unconscious manipulations as simply as possible and to store the results as episode memory [12].

Figure 3 : Examples of research on basic functions for understanding and expressing emotions



A) Humans respond sensitively to eyes and gazes, even if the eyes are presented in quite simplified form. If someone is gazing at an object, people assume that the person is interested in it.
B) Emotion Expression Humanoid Robot WE-4RII chooses and displays one of seven predefined facial patterns of emotional expression in response to external stimuli or gaze tracing. Evaluation by humans judges have shown 100-percent recognition of the state of "anger" on WE-4RII [31].
C) The infant-like robot "Infanoid" can display "eye contact," by detecting a human's frontal facial patterns from video images taken by its cameras and directing its eyes toward the detected face. Infanoid also can display "joint attention," by detecting the location and orientation of a human face or the direction of a pointing finger (based on wide-angle images for peripheral vision), searching in that direction to find an object and directing its own eyes and hands in the same direction (based on narrow-angle images for fovia vision) [13].

Prepared by the STFC from References [13,31]

the contents of decisions without the subject being aware [9,28]. Even in conscious behaviour, the processes preceding self-awareness may be unconscious and represented only physically. Algorithms of processes to find another stable behavioral pattern, even when perturbations are introduced during unconscious, autonomous action, can be both formulated and verified in robots.

Philosophers conduct thought experiments on subjects, such as whether changes occurring within a robot during this process can be regarded as the generation of the equivalence of human "consciousness" [29].

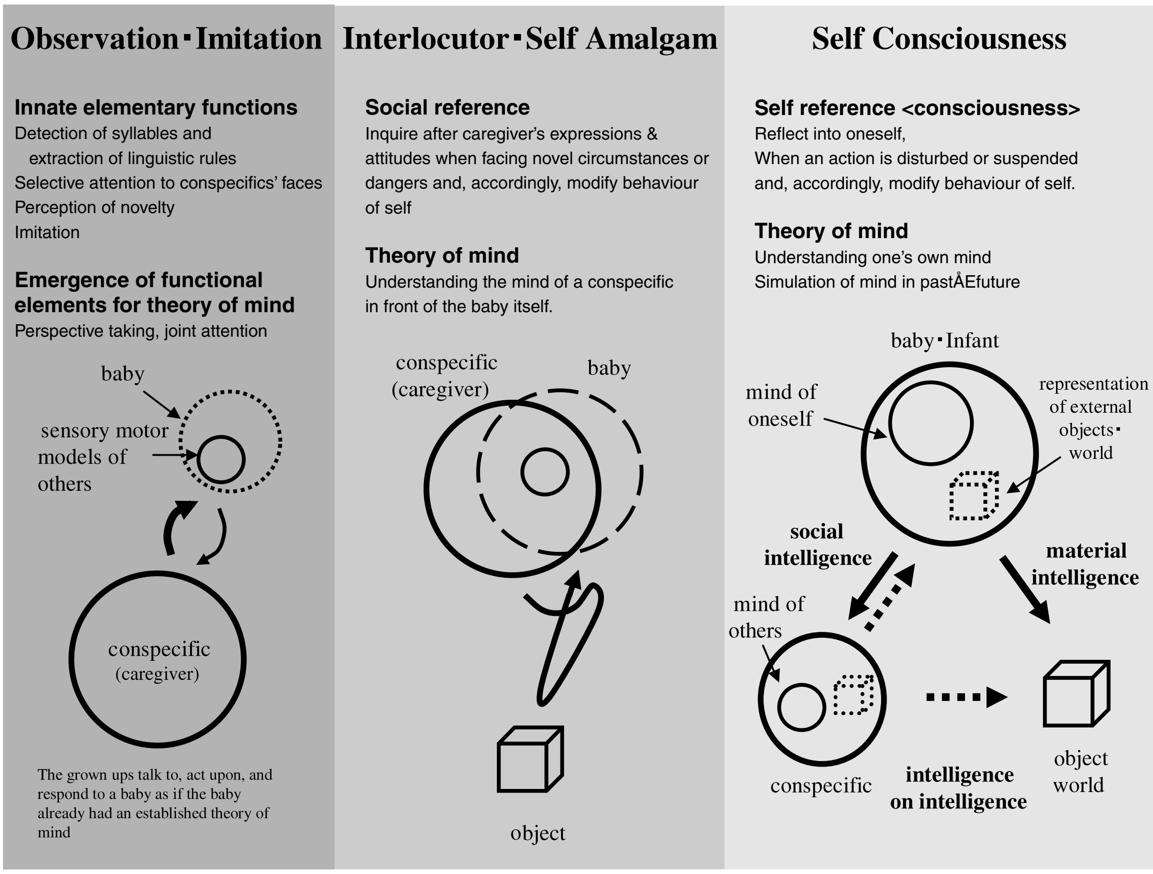
Modern law is based on the existence of free will and the concept of personal responsibility for acts based thereon. Even if science accepted a paradigm that human decision-making, whether performed consciously or unconsciously, is a mechanical process, one's own acts would still appear to be decided by one's own will from the perspective of everyday intuition and "naive psychology,". This shows that legal research is needed on such future problems as how human personal responsibility should be defined under such situations, and whether one can investigate a robot for "personal responsibility" of its acts when robots become able to act autonomously in ordinary society.

6-2 Understanding and expressing emotions

There are three potential subjects in robotics research that attempts to address "emotion": (1) elementary functions constituting emotional self-experience, (2) expression of emotions, and (3) the recognition of others' facial expressions and emotions. Research can be carried out with robots in all of these areas, and it is already underway for (2) and (3). Such research sometimes goes no further than the reproduction of experiments, which are already done with human subjects, simply replacing the latter with robots. In the near future, however, robotics research on emotion will examine how robots as manufactured products are accepted by users.

The most significant of these three concerns for cognitive robotics as a means for human understanding is (1), which deals with attempts

Figure 4 : Mind development



A) While babies have innate devices for mental development, they need caregivers who actively act upon and interpret them.
B) Babies first learn the significance of social interaction tools (gestures, language, objects, etc.) through interaction with their conspecifics. Since babies cannot clearly distinguish their own minds from others', they may cry in response to another's pain as if it were their own.
C) Babies soon begin to apply these tools to themselves and use them as tools to think. They also come to utilize interpretation of the contents of others' minds as knowledge. Even for adults, the self is not completely distinct from the other as represented in the chart, and this tendency is more evident when the other is affectionally close to oneself. When one observes someone close to oneself subject to a painful stimulus, it evokes the same brain activities as if one's own body were exposed to the same stimulus. An established model to distinguish the self from others can regress due to artificial factors, such as confinement and brainwashing.

Prepared by the STFC based on References [13][32]

to construct and verify functions of emotional self-experience in robots. Advances in this research will also deepen research on (2) and (3).

Chomsky's suggestion that "humans have the innate ability to voluntarily acquire language" has had an impact on various fields of research. "Baby science" and fetology have shown that humans start actively seeking stimuli and constructing their worlds as early as immediately after birth or even at the late embryonic stage. Newborns display innate functions (genetically obtained anatomical/physiological properties), such as imitation, selective attention to human faces, identification of novel stimuli from the outside world, and syllable identification and rule extraction from speech (Figure 4, A).

In psychology, on the other hand, Vygotsky proposed an "outside-to-inside" model to explain his idea that "during development, humans initially learn the significance of social interaction tools (gestures, language, objects, etc.) through interaction with others, and eventually begin to apply these tools for themselves and use them as thinking tools"[13] (Figure 4, A through C). The theory has been revaluated recently, and the importance of intervention by caregiver is emphasized in the "zone of proximal development", which children cannot reach easily by themselves. Interaction from others must initially take place in order that babies come to understand others' emotions and to express their own emotions. Self-experience of emotions, such as understanding, recognizing, and expressing the same, is established by applying the cognitive procedures one has developed to understand others' emotional expressions to oneself. Human babies initially gaze selectively into the eyes of their conspecifics, mainly caregivers, and then initiate eye contact, identify the targets of others' gazes, and point to a subject of interest to attract others' attention to it (joint attention) (Figure 4, B). This behaviour does not occur spontaneously in autistic people, who lack the ability to understand others' emotions due to developmental neurological factors.

Humans display emotion-related physical responses to stimuli before they become aware of their own subjective emotions. It is known in experimental psychology that manipulation of such emotional physical events can artificially evoke or modify subjective emotions. The mechanisms of subjective emotion largely depend on physical changes. For example, consider the process that leads to the expression of pleasant feelings through smiling.

(1) At first, the caregiver smiles at the baby. Because of an innate device to imitate others, the baby mimics it and then experiences pleasure induced by the action itself. As a result, the baby learns to smile repeatedly just to be rewarded with the pleasant sensation.

(2) The caregiver responds to the baby's smile as if it were the her/his "expression of emotion" (e.g. as if the baby were interested in something funny). Smiles are thus exchanged between the caregiver and the baby. This interaction expands when the caregiver and the baby involve outside objects as players (e.g. by pointing to, grabbing, or shaking them). Even before the baby is able to understand language, the caregiver casts it various words related to pleasure and smiling, etc. and responds to her/his actions and vocalizations as if the baby understood the linguistic expressions and their meaning. The caregiver thus integrates the baby into a language game. The baby's perception of others' facial expressions (perception model) forms in close connection with the expression of its own emotions (behavior model).

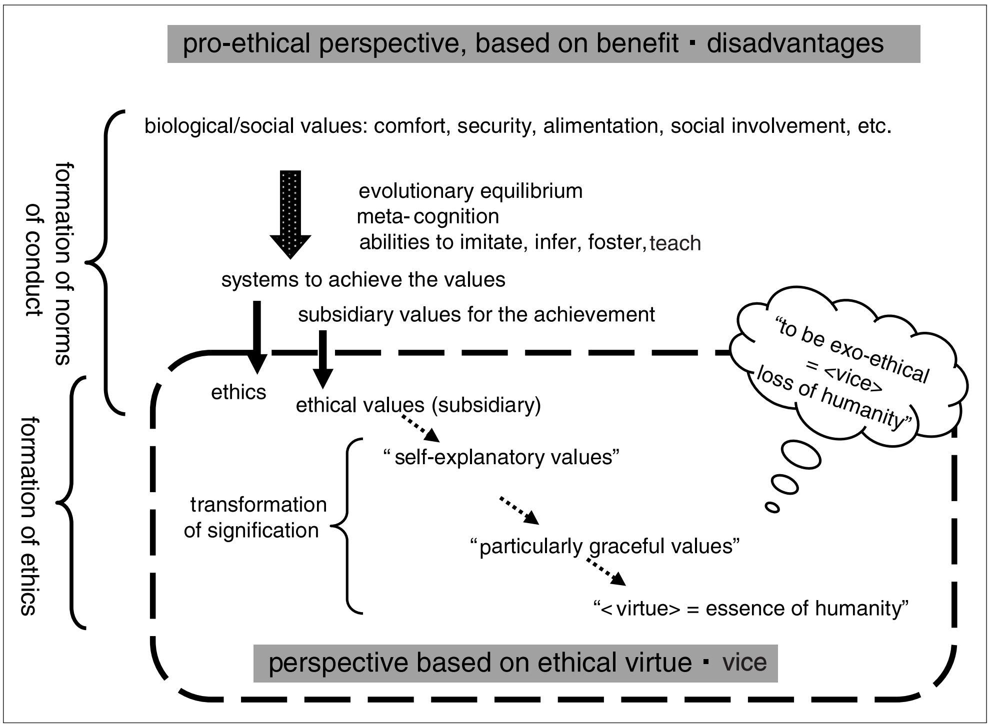
(3) When the baby sees someone smiling, it uses a reverse model of its own behavioral model and assumes that the person is experiencing a pleasant feeling (understanding others' emotions). Linguistic expressions such as "smile," "funny," "happy" and "pleasant" are linked with these assumptions through the language game.

(4) When the baby smiles (with a behavioral model), it uses understanding of others (perception model) and associated linguistic expressions to form understanding of its own emotions, i.e., "I smile because I'm happy."

It is expected that such a series of phenomena and brain algorithms can be constructed in robots to evaluate the mechanisms by which human interaction develops the elementary functions of emotion.

Children are believed to develop a "theory of mind" (a theory about the state of others' minds, which is unverifiable) to estimate and understand the mental states of others. Because it can be said that one "has a theory of mind" when becoming capable of estimating another's beliefs, intentions, and knowledge, this can be tested with the ability to discern a false belief in another (a false belief task). Research on monkeys showed that a theory of mind could not be detected with false belief tasks, even though they demonstrated joint attention and other abilities necessary to establish a theory of mind[32]. Human babies seem to develop such abilities spontaneously. However, to allow children to fully develop a theory of mind, it is important that parents and caregivers talk to and respond to them as if they already had a complete theory of mind, even before children have actually developed one. Monkeys and current robots cannot develop their own theory of mind in response to humans, even if humans project emotions onto them and interact with them as if they had minds. Simulations of human development with robots will shed light on mechanisms (1) to perceive communication behaviour from others and to form in oneself a model for the same behavioiur and another model of one's own mental state, induced by communication, and then (2) to act upon younger

Figure 5 : Mechanisms for the generation of norms of conduct



Prepared by the STFC based on References [33, 34]

conspecifics to help them develop a theory of mind.

6-3 Research on the mechanism for establishing social codes of conduct

Since human beings are highly social animals, codes of conduct are significantly influenced by the interests of the community as well as those of individuals. Social psychologists believe that algorithms concerning the generation of social comportments and social codes can be mathematically formulated, while taking into consideration evolution and the balance of rewards resulting from selfish behavior and altruistic behavior (evolutionary stable equilibrium[33] in Figure 5). For instance, individual drivers on a freeway choose their lanes and speeds based on their own best interests. On a macroscopic level, however, the movement of a group of vehicles on a freeway can best be described by fluid dynamics. While it is almost impossible to convey an algorithm for the relationship between the behavior and interests of an individual driver to the mass of drivers, developing an algorithm for the optimization of the macroscopic movement of a group of vehicles is relatively easy, and it could be "genetically" passed on to all drivers. This also applies to the generation of behavior patterns in many non-human organisms as well.

Because such genetic factors impose only loose constraints on individual human beings' behavior, diversity is generated. In humans, neural circuits have developed that enable humans to (1) imitate the actions of those who are closely related to themselves, (2) observe others and imitate actions that have brought them profits, (3) integrate the actions of others into their own inventory of actions (learning), (4) reverse the neural model for behavioural learning and use it to interpret others' behaviour and to infer their mental state, (5) change their own behaviour according to such understanding, and (6) generalize cognitive and behavioral procedures acquired in actual situations to apply them to different situations (meta-recognition). At the same time, humans have acquired the computational ability to predict and evaluate, from distant temporal and spatial perspectives as well as actual ones, rewards (safety and comfort) and punishments (risk, hunger, isolation, instability of the community as a whole, etc.) resulting from their own actions.

Robots in the form of experimental rodents were designed to simulate the neural networks responsible for reward prediction and evaluation (Cyber Rodents). Parameters of their expectation of rewards, patience for reward acquisition, and sensitivity to punishments are manipulated and the various behavioral patterns are analysed[35]. The rodents are designed to give and receive battery chips (foods) and to imitate others' behaviour, so that their learning, propagation, and genetic transfer of social behaviour can be simulated. Through the fusion of research of evolution in biology and anthropology, social psychology and cognitive robotics, it is expected to clarify the genetic bases and algorithms of cooperative behaviour.

The algorithm to optimize the interests of the community is rather something to minimize the possibility of the majority of people suffering from evil deeds than to prohibit specific individuals from committing an evil deed. If one cannot infer another's mind that "wants not to suffer" and cannot control one's behaviour based on estimation and understanding, her/his evil deed will never be self-controlled. Groups of robots that simulate cooperative behaviour can facilitate exploration of the relationships between the theory of mind and ethical behaviour.

It may be possible that human specific psychoneurosis and behavioral disorders have resulted from an enormous increase in the amount and complexity of information processing in the brain and patterns of social behaviour. For example, it is supposed that "schizophrenia is a by-product of the evolution of linguistic ability," and that "the dissemination of phonemic characters, printed documents, and new technologies have changed human sensory and cognitive patterns" [36]. In the course of increasing the complexity of cognitive functions of robots to make them more humanlike, researchers may accidentally and unexpectedly encounter robots that display cognitive/behavioral patterns inconvenient to others. Given that advances in neuroscience have been driven in part by the elucidation of neurological disorders and developmental diseases, scientists can build robots that simulate diseases that may cause deviations from normal cognitive/behavioral patterns under specific conditions, and analyze them to elucidate how the brain shifts between normal and abnormal states. They can also develop systems that are robust against deviation from normal states.

Most scientific findings on the unconscious sides of mental processing, decision-making, and the manifestation of codes of conduct may not be compatible with "naive psychology," relying upon the conventional understanding of the world. Although people may benefit from scientific knowledge, it is not always easy for them to use such knowledge to interpret their daily lives. Indeed, people may not need such knowledge in their everyday lives.

It is important that philosophers and social scientists engage in research in cognitive robotics by analysing findings from their own viewpoints in order to formulate theories and models compatible with the real world.

7 Ethical Debates Raised from Cognitive Robotics

In a stable society, perhaps "the fact that morals are nothing but means (to realize a safe and comfortable society) is better kept as tacit knowledge. Therefore, people may prefer to be passively convinced of morals"[34] ("formation of ethics" in Figure 5). This is a reason why explanations of human behaviour with pro-ethical values, such as profit/loss, or comfort/discomfort, are in themselves considered a vice. Ordinary people may not necessarily feel agreeable about sciences clarifying the mechanism by which norms of conduct are formed.

In human history, there have been many occasions when existing moral systems had to be reviewed and reconstructed facing the collapse of social orders or in the course of social reform. Traumats of these events have been passed down in the form of myths, legends, and histories. In general, Japanese natural scientists know little about the relationship between the formation mechanisms of ethics and norms of conduct, although they are usually eloquent in explaining the latter. It is imperative to involve social scientists and cultured persons in debates on desirable procedures to communicate scientific knowledge to the public and on the social impact of scientific knowledge. Political efforts will be needed in such areas to organize forums collecting participants from diverse fields.

Those who believe in the existence of virtue and vice without questioning their origin may assume that advances in genetics, neuroscience, and behavioural sciences will make it possible, through appropriate use of medication and gene manipulation, to prevent individuals "born with the propensity to commit crimes" from committing actual deeds. However, if neither virtue nor vice is inherent in each individual, this prediction or expectation is misplaced.

For academic disciplines intended to improve our understanding of humanity, broad and serious discussions should be held not only on how far we can explore scientifically, but also on how far we can conduct research and whether there are areas, topics, and depths that must not be reached. If such discussions result in a decision whereby some restrictions should be imposed on research activities, actual procedures to implement them would then have to be discussed, and conclusions should be made publicly available to ensure effective implementation.

8 Policies to Promote Cognitive Robotics Research

8-1 Fundamental concepts in cognitive robotics

For new sciences and technologies to emerge and advance, conceptual bases of development is required. Crucial concepts arise in the very early stages of research. They influence the selection of noteworthy issues, effective methods, and feasible goals, and impact on the feedback circuits of verification processes. Researchers should recognize a comprehensive framework of concepts from their earliest inception and intentionally construct theory likely to lead in the direction of their ultimate goals.

Humanoid robot research is based on a variety of visions and concepts (Table 3). For example, in Japan the concept of "mechatronics" was proposed in the 1970s as a complete fusion of mechanics and electronics. The idea of compromising quite different elements has been described as very Japanese[16]. One Japanese robotics researcher states, "although the creation of the concept of mechatronics may have had no direct influences on society, it helped Japan decide in which direction to go, and with this reliable guide into the future, people felt at ease to follow the direction" [37].

Mechatronics was a product of the fusion of scientific concepts among different areas of engineering. By contrast, cognitive robotics to understand human beings, as an emerging discipline, requires the incorporation of concepts from fields other than the natural sciences and engineering, interaction among vague notions that have yet to be established as academic

Table 3 : Fundamental concepts of humanoids

Concepts	Effects • Results
A biological system can be studied, in principle, relative to the analogy of machines (Macy conferences, 1946 - 53)	Feedback
Based on biological principles, machines can be designed to have biological functions.	Bionics (1960 -)
In order to release humans from labour that is unsuitable for humans (monotonous or tough), machines should be created to undertake it (Wiener)	Automation
Mechatronics The unification of mechanics and electronics (1972 -)	Amelioration of structure / actuator / control systems of robots
Autopoiesis, neural network, connectionism	Robustness of robots against incidental changes
Embodiment, embedding, situated	Emergence
To investigate information processing of the brain to the extent that artificial machines, either computer programs or robots, can solve the same computational problems, as the brain, essentially in the same principle	Cognitive developmental robotics (1994 -)
Comprehensive studies, including theories & the humanities	Cognitive robotics

Prepared by the STFC based on References [3,37] theories (requiring the creation of new fields), and interaction with real-world knowledge, culture, and naive psychology, which are not academic disciplines.

8-2 Emphasis on theory-oriented research

In Japan, research in both neuroscience and robotics often focuses on material oriented subjects, as described in Figure 1. For example, neuroscience focuses on analysis of the brain's structure and functions, while humanoids research emphasizes the development of structures and actuators, and the analysis of their motor controls. The same tendency is seen for research budgets. While large budgets are appropriate for research projects in experimental brain sciences and research intended to lead to physical products rather easily, it is hardly the case for those in theoretical and mathematical research. Psychological, theoretical and computational research is essential for a comprehensive understanding of brain functions and the mechanisms of the mind based on physically oriented research, as well as for building robots with cognitive patterns so humanlike as to be able to walk autonomously in actual societies. However, such less material-orientated researches are often despised. Although Japan has had outstanding researchers in computational neuroscience for many years, they remain few in number and have little opportunity to interact with most experimental neuroscientists and robotics researchers. Participation in brain science by mathematicians and theoretical physicists is also insufficient. Some Japanese humanoids manufacturers take advantage of European strengths in mathematics and physics by assigning European labs to perform research on cognition and theories of cognition-behavior correlation, while their domestic laboratories develop exclusively structures and actuators. While broad cooperation with overseas researchers may be important, Japan should first consolidate its own human resources for research, and facilitate domestic exchanges of knowledge and ideas for further refinement. As research in brain systems, including their interaction with the body and the environment, advances, research may reach a point where it cannot progress farther without breakthroughs in research on functional units, such as visual or auditory, and modules. A potential solution is ensuring an environment in which research projects adopting diversified approaches, ranging from analytical study of individual functions to comprehensive research on systems, progress in parallel while interacting with each other. This is essential for the culture of science to thrive in this country.

Japan should therefore first build a continuous chain of knowledge sharing and cooperation on various levels, through material-oriented research in biology, theoretical and mathematical research, to material-oriented research in engineering. For example, researchers in neuroscience, psychology, and engineering may as well provide opportunities to clarify the theoretical problems that must be solved for the construction of robots, to consult extensively with mathematicians and theoretical physiologists on how these problems can be solved, and to cooperate with these scientists in solving the problems.

8-3 Selective promotion of philosophy and social science

The relationships between mind and body, the self, conspecifics, or the environment are subjects of research, not only in the natural sciences, but also in the humanities and social sciences. Scientific findings on the human mind usually require verification by philosophy and social science before they can be seen as truly applicable knowledge in society. Natural scientists would have to be reinforced with philosophers and the social scientists in order to clarify visions and conceptual framework of their research.

However, in today's Japan, there are not enough research activities in philosophy and the social sciences that could immediately make such contributions. An effective solution is to clearly distinguish research that rigidly adheres to the history of philosophy (or social science), to the interpretation of preceding studies, to imported knowledge or to issues focusing only on lectures, from that research endowed with flexible thinking and the potential for verification that allows research to address actual problems in the world. At the same time, research organizations should selectively hire researchers with flexibility and criticism. This will help foster philosophers and social scientists who can derive original ideas, using cognitive robotics as a practical test platform.

Philosophical research should not necessarily be confined to the department of literature of universities. The efficiency of philosophical research could be improved by moving philosophy laboratories from environments that can no longer encourage the proposal of new questions and solutions to centers of active research in natural sciences and engineering, such as cognitive robotics and neuroscience. This would allow philosophers to perform research that involves interaction with researchers in other fields. Philosophers could verify their theories through psychological experiments and simulations with robots, while researchers in robotics, cognitive science, and neuroscience could seek advice and criticism from a philosophical perspective on their research concepts and interpretation of experimental results. Providing philosophy laboratories that adopt such research systems with as much research funding as natural science research labs receive, namely to a level sufficient for conducting simulation experiments by themselves, would raise the self-esteem of active philosophers. Another effective measure would be to allow philosophy majors to be fostered in such research laboratories, after being taught in basic undergraduate programs for two years, so that they could develop new areas of research outside the traditional world of philosophy research.

8-4 Establishing a virtual research center

When there are several organizations on the frontiers of research, they can operate more efficiently when combined into a research center where they could develop comprehensive visions and conceptual framework and verification systems. It would also serve as a driving force for other research projects and organizations. In a situation where this is not immediately feasible, an effective alternative is the establishment of a virtual research center that can provide ample funds, better research environments, and release from routine burdens, as well as assists in contacting and cooperating with other domestic or overseas organizations. Guidelines, objectives, and evaluation of the outcomes of research conducted there must be made widely available to the public.

In this virtual research center, graduate students and postdoctoral researchers (e.g. in philosophy, psychology, theoretical biology, mathematics, etc.) would be allowed to constantly participate in research activities of engineering and information technology labs. For example, a cognitive robotics research project at a mechanical engineering lab may need the in-situ participation of researchers in philosophy, psychology, and theoretical biology, but it is often not easy for the lab to hire specialists from other fields or to grant their academic degrees. By hiring researchers and assigning them to such a lab (or labs), the virtual research center could benefit by flexibly utilizing competent human resources and broadening researchers' perspectives.

8-5 Developing science policy perspectives based on advanced research

The paradigm "to investigate information processing of the brain to the extent that artificial machines, either computer programs or robots, can solve the same computational problems as solved by the brain, essentially in the same principle," has inspired research attempts that are quite radical, albeit scarce. It spurred movements to verify theories and models of the human brain by integrating findings in diverse fields and constructing robots, even before brain structure and functional modules were completely elucidated. This approach of "constructing robots at first"[8] and attempting verification second assumes that robots can be made with minds, based on a broad understanding of what the mind is. This yields higher intellectual productivity than the conventional approaches of "taking an action only after it has been enforced with theories in a specific field."

Many of these researchers have promptly introduced findings and perspectives in psychophysics into their research. As a result, they have come to address consciousness and unconsciousness and the boundary between subject and object, i.e., the self, in addition to traditional approaches on individual function, such as sight, hearing, motion, memory, or emotion.

The significance of such radical approaches originated by Japanese researchers has caught the eyes of European and American researchers and science policymakers more quickly than their Japanese counterparts. For example, the European Commission launched research projects such as Neurobot and Cognon in 2004 under the financial support of its 6th Framework Program, forming consortia to promote them. Unlike Japan, Europe is skeptical of the idea of producing humanoids for the use of the general public, but in 2004, it organized RobotCub, a consortium to create infant-like robots as an open platform for research in cognitive science and neuroscience. Now that humanoid robots made in Japan are employed at overseas research institutes, European and American researchers are going to use them actively as platforms for developing software to serve as the cognitive mechanisms of robots.

Many administrators working in the European Commission have doctorates in specialized areas, such as science, engineering, medicine, and psychology. They have carried out research and written scientific articles by themselves. These experts are engaged in diverse areas of work, ranging from general research funding to science and technology foresight. When innovative articles and reviews are published, these officials can detect their potential and significance at an early stage and plan and promote research projects in those areas. Although Japanese organizations participate in the European Commission's consortia, so far there has been no Japanese equivalent. There is even the possibility that the buds sprouting from the seed of Japan's advanced research will be harvested in Europe. As certain Japanese researchers stand at the forefront of the world research community, the Japanese government should have a comprehensive plan to promote their research by clarifying what kind of system of knowledge should be constructed and how scientific findings should be applied for future social systems.

9 Conclusion

Knowledge on the human mind and behaviour has to be shared by all human beings. During past debates over the Human Genome Project and the patenting, industrial application, and market value of the DNA sequence, a major concern was, "to whom does the human genome belong?" The question "to whom does knowledge of the human mind belong, or can it belong to anyone at all?" is likely to spur even more serious debates. Japan should take leading roles in building a system that allows all people worldwide to share accurate knowledge. Particularly in the 21st century, applied technologies that make use of findings on human cognition or that control cognitive processes - so-called science and technology to exploit the brain - will no doubt bring advances in many ,fields such as economics, manufacturing, labor, entertainment, medicine, education, politics, and diplomacy. Preceding the spread of this sort of practical applications, the promotion of "studies to explore the brain" has to vitally deepen our fundamental understanding of the mind as actually grasped by human beings.

In cognitive robotics, scientists from different disciplines can unite, scientifically elucidate questions on the mind by using robots as a common concrete platform, and interpret those issues in social contexts. Because robots easily attract public attention, comparison of robots and human beings is expected to facilitate the discussion and examination of questions on the mind.

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2

Technical Trends in Optical Interconnection Technology
—Towards its Implementation in the "Keisoku" Supercomputer—

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1 Introduction

Japan is planning to launch a large-scale project to construct a 10 PFLOPS *1 level supercomputer, or Keisoku *2 supercomputer system, by FY2010 [Note 1]. The true value of supercomputer development lies in the widespread effects and ramifications it has on science and technology, rather than the effect on computing speed. It is expected to have a revolutionary effect on sectors such as healthcare, life science, automobiles, nanotechnology, and material science, to name just a few. It will enable such complicated calculations as: a simulation that covers the whole human body from genes to blood flow; a simulation of a car crash, accounting for all parts of the car; a simulation of the whole earth, using much higher resolution meshes than have currently been attempted. Detailed simulation of entities that have hitherto been out of the range of computing power will become a reality. Simulation results and drastically reduced computing times (Time to Solution) will surely contribute to maintaining a competitive edge in the international market. The development of a supercomputer is one of the key projects that will foster future technological development in a wide spectrum of industries.

The outlook of large-scale research facilities presented by the U.S. Department of Energy in 2003 ranked "UltraScale Scientific Computing Capability" in second place in terms of priorities for technical development over the next 20 years[1]. The U.S. is devoting more of its energy to scientific computing as a national project. This is clearly evidenced by the fact that the National Coordination Office for Networking and Information Technology Research and Development (NITRD) allocated more than 40% of its FY2003 budget (1,880 million dollars) to High-End Computing (HEC)[2]. IBM's BlueGene recaptured the title of world's fastest computer in 2004 by surpassing Japan's Earth Simulator according to the LINPACK benchmark*3, although this benchmark can cover only a limited range of measurements. It is against this backdrop of critical need that the large-scale project for the next generation supercomputer will be launched.

Many problems have to be overcome before this feat can be achieved. These include the conventional problems that always accompany computer development, such as the system architecture and software that are most suited to the computer. Additional problems arise from a hardware perspective - the new generation supercomputer will demand a much higher level of hardware resources and a transmission rate that is almost impossible with conventional hard-wired architecture. Optical interconnection is the most promising candidate for delivering a solution to the communication link problem for the supercomputer.

This article reviews the optical interconnection technology trend and also discusses the long-term direction of the Japanese supercomputer project. This theme includes the categories of ultra high-speed computers, such as a supercomputer, grid computing, cluster servers, and ultra high-capacity routers. The emphasis is on the next generation supercomputer.

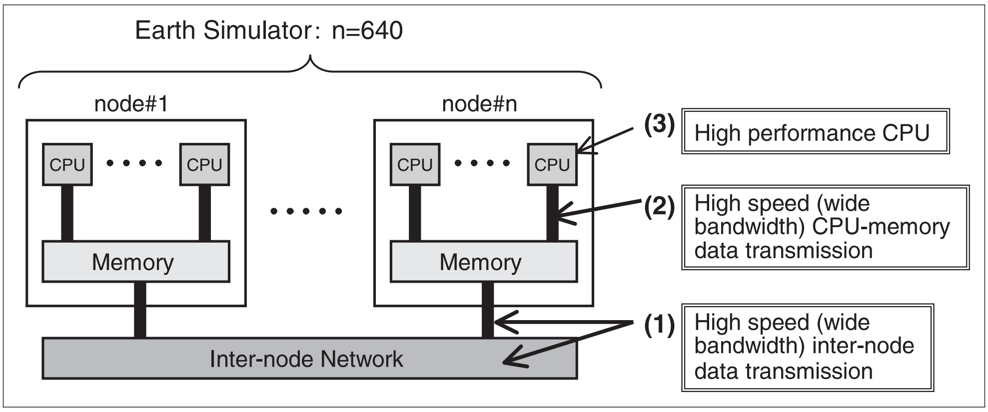
2 Limitations of Hard-Wired Systems

2-1 Limitation due to hardware resources

Figure 1 is a schematic representation of supercomputer architectures. A supercomputer comprises multiple nodes*4 that carry out parallel processing, each of which consists mainly of a CPU (Central Processing Unit) and memory. Parallel processing requires dense inter-node data communication that is generally realized by efficient control of communication counterparts by means of switches. This configuration, including the switch, is called an inter-node network. From a hardware perspective, acceleration of the CPU itself ((3) of Figure 1), CPU-memory ((2) of Figure 1), and inter-node ((1) of Figure 1) data transmission rates are essential for speeding up the system.

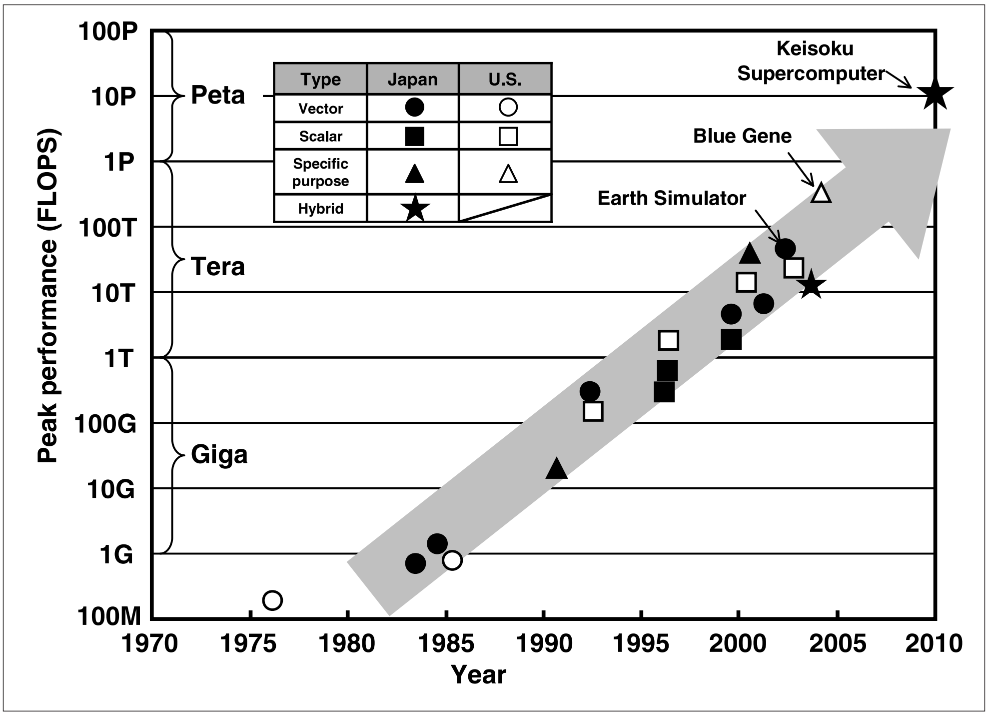
The recent history of supercomputer development is characterized by fierce competition between the U.S. and Japan[Note 2] (Figure 2). The Earth Simulator from Japan recorded 35 TFLOPS in 2002 using the LINPACK benchmark, but the title was recaptured by IBM's BlueGene in 2004, which attained 137 TFLOPS and was followed by the new record of 280 TFLOPS established by BlueGene in November 2005. Japan is planning to challenge the current

Figure 1 : Schematic view of the basic configuration of a supercomputer



Prepared by the STFC based on Reference [3]

Figure 2 : History of the U.S.-Japan competition in the development of a supercomputer



Prepared by the STFC based on Reference [5]

Table 1 : Comparison of material resource requirements (estimated value): PFLOPS-class supercomputer vs. Earth Simulator (use of currently available technology is assumed)

		PFLOPS-class Supercomputer (Peak performance 3 PFLOPS is assumed)	Reference: Earth Simulator (Peak performance 40 TFLOPS)
Crossbar switch		600	130
Conductor cable (inter-node connection)	number	270,000	83,200
	total length	20,000km (global scale)	2,400km (Japanese archipelago scale)
	weight	450ton	140ton
Power Consumption (ventilation included)		30MW (small-scale power plant)	5.5MW (transformer station)
Footprint		8,500m^2	3,590m^2

Prepared by the STFC based on References [6, 7]

titleholder by finishing development of the Keisoku supercomputer system in around 2010.

The race to develop supercomputers with improved performance has hitherto been supported by three main factors: a spectacular improvement in CPU performance (Moor's law), an increase in memory capacity, and parallelization. A next generation computer that surpasses the level of 10 PFLOPS is very likely to enter into uncharted terrain that a conventional technological approach cannot navigate.

According to a provisional estimate by Fujitsu Laboratories Ltd., constructing a supercomputer with 3 PFLOPS peak performance using Fujitsu's currently available technologies will require 20,000 km of total (coaxial) cable length for inter-node links, the total power consumption will be 30 MW, including ventilation, and the system footprint will be 8,500 m^2. This enormous cable length is equivalent to half the earth's circumference and a relatively small power plant will be required to supply sufficient electricity (Table 1). Naturally, the Keisoku supercomputer system, which will have a calculation capability of more than 10 PFLOPS, is expected to require much more resources and will therefore be very difficult to accomplish. These considerations conclude that, from the perspective of resource requirements, the next generation supercomputer will never be realized using only the conventional hard-wired architecture.

2-2 Limitations on the data transmission rate

As shown in Figure 1, the keys to higher processing rate can be summarized under three points: higher CPU performance, increased CPU-memory transmission bandwidth, and increased inter-node transmission bandwidth. It goes without saying that increased CPU performance is essential for better computing capability; another decisive factor for achieving "Keisoku"-level performance is a high transmission bandwidth to feed data to the CPU.

By around 2010, when the Keisoku supercomputer system will be realized, the CPU-memory and inter-node data transmission rate per channel will have to be much faster than they are at present. Conventional hard-wired technology has fundamental drawbacks in wide bandwidth transmission: the high frequency components of a signal are attenuated due to increased conductor resistance in the high frequency region and printed-circuit board (PCB) and cable material also degrade the signal intensity as frequency increases. The transmission distance has to be shortened for higher transmission rates to occur. This limitation has a crucial effect on the board and system design.

Possible approaches for higher transmission capacity using conventional hard-wired technology include multiplication of channels for more efficient parallel processing and multi-valued signals for better per-channel throughput. An increase in the number of parallel processing channels, however, makes the so-called skew problem (misalignment of data arrival time) more pronounced, as well as the increase in the pin outfits of the LSI package. Many techniques have been devised to address these problems: addition of skew-adjustment circuitry or encoding circuitry for a multi-valued signal, a pre-emphasis method for enhancing high frequency signal components, and an equalizing method to adjust the frequency component strength when a signal arrives. All of these techniques have a serious side effect in that they complicate and enlarge the LSI, resulting in larger power consumption. In addition, these techniques generally require special board material and a larger number of layers that necessitate difficult optimization layouts, including the through-hole arrangement, resulting in a significant load increase in the PCB design stage. Based on these considerations, it is generally accepted that the useful range of bandwidth for hard-wired circuitry is limited to below 10 Gbps per-channel [3].

The next generation supercomputer with a two-digit or more increase in processing rate compared to the Earth Simulator will inevitably result in a much higher level of parallelization. In view of the fact that the total number of signal lines linking the CPU and memory in the Earth Simulator amounts to 20,000 within one node, a new generation supercomputer implementation using only hard-wired technology will be a formidable assignment in terms of its size and complexity.

The situation is similar for both high performance servers and ultra high-capacity routers. Data transmission bottlenecks in inter-instrument and inter-board communications have become increasingly apparent. The amount of data transmitted will inevitably increase steadily both within and between instruments. To address the imminent hard-wired bottleneck problem, the development of an alternative data transmission technology that can replace the conventional method is urgently needed.

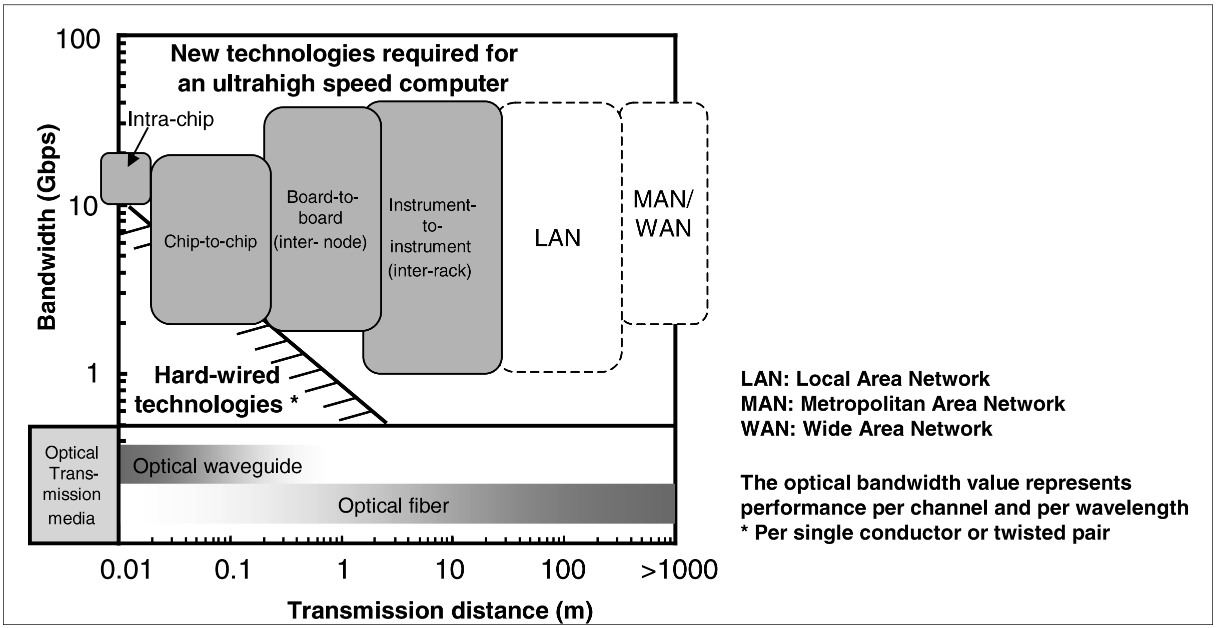
3 What is Optical Interconnection?

3-1 Definition of optical interconnection

Optical interconnection is the most promising candidate for providing a solution for the hard-wired deadlock. In terms of linkages using optical means, optical fiber communication has been in practical use for more than twenty years, mainly for long distance links between cities and continents. In contrast, there has not been a strong need for short-reach optical links. However, as the problems associated with hard-wired links become more apparent, this approach is gathering new focus.

The term “optical interconnection” is often called simply “optical wiring” or “optical interconnect” and can be interpreted in the broadest sense of the word as “any interconnection using optical means.” As this article focuses on its applications in ultra high-speed computers, we define “optical interconnection” as short-reach links between chips and instruments within several tens of

Figure 3 : Relationship between transmission distance and bandwidth (conceptual diagram)



Prepared by the STFC

meters, and make a clear distinction between short- and long-distance links (Figure 3).

3-2 Advantages of optical interconnection

Optical interconnection has many advantages over conventional hard-wired technology, including:

(1) High speed transmission capability independent of link length

Optical links show extremely small frequency-dependent attenuation and resistance, enabling longer and faster links, compared with hard-wired links.

(2) High density multiplexing and flexible implementation

An optical signal is noninductive, is immune to electromagnetic interference, and it has negligible effect on optical crosstalk due to without optical interference[Note 3]. These characteristics enable spatial 3D implementation of links and the use of multiple wavelengths in a single channel (wavelength division multiplexing, or WDM), leading to a dramatic increase in transmission bandwidth, depending on the number of wavelengths allocated to the channel.

(3) Reduction of material resources

As described in (1) and (2), the use of optical links can dramatically increase the transmission rate per channel and enable the use of wavelength division multiplexing. These factors lead to a reduction in material use due to the reduced number of channels required, elimination of electromagnetic shielding, a smaller transmission media diameter, and reduced wiring weight.

Thus, efficient use of materials is one of the many advantages of optical links, as well as extended bandwidth.

In general, the number of channels will increase as transmission distance becomes shorter, and the types of link media used are selected depending basically on the transmission distance. Optical waveguide is preferred for links between less than 10 cm apart, and optical fiber (single or ribbon) is preferred for longer links.

There are many elemental technologies that need further development for practical implementation of optical interconnection. These include vertical-cavity surface-emitting lasers (VCSELs) used as an array implementation of an optical source, a photo-diode receiver, various types of devices for optical waveguide and transmitters/receivers, a high-density mount design, a thermal design, and an electro-optical hybridization design.

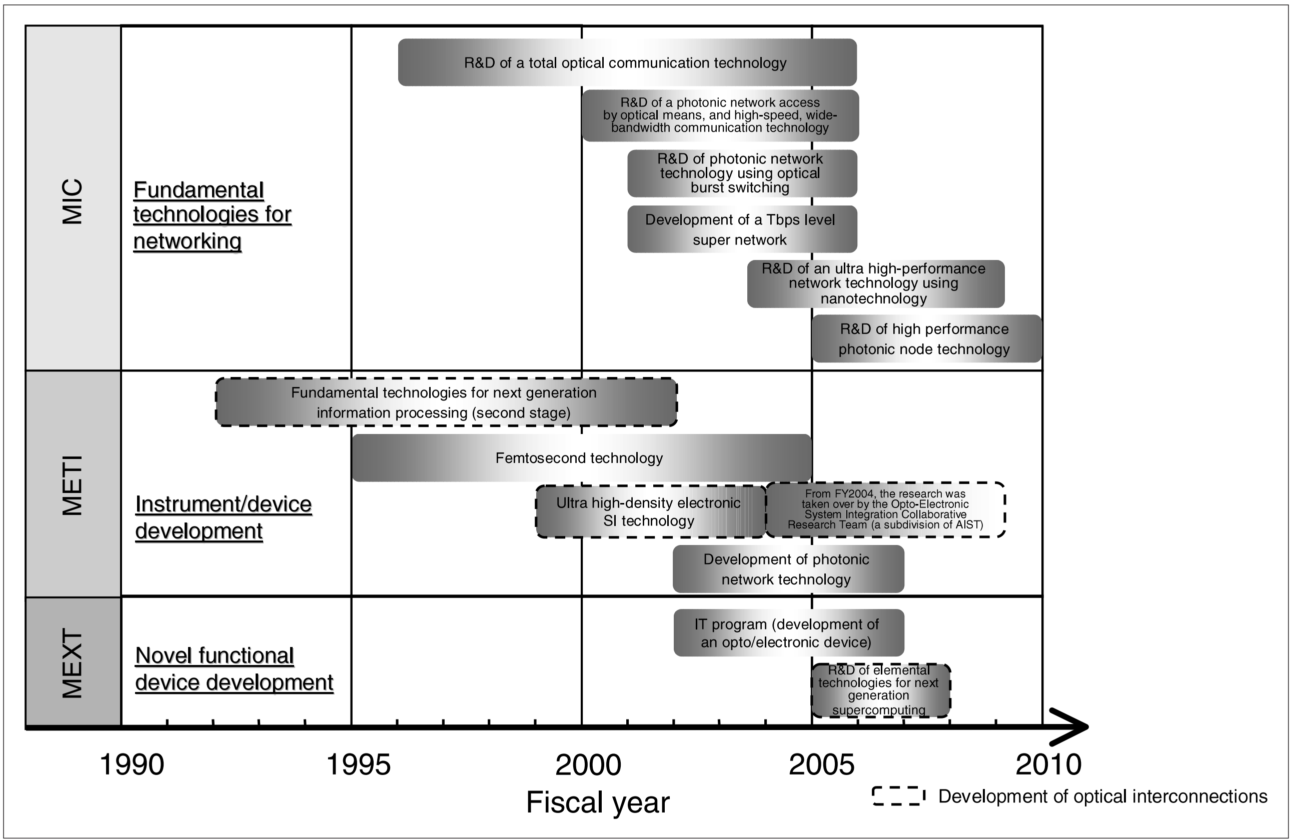
3-3 Past efforts in perspective

From the early days of research into optical communication, Japan has played a globally important role in the development effort in this field and has recorded such accomplishments as continuous wave oscillation of semiconductor lasers at room temperature and improvement/commercialization of optical fiber. It is still fresh in our memory that Japanese enterprises invested heavily from the early 1990s to 2000 in a wide spectrum of technologies aiming at commercializing optical communication systems. It was keeping pace with the booming economy in the U.S. and covered everything from elemental technologies, such as transmission media and transmitter/receiver devices, to system integration for long-distance, large-capacity communication.

Figure 4 lists the optical communication-related government projects in the past decade. In response to demand from the private sector, many of these were long-distance, large-capacity oriented research projects, such as “Research and development of total optical communication technology” (present Ministry of Internal Affairs and Communications, MIC) and “Femtosecond technology” (present Ministry of Economy, Trade and Industry, METI). Elemental technologies for optical interconnection were included only in some of the projects that belonged to “Fundamental technologies for next generation information processing,” which was aimed at the real computing world.

Although a variety of studies into optical communication have been undertaken, the majority of these have been metro-systems and access-systems oriented. However, the emphasis

Figure 4 : List of optical communication related projects supported by the Japanese government



MIC: Ministry of Internal Affairs and Communications
METI: Ministry of Economy, Trade and Industry
MEXT: Ministry of Education, Culture, Sports, Science and Technology

Prepared by the STFC based on Reference [8]

of research objectives is apparently shifting to short-range, intra-equipment communication used in such systems as the next generation supercomputer and ultra high-capacity routers. Optical interconnection is also attracting interest in line with this trend.

4 Technical Trends in Optical Interconnection for an Ultra High-Speed Computer

4-1 R&D in Japan

(1) R&D of elemental technologies for future supercomputers

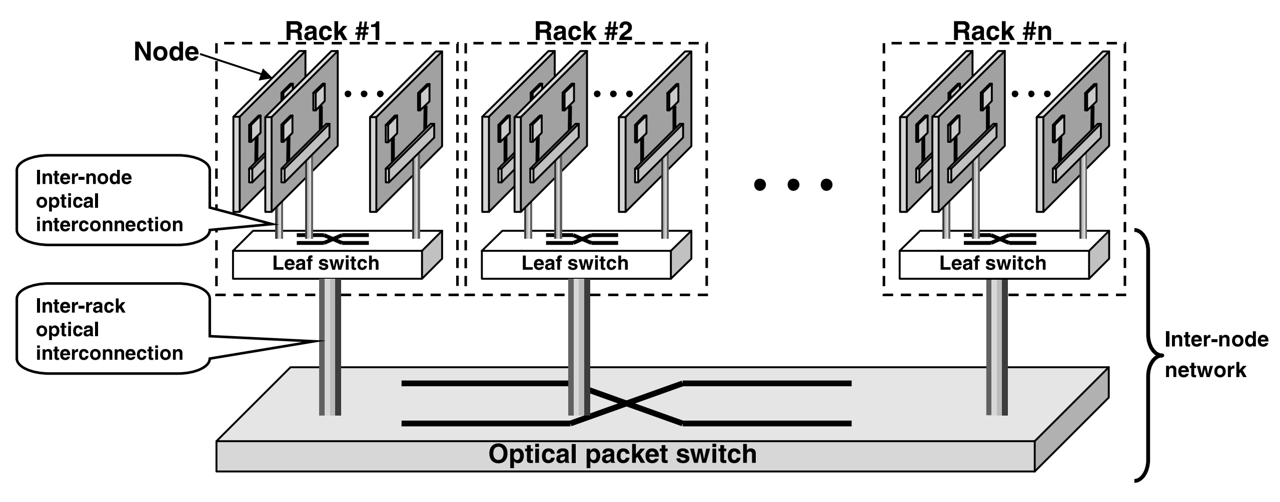
Japan is planning to launch a project to construct a supercomputer with a 10 PFLOPS level of computing power (the Keisoku supercomputer system) by FY 2010. In May 2005, two studies for this project were established with themes relating to optical interconnection aiming at "R&D of elemental technologies for future supercomputing"[9]. These studies are predicted to continue for three years through 2007. Both are industry-university collaboration projects aimed at elemental technology development for the realization of the Keisoku supercomputer system.

(i)Application of optical interconnection to inter-node networks

Kyushu University and Fujitsu Ltd. are planning to develop inter-node optical interconnection, aiming at eliminating the inter-node transmission bottleneck. The first phase of the project is to apply optical interconnection to the node-to-leaf switch link to enable much faster communication (Figure 5). This project includes comprehensive R&D from the definition and design of a board-level interface to the development of an optical module that is both small and fast. Application of optical links to node-to-leaf switch connection is expected to reduce electric cable resources to less than 10% of their calculated value (as shown in Table 1, more than 20,000 km of electric cable is required using hard-wired technology).

This theme also includes the development of rack-to-rack optical interconnection (Figure 5).

Figure 5 : Typical configuration of Inter-node network optical interconnection



Prepared by the STFC based on Reference [6]

Table 2 : Estimated CPU-memory transmission specifications: next generation supercomputer vs. Earth Simulator

		Next generation supercomputer (around 2010)	Earth Simulator (peak performance: 40 TFLOPS)	Earth Simulator ratio
Processing rate / CPU		> 100 GFLOPS	8 GFLOPS	> 10
CPU-memory transmission	Rate per signal line	> 20 Gbps	0.5 Gbps	> 40
	Number of signal lines per CPU	1,000 signals (optical)	2,000 signals	$\frac{1}{2}$

Prepared by the STFC based on Reference [3]

Combination of these technologies is expected to greatly enhance the node-to-node and inter-node network communication rate, as shown in (1) of Figure 1. The main point of this approach is to apply an optical packet switch in place of the existing electric crossbar switch, which requires the development of a new semiconductor optical switching device with nanosecond level switching velocity. Optical packet switching can directly switch an optical signal, providing such advantages as a reduction in the number of cables required by using WDM technology, a reduction in the number of switches required by lumping switching capabilities in fewer devices, and the elimination of E/O and O/E conversion devices. These advantages combined will contribute to a drastic reduction in the amount of material resources and power consumption.

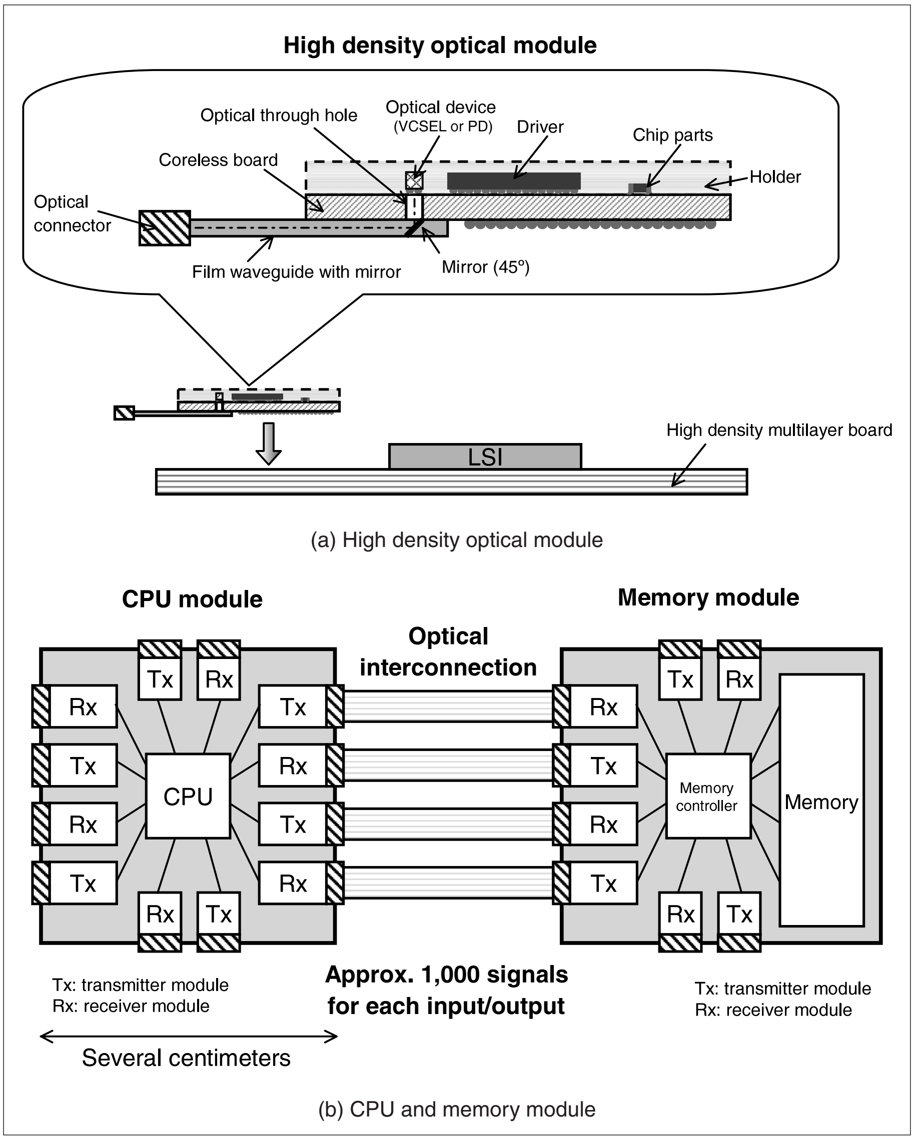
(ii)Application of optical interconnection to the CPU-memory link

Progress in the data transmission rate between the CPU and memory has been relatively slow, compared with the amazing speed at which CPU performance has improved. This may be a worrying situation in future computers as the CPU-memory transmission rate limits the total performance of the system.

NEC Corporation and Tokyo Institute of Technology are currently undertaking research into optical interconnection between the CPU and memory as an alternative technology for speeding up the CPU-memory link ((2) of Figure 1), which would be the world's first instance of such a link if it is successfully developed. The performance target is optical interconnection with a signal transmission rate of more than 20 Tbps per CPU.

A provisional estimate by NEC predicts that CPU performance will surpass 100 GFLOPS in the years around 2010 (Table 2). Assuming a 0.5 Gbps transmission rate per signal line (equivalent to those used for the Earth Simulator) and pursue a performance upgrade simply by extension of parallel processing, one CPU will require a prohibitive 25,000 signal line outfit. Reducing the number of signal lines required by enhancing the transmission rate per line is highly desirable, and

Figure 6 : Configuration of CPU-memory optical interconnection



Prepared by the STFC based on Reference [3]

this would also be an effective way of avoiding the skew problem. From these considerations, the target rate for CPU-memory transmission is set to 20 Gbps or higher, more than a 40 times increase on that of the Earth Simulator, and the number of signal lines per CPU will be halved to 1,000 by extensive employment of optical links. These factors all add up to a targeted system performance of 20 Tbps.

More specifically, a high-density optical module (Figure 6) will be developed and it will be mounted on the same board with other LSIs. Using currently available technologies, the module will take up nearly the size of a tatami mat (1-2 m^2). The module footprint must be reduced to several square centimeters by taking full advantage of optical links. To realize these objectives, the group is scheduled to carry out multifaceted studies, including the development of a high-density packaging technique for a high-speed optical device (>20 Gbps), and research on the integrated design of an opto-electric device/system to combine optical technology and LSI technology.

(2) Application of optical interconnection to ultra high-capacity routers

Proliferation of visual data on the Internet, in addition to text and audio data, is certain to continue. Spurred by this trend, switch capacity is expected to double every year[10]. Current technology routers will certainly be a bottleneck with respect to the proliferation of data: this is one of the areas where hard-wired technology is reaching its limit.

According to Hitachi Ltd.'s estimate[10], a hard-wired scheme for ultra high-capacity routers that surpasses 2 Tbps per switch fabric will reach the limit of feasibility because of the large amount of power LSIs require and economic problems due to the excessive number of pins required for such a layout. Hitachi is now developing an intra/inter-optical interconnection used for routers. The development effort in the first stage is expected to focus on an electro-switch centered backplane configuration to reduce I/O pins.

Inherently, however, replacing an optical router's electro-switch with optical packet switches is desirable, as is the case with inter-node networks. Research on optical routers is also being carried out in other projects, including the "Development of photonic network technology" (METI) and some of the photonic network projects under the auspices of MIC. Well-organized mutual exploitation of the results obtained from these optical inter-node networking and router development projects is expected to have a beneficial effect on overall progress.

(3) Technology inside the chip: for a higher transmission rate

As the processing capacity continues to increase, the need for an optical link moves from the inter-node to inter-chip, and further into the intra-chip level. This is one of the fundamental requirements for achieving ultra high-speed, as shown in (3) of Figure 1. To cope with the future intra-chip bottleneck, research on elemental technologies used in developing an intra-chip optical link has already begun. In recent years, a silicon-based approach (silicon photonics) has attracted strong attention in this area. This approach integrates silicon electronic devices and optical integrated circuits.

NEC announced in February 2005 the successful development of a silicon photodiode that can be used as an optical receiver for an intra-chip optical link[11]. The operational frequency range of silicon devices has been limited to below several GHz. Its lower carrier mobility compared with compound semiconductors and its poor photosensitivity have hindered high-speed operations. Because of this drawback, optical receivers for long-distance communication are manufactured using compound semiconductor technology. NEC focused on a silicon surface resonance plasmon*5 and achieved an operational frequency of 20 GHz; further, the company reached 50 GHz in December of the same year[12]. The possibility of a 100 GHz operation, in principle, has been reported by using the same technology and reducing the receiver surface area. This technology represents a new possibility for the realization of optical intra-chip links and it also has broad implications outside the domain of the intra-chip signal path problem.

In addition, a new technique has been reported[13] for forming a fine line waveguide by etching silicon (Photonic wire) that is capable of high-density integration inside the chip and provides high-speed, low-loss optical transmission. The future development of photonic-wire technology deserves attention because it is not only an integration technique for silicon, but it also has wide applications for implementing optical modulators and filters.

4-2 R&D in the U.S.

(1) National projects

The U.S. government certainly appears to be enthusiastic about propelling optical communication technologies for both long and short distances. Table 3 shows the list of optics-related projects that are supported by the Defense Advanced Research Projects Agency (DARPA) of the U.S. Department of Defense. The wide variety of applications shown in this chart clearly exemplifies the well-established system for supporting multi-faceted optical technology development.

As for optical interconnection, a project called "Chip to Chip Optical Interconnects (C2OI)", a four-year project, started in 2003 and now is in progress. As the name indicates, the objective of this project is to establish inter-chip optical interconnection. The members of this project are listed in item "C2OI" of Table 4, indicating that this is a government-industry-academia collaboration in which each member entity will take full advantage of past research results. One project that deserves special attention is the

Table 3 : List of DARPA's optical technology related projects

Project name	Period	Budget (Million USD)	Summary
Analog Optical Signal Processing	2002-2005	37	Performance enhancement of the RF system by means of optical analog signal processing technology.
Chip to Chip Optical Interconnects	2003-2007	45	Inter-chip optical link technology. High-speed link between processors.
Chip-Scale WDM	2002-2005	40	R&D for a next generation dynamically re-configurable network using WDM and its components.
Data in Optical Domain - Network	2002-2006	60	Development of a >100 Tbps scalable optical router using electronics, photonics and MEMS technology.
Optical CDMA	2003-2007	45	Proposal for hardware used for optical CDMA and networking architecture.
Photonic A/D Technology	1998-2001	40	Establishment of a signal digitization technology by means of optical processing. Centered on the development of a mode-synchronization laser and a high-speed modulator.

DARPA: Defense Advanced Research Projects Agency
* Period and budget are compiled based on the planning documents submitted in response to public offerings.

Prepared by the STFC based on Reference [14]

Table 4 : C2OI project membership

Member	Summary of development
IBM, Agilent	System demonstration. 40 Gbps transmitter device technology
University of California Santa Barbara University of Texas at Austin	40 Gbps transmitter device technology 40 Gbps amplifier-less optical receiver device technology
Colorado State University	High speed VCSEL technology
Mayo Foundation	Evaluator
US Army Research Lab	Integration technology and low-power transmitter/receiver device design (University of Delaware)
The Air Force Research Lab	Evaluation of polymer materials Waveguide fabrication method
MIT Lincoln Lab	Architecture

Prepared by the STFC based on Reference [15]

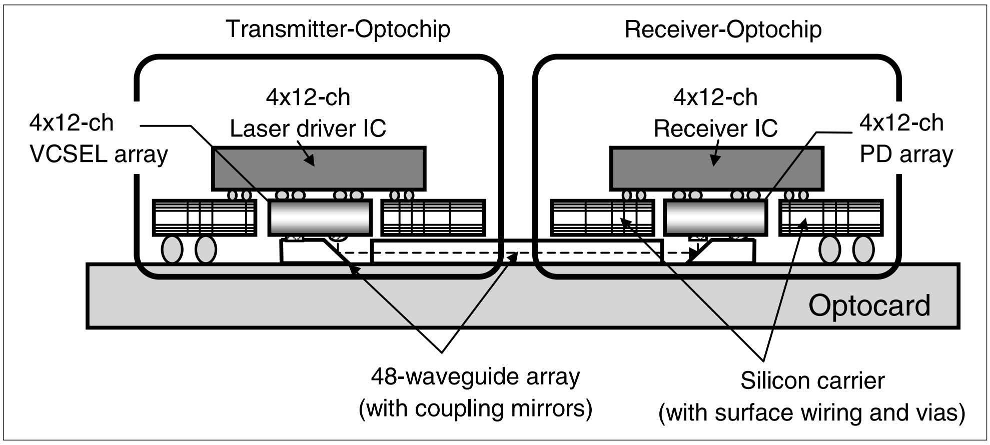
"Terabus", a joint research project between IBM and Agilent Technologies. To this project alone, 30 million dollars has been allocated in four years.

The amount of information handled by the server is ever increasing: total bandwidth inside the server has increased tenfold in four years. IBM predicts that in 2010, a total bandwidth of 40 Tbps will be required for inter-processor transmission. The Terabus project aims to provide a solution to this problem and its final target is to establish a low-power, low-cost, small-sized transmission solution by 2010. The projected configuration of the Terabus solution consists of an optical transceiver module (Optochip) mounted on the PCB that incorporates waveguides (Optocard), as shown in Figure 7.

The immediate target of the project is to achieve a >20 Gbps transmission rate per channel (the initial target is to achieve 15 Gbps), and to construct a 48-channel system to establish >1 Tbps performance. High-density implementation of optical waveguides (line-to-line distance: 62.5 μm) will enable the system to have a footprint of only 1 cm^2. A future objective is to achieve a 40 Gbps transmission rate per channel.

IBM and Agilent Technologies were invited to speak at ECOC2005 (the largest optical communication society meeting in Europe, held in Scotland in September 2005) and announced a successful 48-channel parallel transmission. Each channel of this system has a transmission rate of 20 Gbps per transmitter channel and 14 Gbps per receiver channel[17]. The 0.13 μm-CMOS technology was used to fabricate a high-speed driver and receiver, aiming for low power consumption per channel (<10 mW/1 Gbps). The announcement clearly showed that the U.S. is

Figure 7 : Terabus configuration



Prepared by the STFC based on Reference [16]

making steady progress according to its roadmap. Japan, on the other hand, is only launching a full-scale project in the days ahead and is lagging behind the U.S. in device development.

These development projects for high-speed optical interconnection technology are also in line with the roadmap laid out for the U.S. High-End Computing (HEC) plan [18]. In the near future, the results of these projects will be fully exploited for the realization of HEC. The fact that IBM, creator of BlueGene, is undertaking R&D activities for the Terabus project seems to indicate that it will commit deeply to the HEC plan in the future.

(2) Other trends

Intel is carrying out silicon photonics research to further develop its proprietary silicon technology. This move is also a future provision against the hard-wired scheme bottleneck. Intel is proactively driving R&D in optical technologies: “Today, optics is a niche technology,” said the Senior Vice President Patrick P. Gelsinger, “but tomorrow, it’s the mainstream of every chip that we build” [19].

The progress of intra-chip optical interconnection development deserves special attention. In February 2005, Intel announced the world’s first continuous wave oscillation of a Si-based Raman laser*6. The device was manufactured using standard CMOS silicon technology, which indicates the possibility of extending the technology into the domain of optical integrated circuits. If successfully developed, Intel will be able to mass-produce inexpensive optical devices using its silicon manufacturing technology. Intel's comprehensive ongoing efforts to develop intra-chip interconnection include, among other things, on-chip integration of an optical modulator[20] and receiver.

4-3 Technical challenges

Optical interconnection is the technology of the future and poses many challenges. From the selection of material to the method of implementation, we have not yet established standard methods. Because parallel transmission is the basic architecture suited for optical interconnection, VCSEL is the preferred scheme for the design of a light-emitting device that allows relatively easy parallel array structure. Still, it is to be noted that reliability requirements will become stringent as the level of parallelization increases. An imminent problem to be addressed is the sudden death of the key transmitter device VCSEL*7. This problem has been increasingly reported in recent years[21, 22], but some believe that it is just a matter of time until total resolution of the problem is achieved. This problem is directly connected to the reliability of the device and can very well hinder progress towards practical use of optical interconnection technology. Close cooperation across the related industries is desirable for early settlement of the sudden death of VCSEL.

The thermal problem is another important factor. The pursuit of higher density implementations will inevitably increase heat generation per unit area. For example, the CPU module shown in Figure 6, with a few centimeters on each side, will generate 200-300 W of heat. The degree of heat generation is closely related to the lifetime of the device: new cooling technology is needed to address this problem.

The final target is a totally optical system: this will reduce the number of electro-optical conversion modules required and offer the promise of drastically reducing the power required. One challenge to be overcome is optical route switching. This is an easy task for a hard-wired system, but the development of devices for memorizing optical states and route switching using optical means is still in its infancy.

In light of these formidable challenges, it is highly unlikely that the hard-wired scheme will be replaced by optical links in a straightforward, one-step fashion over a relatively short time period. Rather, it will be a gradual process and the steps are likely to proceed in the following sequence (based on predicted level of difficulty): inter-node, CPU-memory, and finally intra-chip links.

5 Future Directions

5-1 Need for a strategic roadmap

The Japanese supercomputer project has hitherto lacked the continuity typically exemplified by the development of the Earth Simulator. Such an isolated project cannot foster the continued development of elemental technologies. The Council for Science and Technology Policy, which discussed the subject “Development and utilization of an advanced, high-performance general-purpose supercomputer” in November 2005, has already pointed out that the lack of a roadmap for next generation machines is one of the main reasons why Japan has fallen behind the U.S. in the race to develop a supercomputer[23]. A long-range strategy based on a roadmap is essential for future technological development in Japan. The roadmap should be envisioned as a comprehensive guiding principle not only for supercomputers, but also for ultra high-capacity routers with the imminent need for much higher speeds. One of the main themes for the roadmap is to present a grand picture of the process of replacing hard-wired technology with optical methods.

The long-range strategic roadmap will enable the launch of more challenging elemental technology development than can be achieved in an isolated project. For example, a development project for a future technology, such as intra-chip optical interconnection, can be launched early along the lines of a national project. Although each private sector entity acknowledges the need for optical interconnection technology and undertakes their own development, the resources allocated to, and the time requirements for these preemptive projects are naturally limited, unless it is directly related to the business in hand. Judging the situation in Japan from an objective perspective, hardly any company is willing to give priority investment to these tasks without the promise of continued support and guidance from the national engagement.

With continual and consistent planning, or a strategic roadmap, Japan will be able to position elemental technologies, such as optical interconnection, in the grand perspective of a long-range strategy. This will enable a long-range, steady development effort, without losing focus as can occur in an isolated project, to foster optical interconnection as one of the core technologies required to realize the next generation Keisoku supercomputer system, even more advanced computing and ultra high-capacity routers.

5-2 Strategic arrangements for the future

As is well evidenced by the fact that the level of supercomputer performance in past decades has already been realized in commercially available PCs, it is only a matter of time before hard-wired connections will be considered the bottleneck for these off-the-shelf products. It is fairly certain that, in the near future, optical interconnection will be the integral part of the CPU system. As is well known, the CPU market for commercial computers is almost entirely dominated by Intel. Incorporation of optical interconnection to inter-chip and intra-chip links is certain to inspire drastic modification of the current architecture, which may trigger a revolution in the competitive landscape. Superiority in optical interconnection technology could act as the cornerstone for gaining a competitive edge in the next generation CPU, memory and other peripheral devices. Inter-chip and intra-chip links require quite a high level of technology that can provide a long-standing, sustainable technical advantage to the developer. Technological development of optical interconnection is still in its infancy. Timely investment in this area based on a well-laid strategic roadmap will amply reward the effort.

As was described earlier, a bottleneck is emerging in the backplane of ultra high-speed routers. This is also a promising market for optical interconnection technology. U.S. vendors currently dominate most parts of the router market for carrier use and the share of Japanese vendors is becoming increasingly smaller. The total capability of routers is not determined solely by hardware performance but depends on the balance between hardware and software and the inheritance of accumulated know-how. A high-performance instrument is only a partial solution for entry into this market. Still, a well-planned introduction of optical interconnection technology in this area will be able to provide Japan with a window of opportunity and a means of escaping from the current problematic situation.

Incorporation of optical interconnection is also under review for mobile phones and automobiles. Although they do not require ultra high-speed processing, the merits of optical links, such as the elimination of wiring space and EMC-less communication, are of great advantage in these applications. Robotics is an area where the possibility of explosive growth in the near future is high. Optical interconnection has the promise to be used as a key component in the nervous system of these robots, transmitting information calculated in the brain (CPU) to the corresponding human's muscles and limbs. Achievements that result from this cutting-edge technological development will find a broad spectrum of applications.

6 Conclusion

This article introduced the technical trends in ultra high-speed computing; special emphasis was placed on optical interconnection technology, which will be an essential elemental technology in the development of a next generation supercomputer. The need for a strategic roadmap was also discussed. Japan has traditionally maintained a technical edge in optical technology, of which optical interconnection is a part. Japan has a well-established foundation and resources for R&D based on past achievements and experience. This technology promises to provide Japan with a breakthrough and a means of escaping from its current disappointing situation by developing a future supercomputer, next generation CPU and routers. We are in a period of transition from hard-wired to optical links. A window of opportunity has opened that will allow us to regain technical supremacy through the development of a next generation supercomputer, notably the Keisoku supercomputer system.

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Notes

[Note 1] "Development and utilization of an advanced, high-performance general-purpose supercomputer": A large-scale R&D project that spans seven years, starting in 2006, for which a total of 115.4 billion yen will be allocated (planning value).

[Note 2] Currently, European countries are not undertaking supercomputer development. They are specializing in the development of computer application technologies. However, a recent article (December 2005) reported the development of the Bull supercomputer (France). For detailed information, see Reference [4].

[Note 3] Optical crosstalk can occur when optical links are laid out in extreme proximity to each other (within several tens of micrometers).

Glossary

*1 PFLOPS

P (Peta) is a prefix that represents 10^{15}. PFLOPS means the capacity of 10^{15} floating-point number operations per second.

*2 Keisoku

"Kei" is a Japanese character representing 10^{16}. Thus 1-Kei floating-point computing is equivalent to 10 PFLOPS. Therefore, "Keisoku" represents a computing speed of 10 PFLOPS.

*3 LINPACK (LINear equations software PACKage) Benchmark

A software package for solving a system of linear equations used to measure floating-point computing power. One of the most frequently used computer benchmarks in the world.

*4 Node

A system element that includes the CPU and memory. A node itself can be a fully functional computer system. A large-scale supercomputer accelerates processing by allocating a program to multiple nodes simultaneously (parallel processing).

*5 Plasmon

Collective oscillatory motion of electrons on the surface of conductors or metals coupled with an electromagnetic wave, which can be used to control light propagation.

*6 Raman laser

A type of laser using the Raman effect: the light undergoes changes in frequency, depending on the internal structure of the medium.

*7 Sudden death

Phenomena of an abrupt entrance into fault mode due to an unpredictable sudden breakdown during operation.

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3

Prospects for Measures Against Pollinosis in Japan

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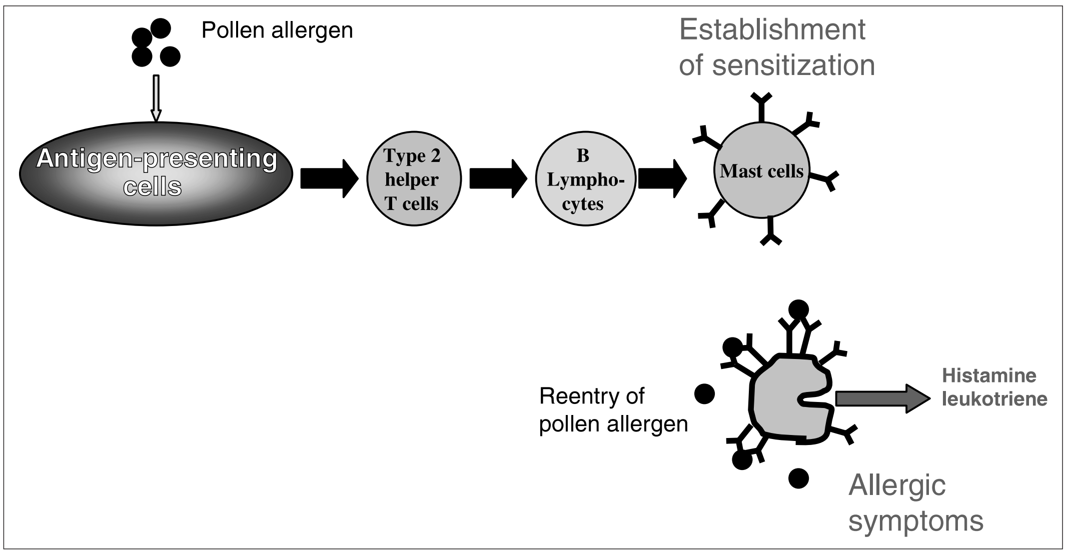
1 Background and Development of Pollinosis Issues

Pollinosis caused by cedar pollens was first reported more than 40 years ago at an academic conference held in 1963. The number of cedar pollinosis *1 patients has increased ever since, and one in every five or six Japanese people is said to suffer from the allergy today. The total medical expenses directly or indirectly related to cedar pollinosis are estimated to reach 286 billion yen per year [1].

The mechanism of pollinosis development is described in Figure 1. First, cells named antigen-presenting cells recognize the allergen (a protein) contained in cedar pollens and transmit its information to type 2 helper (Th2) T cells. Then, the Th2 cells order the B lymphocytes to produce allergen-specific immunoglobulin E (IgE) antibodies. The IgE antibodies bind to the surface of the mast cells, which creates an allergen-sensitized state. When the same allergen enters the body in this state and reacts with the IgE antibodies at the mast cell surface, the mast cells release chemicals such as histamine and leukotriene, which induce allergic symptoms such as sneezing, and running and stuffy noses. Any one of these steps can be blocked in the measures against pollinosis.

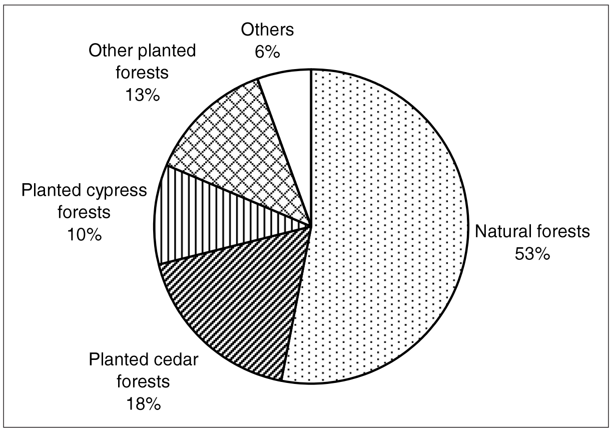
Neither sensitization nor allergic reactions would occur in the absence of the allergen, so the fundamental cause of cedar pollinosis is cedar pollen. As shown in Figure 2, Japan's forest cover is 25.12 million ha, corresponding to about 70% of the total land area (37.79 million ha). Planted forests cover 10.36 million ha, which is about 40% of the forest cover. The total area of planted cedar forests is 4.52 million ha, accounting for 18% and 44% of the forest cover and the planted forest area, respectively, while the total area of planted cypress forests is 2.57 million ha, accounting for 10% and 25% of the forest cover and the planted forest area, respectively. Thus, planted forests of cedar and cypress, together, occupy 28% and 19% of the forest cover and the

Figure 1 : Diagram of the mechanism of pollinosis development



total land area, respectively. Since most natural forests also comprise broadleaf trees, the actual area occupied by these conifers in natural forests is unknown. Nevertheless, natural forests are also included in addition to the planted forests for the actual calculations. The area of cedar plantation rapidly expanded after World War II and remained at a high level until around 1970. As a result, the majority of the cedar trees are currently aged from 30-50 years[3], as shown in Figure 3. Cedars increase their pollen production at around 25 years and, once they reach 30 years, they constantly produce a large amount of pollen for several decades. The expansion of the area of cedar forests aged over 30 years coincides with the increase in the number of cedar pollinosis patients since 1975[3]. Apparently, the most important factors responsible for the increase of cedar pollinosis are the increased pollen counts in the environment associated with the expansion of cedar and cypress forests, and the resulting increase in the strength and frequency of pollen exposure. Since cedars are expected to live almost 100 years, if the cedar forests are left as they are, we cannot expect any decrease in cedar pollen levels for decades.

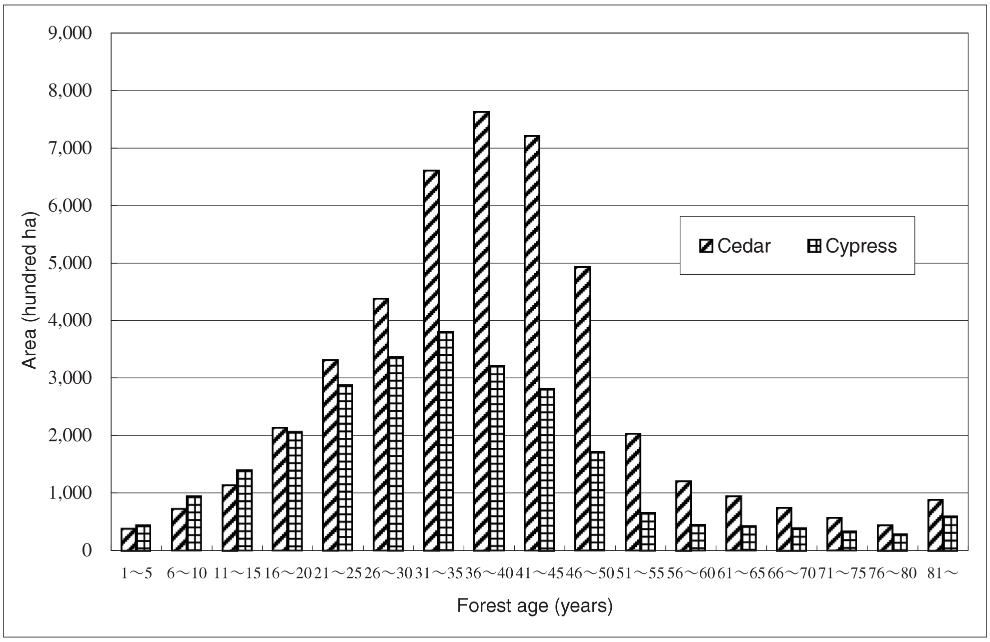
Figure 2 : Proportion of planted cedar/ cypress forests in forest cover



Source: Reference [2]

The increase of pollinosis can be viewed as a part of the worldwide increase in allergic diseases which potentially involve various factors including changes in lifestyle, improvements in sanitary conditions, changes in diet, environmental pollution. The involvement of air pollution in pollinosis has been suspected since a higher prevalence was reported among residents along Nikko Kaido, a busy road, than among those living in areas distant from the street, but potentially inhaling a large amount of pollen[4]. Moreover, interesting results were achieved from an animal test, which demonstrated that diesel emissions could exacerbate allergic reactions. Although results from epidemiological studies lack consistency, a survey conducted on elementary students by the Ministry of the Environment demonstrated that the prevalence of cedar-specific IgE antibody and pollinosis were related not only to the pollen count, but also to

Figure 3 : Areas of planted cedar/ cypress forests by forest age class



Source: Reference [2]

the air pollutant level in the residential area[5]. Many toxicological findings also suggest the involvement of diesel emissions.

2 Past Efforts Concerning Pollinosis Research

Ever since the increase in the cedar pollen count in the environment and the increase in the number of pollinosis patients were first noticed in the 1970s, several studies have been conducted by organizations, including the Ministry of Health, Labour and Welfare (MHLW). In 1975, a study on the airborne pollen count was started utilizing the network of national hospitals and sanitariums and was funded by a MHLW Health Science Research Grant. After that, pollinosis research groups, mainly financed by the MHLW Health Science Research Grant, were organized over several terms. These groups, mainly consisting of otolaryngology and respiratory clinicians, conducted not only epidemiological studies on pollinosis, or clinical and therapeutic research, but also palynological studies such as an airborne pollen survey[6].

Meanwhile, the Forestry Agency approached the cedar pollen issue from a forestry standpoint and started the Cedar Pollen Survey Project in 1987, which involved the investigation of cedar pollen sources in metropolitan areas, surveys on pollen production in cedar forests and related factors, and surveys on cedar pollen dispersion[7].

Through these efforts of the individual ministries and agencies, a committee comprising representatives from relevant ministries and agencies was established in 1990 to investigate and discuss the current status of pollen dispersion and pollinosis as well as the cause of and measures to combat the allergy. From 1997, “Comprehensive Studies towards Overcoming Cedar Pollinosis”, financed by the Special Coordination Funds for Promoting Science and Technology, was conducted over two terms for a total of six years with the cooperation of the related ministries and agencies at the time (Ministry of Education, Science, Sports and Culture, Ministry of Health and Welfare, Forestry Agency, Japan Meteorological Agency, and Environmental Agency)[1].

Apart from the governmental agencies, local governments have also addressed the issue using their own approach. In 1983, the Tokyo Metropolitan Government launched a study group on measures against pollinosis and started cedar pollen count measurements and patient surveys, which have continued ever since. Other prefectures have cooperated with the local medical associations, universities, etc. and played pioneering roles in the establishment of systems for measuring pollen counts or providing information to the residents. In Japan, cedar pollens have been manually counted using a traditional method called the Durham method. For many years, the method was supported by doctors, researchers from various fields, and citizen volunteers. Today, an NPO group, Pollen Information Association, plays the central role.

3 Current Status of Measures Against Pollinosis

In February 2004, the Council for Science and Technology Policy established a Research Committee on Measures Against Pollinosis comprising executives from relevant ministries and agencies, and experts on pollinosis to promote studies on measures to combat pollinosis. The committee announced “Governmental Efforts Concerning Pollinosis for This Term”[8] and suggested some specific policies shown in Table 1.

Among such efforts, those directly related to the measures against pollinosis can be broadly classified into pollen source control, exposure reduction, and prevention and treatment.

(1) Pollen source control

Control of cedar and cypress forests serving as pollen sources is the most basic countermeasure against pollinosis. The pollen source control policies currently promoted by the Ministry of Agriculture, Forestry, and Fisheries (MAFF) are (i) development and spread of low-pollen varieties etc., and (ii) logging and thinning of trees producing many male flowers. The development of low-pollen cedar varieties producing less than 1% of normal pollen production has been somewhat successful, supplying about 240

Table 1 : Efforts concerning measures against pollinosis

Program	Item	Relevant ministries and agencies
Understanding of current status regarding pollen and pollinosis	(i) Prediction of pollen production	MAFF
	(ii) Weather forecast, etc.	Japan Meteorological Agency
	(iii) Forecast and monitoring of the pollen count	Ministry of the Environment
Identification of the cause of pollinosis	(i) Identification of the disease mechanism	MEXT/MHLW
	(ii) Identification of the relationship between pollinosis and general environment	Ministry of the Environment
	(iii) Establishment of a research base	MEXT/MHLW
Measures against pollinosis	(i) Development and spread of preventive and therapeutic methods	MEXT/MHLW
	(ii) Development and spread of low-pollen varieties etc.	MAFF
	(iii) Promotion of logging and thinning of trees producing many male flowers	MAFF
	(iv) Securing appropriate medical service for pollinosis	MHLW
	(v) Provision of information concerning pollen and pollinosis	MHLW/MAFF/Ministry of the Environment

thousand low-pollen trees over the past five years and potentially supplying about 600 thousand over the next five years[3].

(2) Reduction and avoidance of exposure

This class of policies involves the reduction or avoidance of exposure to cedar pollens at any of the stages including pollen production, pollen dispersion in the environment, and human exposure to pollens.

Cedar pollen dispersion is a seasonal phenomenon, so it is important to predict the beginning and end of pollen dispersion. It is also important to predict the total pollen count that greatly varies from year to year. Since anti-allergic drugs are commonly used as the initial drugs administered about two weeks before the pollen dispersion begins, an increase in prediction accuracy at the beginning of pollen dispersion is critical to appropriate treatment, as well as to reducing medical costs and the patient burden.

Another means for reducing exposure to pollens is to reduce opportunities for contact with pollen or to avoid activities that would result in contact with pollen. Pollen forecasts for today and tomorrow, provided as a part of the weather forecast, are critical to the selection of one's activities to avoid pollen exposure. A forecast system for a shorter term, e.g. an hourly forecast, would require pollen production data and meteorological data with the equivalent temporal resolution. In fiscal year 2002, the Ministry of the Environment placed automatic pollen counters in urban and mountain areas in the Kanto, Kansai, and Chubu regions and started to collect and provide hourly data on pollen dispersion. The ministry will eventually place the pollen counters all around the country. Cedar pollens are believed to travel several dozen kilometers, so a pollen dispersion model that covers a wide area is needed. For example, the establishment of a pollen prediction model for Tokyo would require data collected from the entire Kanto region.

(3) Prevention and treatment

Pollinosis can be prevented or treated by blocking any of the several stages shown in Figure 1. The most fundamental form of prevention is to avoid contact with pollen. Meanwhile, another preventive approach is to suppress the allergic reactions developed after contact with pollen in a sensitized subject, in which pollen-specific IgE antibodies are produced and bound to the surface of the mast cells. The latter involves suppression of the allergic symptoms in patients who have already developed pollinosis, so it is difficult to draw a clear distinction between prevention and treatment.

Currently, the Ministry of Education, Culture, Sports, Science and Technology (MEXT) and MHLW are focusing on research and development of cedar pollen CpG vaccines and sublingual desensitization (Figure 4). Meanwhile, MAFF is promoting the development of pollinosis-relieving rice (Figure 5). These

Figure 4 : Road map for development of therapeutic methods promoted by MEXT and MHLW

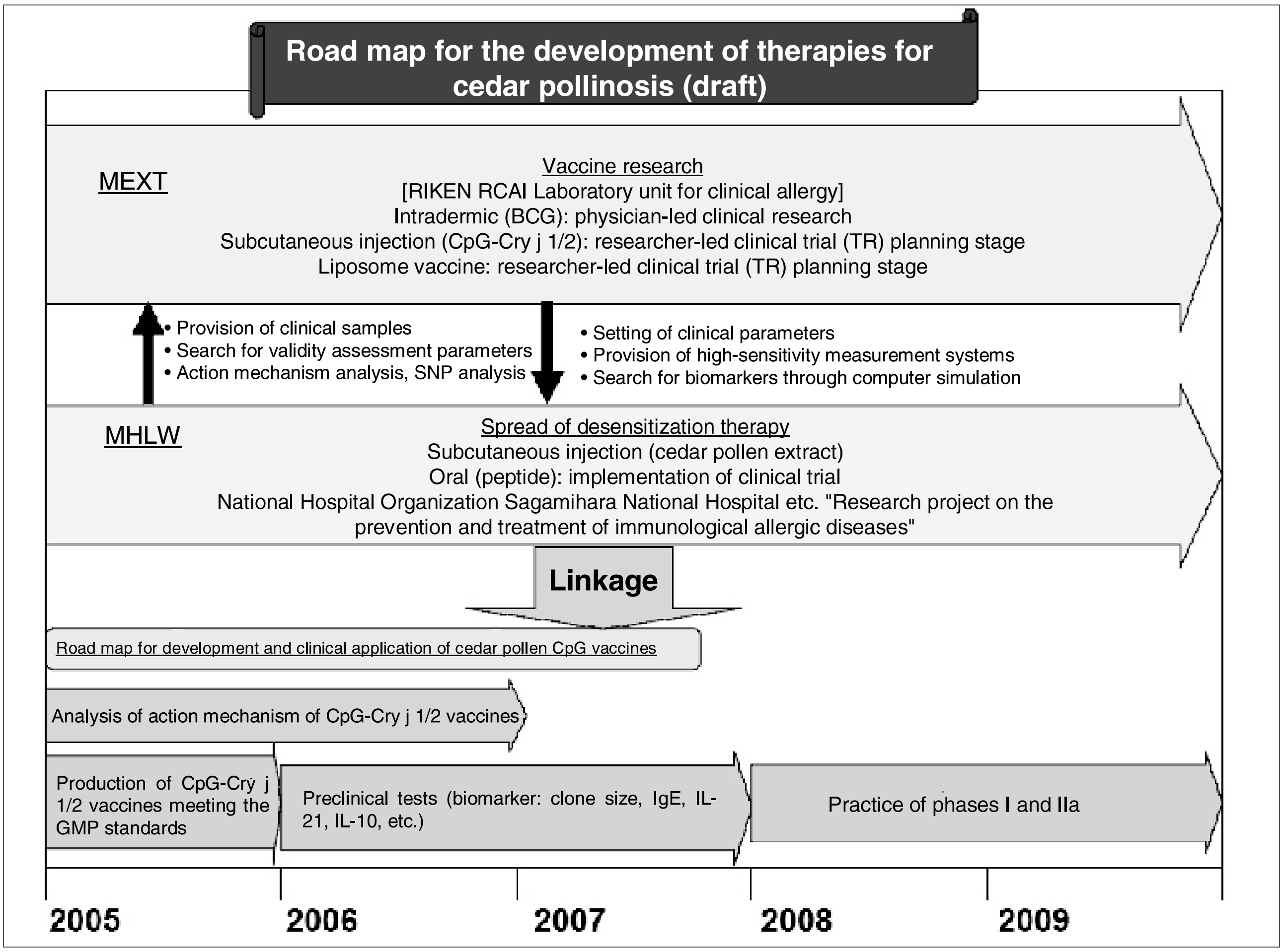
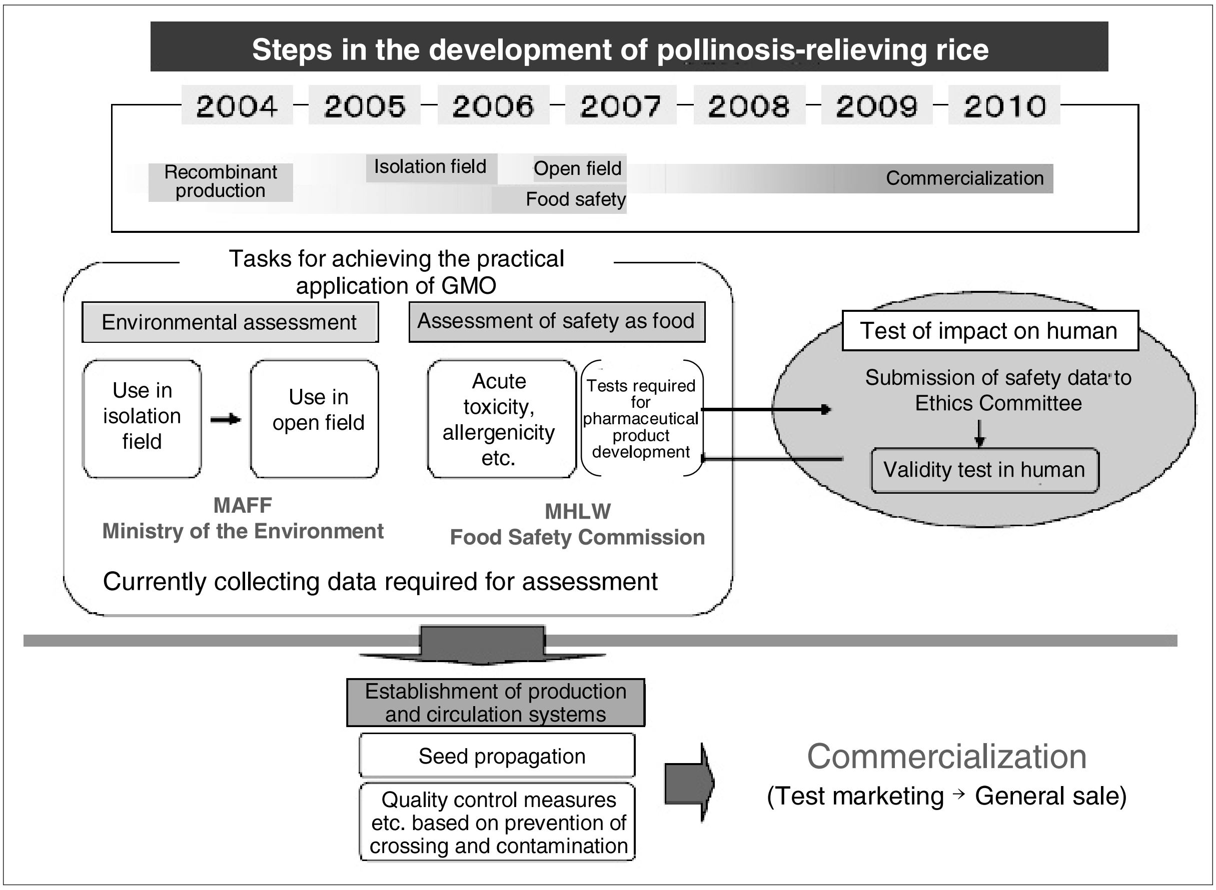


Figure 5 : Road map for the development of pollinosis-relieving rice promoted by MAFF



prevention and treatment methods are extensions of a therapy called desensitization therapy and can be classified as curative treatments, which can be distinguished from symptomatic treatments based on anti-allergic drugs. Such curative treatments seem to be the most promising measures against pollinosis.

Desensitization therapy is an allergen-specific immunotherapy involving the routine injection of cedar pollen extracts over two or three years, starting with low doses and acclimatizing the body to the allergen to suppress the allergic symptoms. This method has been commonly used in the U.S. and European countries but has been rather rare Japan, due to some disadvantages such as the need for several hospital visits over long periods and a low but non-negligible risk of allergy shock. Among the stages for the establishment of sensitization shown in Figure 1, the immunotherapy under study suppresses the action of Th2 cells or B lymphocytes to reduce pollen-specific IgE antibody production.

The use of cedar pollen-specific CpG vaccines involves suppression of the cedar-specific Th2 cells by administering the major protein components of the cedar pollen allergen, Cry j 1 and Cry j 2, bound to bacterial or microbial DNA fragments (unmethylated CpG motifs) known to have strong immunostimulatory activities. In the U.S., their counterparts containing ragweed pollen allergens instead of cedar pollen allergens, have been tested in clinical trials and demonstrated to be effective against ragweed pollinosis. The efficacy of cedar pollen CpG vaccines has already been confirmed in mice, and preparations for their clinical trials are currently in progress. Once their efficacy and safety are confirmed through the clinical trials, the vaccines will be put into practical use two or three years after the beginning of the clinical trials.

Unlike conventional desensitization through injection, sublingual desensitization achieves desensitization by dropping pollen extract under the tongue (or, generally, by placing a piece of bread impregnated with the pollen extract under the tongue for about two minutes). The method has already been approved in Europe, and a large amount of data showing its efficacy is available.

The pollinosis-relieving rice is rice that has been genetically modified to accumulate a peptide considered to prevent cedar pollinosis in the endosperm. The peptide contains a peptide (7Crp) consisting of seven linked major antigenic determinants (T-cell epitopes) of cedar allergens recognized by human T cells among the known T-cell epitopes. The gene encoding the peptide is further linked to some genes required for gene transfer. The rice containing the pollinosis-preventing peptide is approved for use etc. in isolated fields under the Law Concerning the Conservation and Sustainable Use of Biological Diversity through Regulations on the Use of Living Modified Organisms (Cartagena Law). In the road map provided by MAFF, the rice will be first subjected to environmental and food safety assessment, followed by confirmation of its efficacy in humans, before it is put into practical use.

4 Future Directions of Measures Against Cedar Pollinosis

4-1 More effective control of pollen sources and evaluation of its validity

For more effective control of pollen sources, closer linkages must be established between pollen source control and the development of a pollen forecast system promoted by MAFF/ Forestry Agency and the Ministry of the Environment/ Japan Meteorological Agency, respectively. A map illustrating the degree of contribution of cedar/ cypress forests in Japan to the pollen exposure of population groups needs to be produced, and the cedar/ cypress forests must be prioritized as targets for pollen source control. Moreover, the cost and the manpower required for the control must be estimated, and a road map for the entire policy must be produced.

Under existing conditions, it is difficult to predict the decrease in the sensitization rate from the predicted decrease in the pollen count as a result of pollen source control conducted in cedar/ cypress forests in a certain area. Thus, it is essential to promote studies on the relationship between pollen exposure and allergic reactions to pollens.

(1) Cost and manpower required for pollen source control

Application of the pollen source control promoted by the MAFF/ Forestry Agency to the vast area of cedar/ cypress forests would require a huge commitment in manpower and money, but neither has been clearly estimated. In the budget for the fiscal year 2005, 250 billion yen was allocated for the development and maintenance of 6.4 million ha of forest as a part of the global warming policy. The forest development cost related to cedar pollinosis control would perhaps be equivalent to this, or even higher. Meanwhile, forestry workers in our country have become older and decreased in number to about one-third of that 30 years ago (Figure 6). It is unclear whether there would be enough manpower to practice forest development and maintenance as a part of cedar pollen source control.

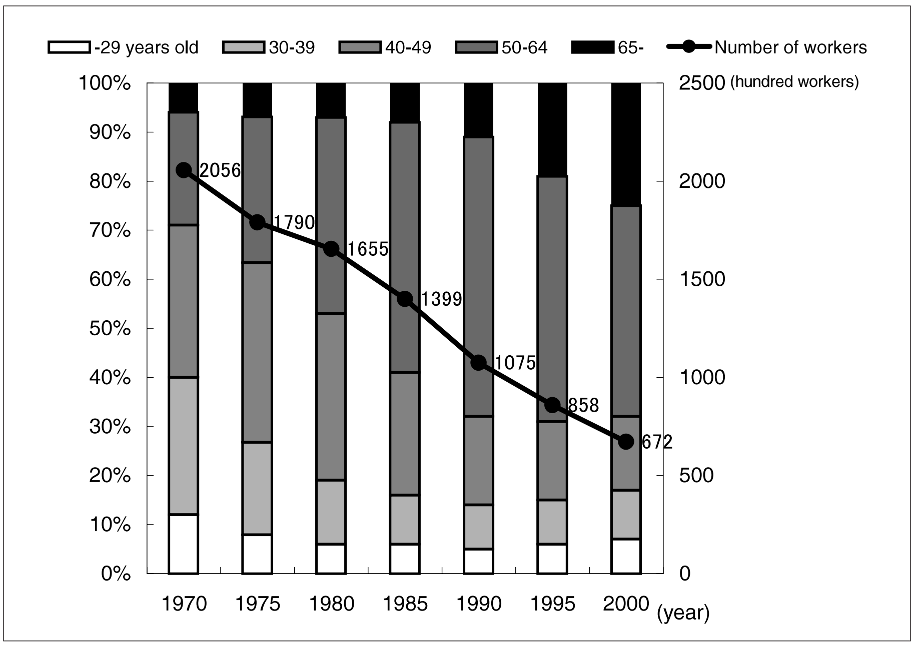
(2) Prioritization of target areas for control based on estimation

Although the existing trees should be replaced with those producing less or no pollen, and trees producing many male flowers should be logged or thinned, it is unrealistic to work on all of the vast cedar/ cypress forests at once. Thus, the first thing to do is an individual estimation of the degree of contribution of cedar/ cypress forests to the pollen exposure of population groups in each area of the country, followed by prioritization of the forests. For instance, it is necessary to identify cedar/ cypress forests that are making the largest contribution to the heavily populated metropolitan areas. The determination of the priority should be followed by an estimation of the funds and manpower required for the policy and the establishment of a road map for the entire policy. Accomplishment of these tasks would require the establishment of a cedar pollen forecast model including a system for predicting cedar pollen production and dispersion, a system for predicting the airborne pollen count described in 4-1(3), and a weather observation/ forecast system serving as its basis. In addition, the prioritization should be performed by taking into account the important functions of the forests from the standpoints of land conservation and prevention of global warming, such as their roles as CO_2 sinks and watershed protection forests.

(3) Accumulation of observation data and the improvement of accuracy

Since cedar pollens are believed to travel several dozen kilometers, a pollen forecast model that covers a wide area needs to be established. Moreover, considering the flow rate of pollens in the atmosphere, the observation data should be collected on an hourly basis. Unfortunately, the currently available observation data on

Figure 6 : Transition of the number of forestry workers and composition ratio according to their age



spatial and temporal pollen distribution are inadequate. Airborne pollen counts were conventionally measured through an approach called the Durham method, in which pollens deposited on a slide glass are stained and counted under an optical microscope. In the Durham method, observations are usually made on a daily basis, making it difficult to establish an hourly prediction system based on the observation data obtained through this method. Currently, real-time data on pollen production in cedar forests serving as cedar pollen sources are virtually unavailable. The monitoring system developed by the Ministry of the Environment has only a limited number of monitoring sites, and a fundamental discussion on the number and the location of monitoring sites would be required to increase the accuracy of the pollen forecast system. Furthermore, since the existing automatic pollen counters are not designed as cedar pollen-specific counters but are merely particle counters that count any particles of the same size as cedar pollens, errors may be observed under certain conditions. Thus, the system and accuracy of the pollen counter itself needs to be improved.

Currently, the prediction of the total pollen count for the year is performed based on the flower setting of the male cedar flowers and is available before the cedar pollen season, i.e. around November or December. Cedar flower buds are formed in the summer, and their formation is affected by weather conditions in the summer. Based on this fact, a statistical prediction system based on summer temperature etc. had been proposed. However, since other factors are also involved in flower bud formation, predictions based only on the summer temperature or other weather conditions produced some errors. Consequently, the total pollen count has been predicted based on the observation of the male flowers in autumn when they show a marked growth and prediction accuracy has increased in recent years.

On the other hand, predictions of the onset and end of pollen dispersion are not sufficiently accurate. In particular, the onset is linked to the initiation of drug administration, so it should be predicted with an accuracy of a few days. Cedar male flowers stop growing in autumn and enter dormancy. The onset of pollen dispersion is predicted by analyzing the meteorological factors involved in dormancy breaking. However, the mechanism of dormancy breaking is not sufficiently understood, and fundamental studies are needed to increase prediction accuracy.

(4) Establishment of a method for evaluating the impact of measures

Many problems are left unsolved concerning the evaluation of the impact of the measures. As mentioned earlier, the development of pollinosis comprises two stages, i.e. sensitization and symptom development, but the dose-effect relationship has not been clearly established for either of the steps. In particular, there are no collective data on the relationship between the degree of pollen exposure and the sensitization rate in certain population groups with a genetic predisposition. Thus, it is difficult to predict sensitization rate reduction from the predicted reduction in the pollen count resulting from pollen source control in cedar/ cypress forests. Meanwhile, there are some findings on the degree of pollen exposure (pollen count) during the pollen dispersion season that triggers the allergic symptoms in a person already developing pollinosis. These findings have been used for ranking cedar pollen dispersion in the forecast. Although such ranking is not reliable enough to accurately evaluate the impact of measures, at least for the time being, there is no choice but to use the development of allergic symptoms as a measure of the impact. Elucidation of the dose-effect relationship between pollen exposure and its outcome requires reinforcement of the pollen monitoring network and continuation of epidemiological surveys on young people at ages that are critical to the establishment of sensitization.

4-2 Solutions for problems concerning prevention and treatment

The results of high priority basic research on the new preventive and therapeutic methods currently in progress, such as vaccine development and sublingual immunotherapy, suggest that these methods have a high potential for practical application. In the future, they need to be tested in clinical trials to be approved as pharmaceutical drugs, which would require some research support. Joint developments with pharmaceutical companies etc. would be essential for their practical application, and problems that may arise during such joint developments should be clarified in advance.

(1) Support for research and clinical trials

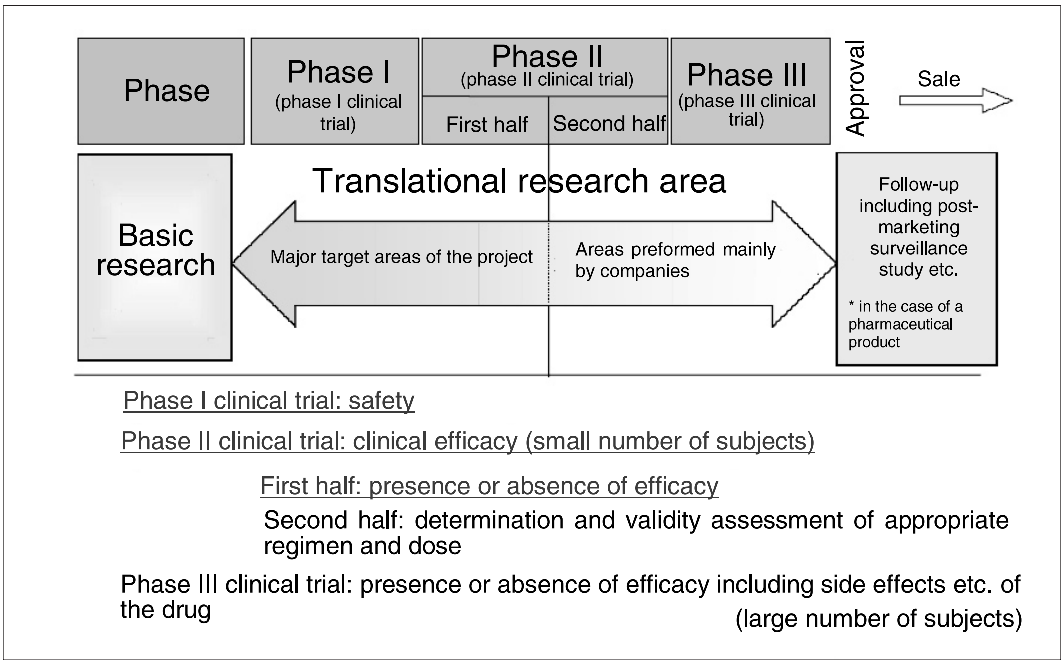
In order to put the currently developed preventive and therapeutic methods into practice as soon as possible, it is essential to provide both research support for basic studies on the immune system and allergies, and practical support for clinical trials. Research performed for developing and commercializing promising diagnostic, therapeutic, or preventive methods based on the results achieved through basic studies in the life sciences and returning the outcome to the patients is called translational research. The development of cedar pollen vaccines is a good example of translational research. In cancer research, MEXT started the "Cancer Translational Research Project"[11] in fiscal year 2004 (Figure 7). This project targets phase I and the first half of phase II of clinical trials, and the Foundation for Biomedical Research and Innovation (Translational Research Informatics Center) provides some support for the preparation of clinical study protocols, management, and statistical analysis of clinical data, etc. Meanwhile, concerning the second half of phase II and phase III clinical trials, the basic policies of the project state "(the target research) shall be feasible, e.g. phases II and III of clinical trials shall be taken over by companies etc.", which assumes that companies such as pharmaceutical companies, that would benefit from the practical application, will bear the costs of clinical trials, and work on approval procedures. The development of cedar pollen vaccines would require similar support.

In a review[12] summarizing 100 reports on sublingual immunotherapy, Cox claimed that, although the method was effective in relieving symptoms and reducing the doses of the therapeutic drugs, there were some questions about the effective dose and schedule, timing, mode of action, and safety in hypersensitive groups. More clinical data should be gathered to optimize the dose and administration method of the allergen, and the efficacy and safety of cedar pollen allergen extract should be evaluated as soon as possible to achieve early approval of the vaccine.

(2) Promotion of vaccine development etc.

The results of basic research on vaccines preventing the development of cedar pollinosis,

Figure 7 : Cancer Translational Research Project



Source: Reference [11]

such as CpG vaccines, suggest that these vaccines have a high potential for practical application. However, drug development is often associated with many problems that have led to the cessation of clinical trials and the failure of many drugs to reach commercialization in the past. The development of such vaccines would also be confronted by many problems that need to be solved. As can be seen from the example of the Cancer Translational Research Project, it is beyond the capacity of individual researchers or research institutions to complete all phases of the clinical trials, achieve governmental approval, and reach commercialization. Yet, the government can only make a limited commitment to the implementation of clinical trials. This problem can only be solved through joint development with pharmaceutical companies etc. The cooperation of pharmaceutical companies is also vital for the development of sublingual desensitization, as pollen extracts that are different from those approved for injection use would need to be newly approved under the Pharmaceutical Affairs Law.

(3) Safety confirmation of pollinosis-relieving rice

Since pollinosis-relieving rice is based on an innovative idea, a highly advanced assessment on procedures of safety and efficacy evaluation is required. The rice would also be confronted by many problems. Following the procedures for environmental assessment of genetically modified crops specified in the Cartagena Law, the next task concerning the rice containing the pollinosis-preventing peptide is to achieve approval for its cultivation in open fields[13]. Regarding the assessment of its safety as food, the Food Safety Commission has established standards for safety assessments of genetically modified foods[14]. Thus, if the rice containing the pollinosis-preventing peptide is viewed only as a genetically modified food, well-defined procedures are already in place for its environmental and food safety evaluation. However, for the practical application of peptide vaccines or other immunotherapy methods using 7Crp itself, their efficacy and safety as pharmaceutical products must be assessed under the Pharmaceutical Affairs Law. Consequently, if the rice is viewed as a pharmaceutical product, it must undergo all phases of the clinical trials shown in Figure 7. Moreover, it would have to overcome the negative views of consumers about genetically modified foods in general.

5 Conclusion

The present article focused on cedar/ cypress pollinosis and provided an outlook of the prospects for measures to combat this problem, which is of national concern. A substantially high incidence is reported for other types of pollinosis caused by, for example, Gramineae pollens, although conditions for their development are not fully understood due to the limited range of pollen dispersion, etc. The involvement of environmental pollution such as air pollution in pollinosis is often highlighted, but environmental pollution seems to be involved in all other allergic conditions as well. A drastic increase of allergic diseases has been observed worldwide, although the increase in cedar pollinosis seems to have a history that is unique to our country. Nevertheless, before starting individual research, first we must clearly define the position of the measures against cedar pollinosis in the prevention and treatment of allergic conditions in general.

Glossary

*1 Cedar pollinosis
Otherwise known as cedar/ cypress pollinosis, as most cedar pollinosis patients develop allergic symptoms in response to cypress pollens as well as cedar pollens. Unless there is a need, this article does not distinguish between cedar pollinosis and cypress pollinosis.

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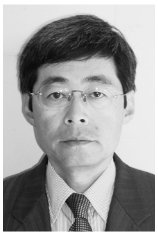

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4

Trends in Materials Informatics in Research on Inorganic Materials

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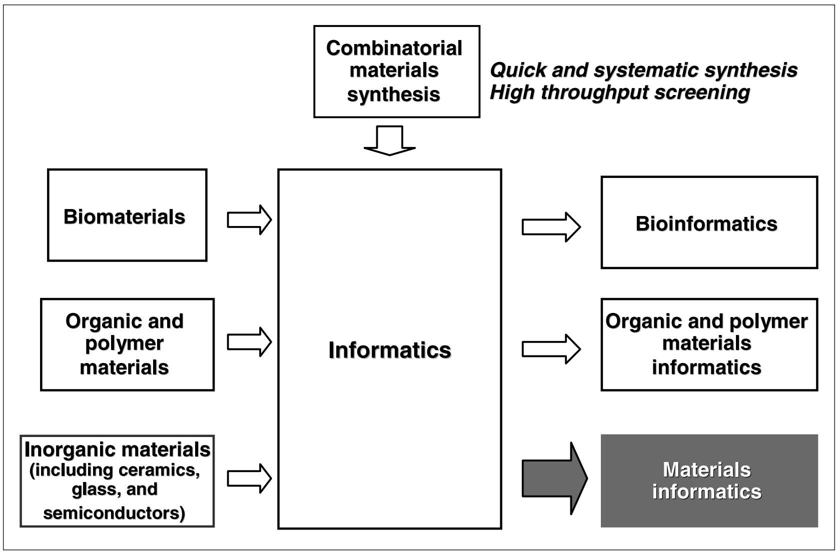
1 Introduction

Informatics is a science in which a new knowledge system is built up by collecting and classifying information using computers and networks. Materials informatics is a technique that aims at innovative materials development by way of informatics, which includes such elements as materials design using computation science and databases, preparation of experimental design schedules for materials synthesis, automatic combinatorial synthesis when searching for new materials, high throughput screening, compiling databases from obtained data, data sharing through networks, visualization of data, and data mining to predict future materials. Materials informatics requires the integration of all these elements [1].

In the application of informatics, more progress has already been made by bioinformatics and organic materials informatics than by inorganic materials informatics. Automatic analyzers have been developed for bioinformatics, and large-scale data processing is carried out for the analysis of gene sequence data. These data are then used for the construction of gene information databases and statistical analysis. Personalized medicine is one of the accomplishments of this sort of bioinformatics analysis. In the fields of organic materials and polymer development, new materials are also being developed by means of systematic synthetic methods using combinatorial methods and data processing technologies to cope with the large amounts of data involved.

Although informatics has not yet been widely used for inorganic materials, such as ceramics, glass, and semiconductors, some organizations are now conducting research and development into the use of informatics for synthetic processes, developing new catalysts by means

Figure 1 : Relationship between the development of various materials and informatics



of combinatorial materials and integrating various processes from materials design through to collection of the data in a single data set. Particularly in the research being carried out by commercial companies, systematic searches for new materials are now being made which require large-scale data analysis, resulting in the need for materials informatics in this field also [2].

2 Similarities to and Differences from Informatics in Other Fields

Similarities and differences with inorganic materials informatics can be clarified by comparison with other existing fields in informatics. As mentioned above, informatics has already been used in the fields of bioinformatics and organic synthesis.

The bioinformatics system has been established by integrating gene information and genetic statistics [4], and research on bioinformatics is being actively pursued. Bioinformatics aims at organizing the genetic information of organisms (the genome) and consists of database-related functions such as the systematic collection and storage of data on DNA base sequences, and data analysis software that visualizes the data so that they can be intuitively compared. Bioinformatics analyzers create these large-scale databases automatically, using the most advanced computer technologies available to process large amounts of data rapidly. Since there is a problem of compatibility between the data obtained by different research organizations, tools are used to transform the data so that they can be shared among these organizations.

Organic synthesis is another field in which informatics is being developed. Since combinatorial methods, by which a large group of compounds can be synthesized at one time by combination, greatly increase the speed of materials synthesis and make it possible to pioneer the creation of new materials, this technique has been widely used for the development of new polymers and pharmaceuticals. The use of combinatorial synthesis makes it possible to create a large-scale library of compounds with similar molecular structures, and the activities of specific chemical structures and their reactions with functional groups can then be predicted utilizing such a library. When possible candidate combinations for a specific purpose are found, such combinations are selected and commercialized. The process is being automated further using robots, and many venture companies have been established in this field. However, since the purpose of informatics is to monopolize the results ahead of other companies, these databases are often kept within the confines of a company or group.

Also in the field of inorganic materials research, much data on ceramics, glass and semiconductors have been accumulated with regard to their material characteristics, crystal structures, and suchlike. However, past data in this field have often been collected by different research groups and stored in different forms, some numerical and some graphical, and not all of these are compatible with each other. Another difficulty in applying informatics to research on inorganic materials results from the fact that a material can have diversified aspects and properties that cannot always be simply defined digitally. Research on inorganic materials is quite different from that on organic materials or biology where digital expressions can be used. For example, while zirconium dioxide (ZrO_2) is used as a material for gate insulating film, it is also used as an ion conductor. When zirconium dioxide is used as a material for gate insulating film, it is necessary to reduce the number of oxygen-induced holes so that the insulating characteristics are improved. In this field, therefore, most of the data accumulated refer to the addition of agents to improve the insulating characteristics and the values of the insulating characteristics obtained. In contrast, when zirconium dioxide is used as an ion conductor or sensor to increase conductivity by increasing the oxygen-induced hole concentration, most of the data collected apply to processing conditions that reduce electrical resistance and impurities that increase conductivity. In this way, completely different data are required for the same material, depending on the purpose of the research. Therefore, a materials informatics system cannot be built by conventional methods in which different materials are synthesized by different methods and only specific characteristics are evaluated.

The use of the combinatorial materials synthesis method in the development of inorganic materials can change all this [3]. It has been shown that the use of combinatorial method to synthesize a large group of compounds by combination is a very effective way to develop new materials such as catalysts. Building an informatics system requires that the relevant characteristics are measured automatically and systematically at each stage and that the data are then stored. Therefore, in addition to “Combinatorial Materials Synthesis”, the establishment of “High Throughput Screening” is indispensable when building a materials informatics system.

When developing an informatics system, experiments must be carried out by combining the combinatorial materials synthesis method, which enables systematic changes to be made in composition and growth conditions, with the evaluation of the characteristics of synthesized materials. In the example of zirconium dioxide, mentioned above, characteristics such as oxygen partial pressure and electrical resistance are automatically measured and these data are stored in a single data set along with the synthetic conditions. Some data from this data set can then be used to provide information on insulation films for dielectric gates while other data can be used to provide information on ion conductors. The collection and compilation of such a data set is the first step in building a materials informatics system. In other words, it is necessary to take the data format to be used for materials informatics into consideration when developing new materials. The automatic processing of large amounts of data is also an indispensable requirement for the use of combinatorial methods.

At present, there are only a few such sets of data available, and the various research organizations developing materials informatics systems are aiming at different targets, so the results are not always organized in a mutually compatible form. Since materials informatics is still only in the initial stages of development, it is necessary to share databases in order to mutually complement the database information already available. Evaluation items in materials research are so diversified that it is difficult, in practice, to automatically measure all the data involved, so it is in everyone’s benefit that all research organizations assist each other by sharing data.

3 Present Status of Materials Informatics and Issues to be Addressed

Research activities in inorganic materials informatics are being conducted separately by each research group in each country, and this limits their achievements considerably. Activities are still focused at the discussion stage concerning the control and storage of data relating to combinatorial experiments and have not yet reached the stage of data mining in which searches are carried out for new materials. This results from the fact that different research groups collect data using different methods so that data cannot always be shared. As a consequence, data suitable for data mining have therefore not yet been collected. In addition, characteristics evaluation takes considerable time, making it difficult to collect much data in a short period. Thus, it will take a long time to achieve the materials informatics goal of being able to predict new materials by means of data mining.

However, research towards this materials informatics goal is making progress in other fields. The field of catalyst research is particularly active, since catalytic ability can be digitally evaluated. Miyamoto and Kubo’s group at Tohoku University and other groups elsewhere have made appreciable progress in predicting new catalysts and verifying their commercial production process, predicting their material characteristics using computation science[5].

Although many reports on materials development using combinatorial methods have been published recently, it is estimated that only about 10% of them contribute to the advancement of materials informatics. Moreover, these methods are applied only to a limited range of materials, such as catalysts, borrowing from the methods used in informatics in other fields such as bioinformatics.

The use of existing databases for building a materials informatics system is also being investigated. For example, databases on X-ray diffraction, phase diagrams such as Linus Pauling Files, JANAF Tables necessary for the calculation of free energy, and so on are provided by overseas national research institutes, including the National Institute of Standards and Technology (NIST). In Japan, the National Institute for Material Science and other organizations provide access to many international databases that provide the basic data necessary for materials development. However, as described above, some of these data are numerical and others are graphical, so they cannot always be used as suitable databases for predicting new materials, in practice.

Taking the above-mentioned circumstances into consideration, the main issues to be addressed regarding the development of materials informatics can be summarized as follows:

(i) Redefinition of database formats, aiming at improved data sharing
(ii) Database networking and the development of software for data sharing
(iii) Development of data analysis software and visualization software
(iv) Development of software for data mining from databases
(v) Prediction of new functions by the combination of data mining and computation science
(vi) Standardization of platforms that integrate all these factors

Of these, item (vi), in particular, will form the foundation of materials informatics. Since no single organization can address all these issues, domestic as well as international cooperation from the long-term perspective is required.

4 Realization of Materials Informatics

4-1 Introduction of combinatorial methods and the sharing of data formats

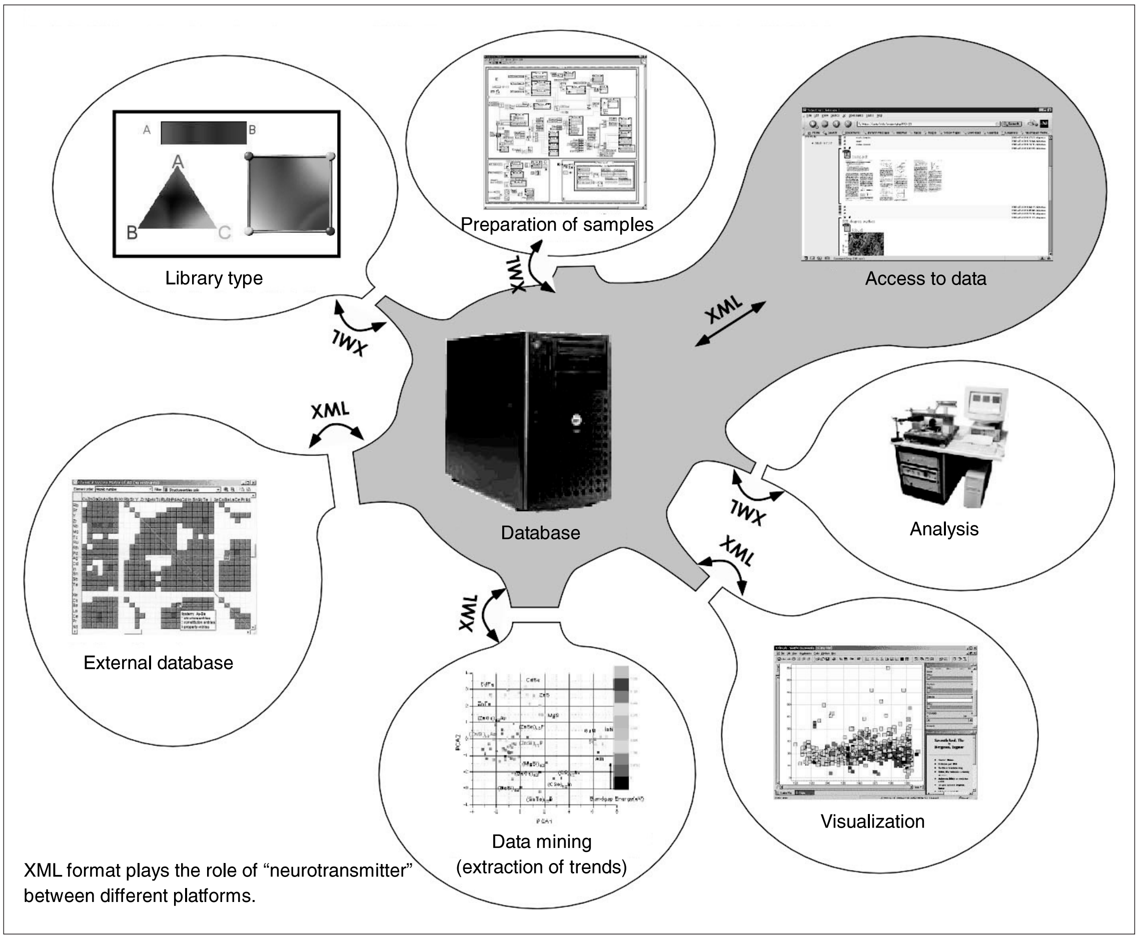
Increasing the efficiency of materials development is one of the targets for materials informatics. In the past, experimental samples of inorganic materials have been prepared individually and evaluated individually. When using combinatorial methods, several hundred samples can be synthesized at one time so the introduction of the combinatorial method becomes a prerequisite for the development of materials informatics. New research into inorganic materials, based on the use of combinatorial methods, has already started [6-8].

When using combinatorial methods, data are collected throughout the materials synthesis, evaluation, and analysis process. To obtain data on the synthetic process as efficiently as possible, equipment is required to integrate, control and implement each rate-determining stage of the process as quickly as possible. Since the evaluation and analysis of data are independent processes, different equipment is required for each one and these processes constitute most of the time required for data collection. Furthermore, tools for data control and analysis are also required for the efficient analysis of the data in a systematic manner. It would be even better if all these processes were automated.

The characteristics evaluated are dependent on the objectives of the materials development process. However, in order to share the data obtained to build an informatics system, it is necessary to measure and store data related to a minimum number of common properties, such as the structures evaluated by X-ray diffraction and electrical resistance and those properties specific to each material, in a common data format. One thing that may differ from informatics in other fields is that there may be several blank items in the data matrices produced.

First, data are stored in the data servers of individual research organizations and then these servers are linked together to form a

Figure 2 : Outline for establishing a shared database among different platforms



Prepared on the basis of material provided by Associate Professor Lippmaa

massive virtual database. The most practical way of linking servers is to use Web technology. Furthermore, by obtaining information on synthetic conditions for the establishment of future experimental plans by exchanging data with other research organizations over the Web, the efficiency of the research undertaken will be significantly improved.

Even if the existing data (such as phase diagrams and thermodynamic data) necessary for the development of new materials are dispersed, the speed of materials design will be significantly accelerated by obtaining them through the Web. At present, there is no system in the field of inorganic materials that enables the reuse of past data on synthesized materials among different researchers and research organizations. Since past reports on the synthesis of materials do not always contain details of the experiments conducted, other researchers must often repeat the same experiments again. Lack of information exchange leads to situations in which different researchers duplicate the synthesis of the same material by the same method even though their experimental aims and objectives are different. For example, many of the materials used for the catalysts of fuel cells and the metallic gates of integrated circuits are common to both and the properties to be evaluated, work function for the former and surface potential for the latter, are very similar. Therefore, research into the synthesis of materials in both fields would be greatly accelerated if both were synthesized and evaluated in the same manner. To achieve this, it is necessary for all research organizations to store data in a common format so that they can be retrieved through the Web. To start with, therefore, it is important to develop a common data format and enrich the existing data so that it can be shared among all researchers (Figure 2).

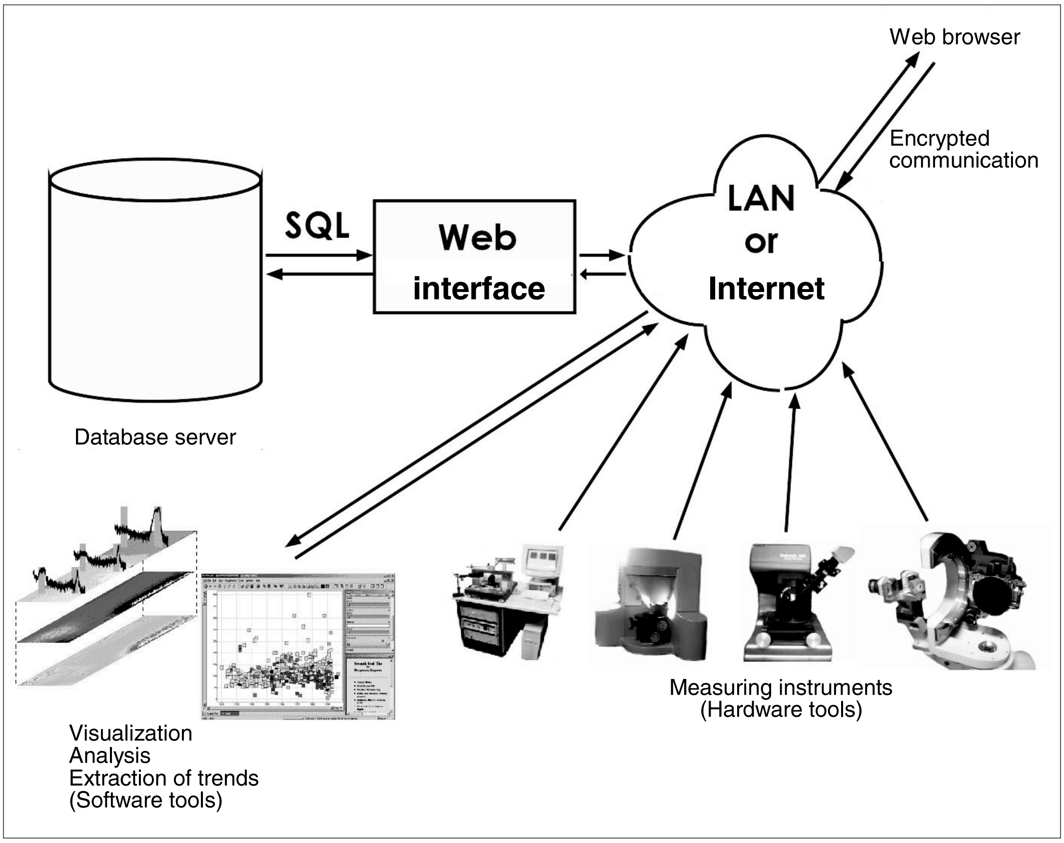
4-2 Common data format

In a sense, a materials informatics system is a combination of the databases and software tools needed for experiments and the core of the system is a group of shared databases consisting of experimental data. Present materials informatics systems being built by some organizations provide data sharing and retrieval only within a closed system, and relational database formats such as SQL (Structured Query Language) are usually used for data description. Because most data are only monopolized by an organization in order to implement materials syntheses and evaluation over a short period of time, the SQL format seems to be sufficient. However, it is not adequate for making use of the data for the development of other materials by building an informatics system.

In building a materials informatics system, many kinds of data relating to synthetic methods and processes must be collected, and these data are often described in diversified formats. Therefore, it is necessary to store the data in extensible formats. At present, the most effective data format is XML (extensible markup language), which predefines the data to be described. XML files are a convenient means for multiple organizations to share materials informatics because they are text files. The biggest advantage is its extensibility. Data description using XML not only solves the problem of compatibility but can also use existing software. It is also possible to use various existing analytical software tools for data analysis. The adoption of this format was proposed by Associate Professor Lippmaa of the University of Tokyo, at the Gordon Research Conference held in England in August 2005 [9]. This proposal attracted the attention of many countries, and it is very possible that this format will become the global standard (Figure 3).

Once the collection of massive amounts of data is begun using a common format, the search for new materials using data mining becomes possible. Data mining refers to the technology used to extract information from a large-scale database to disclose previously undiscovered relationships. Data mining technology is already being used in organic synthesis to elucidate the principles of chemical reactions and to build reaction models.

Figure 3 : An example of materials informatics structure using XML



Prepared on the basis of material provided by Associate Professor Lippmaa

5 Trends towards Materials Informatics Development in Various Countries

Organic chemical and catalyst industries around the world have already established a market using combinatorial methods. According to "Combinatorial Chemistry: Products & Service" published by the U.S. market research company, Freedonia Group Inc., the combinatorial chemistry market is expected to grow by 15 - 21% annually between 1996 - 2011, reaching $6.3 billion[18]. Of this $6.3 billion market, the sale of catalysts is expected to contribute $1.35 billion and that of polymers $401 million. Including other markets and related industries such as that of inorganic electronic materials and devices, the total market is expected to reach $8 billion in the future. Therefore, many countries are trying to build more effective informatics systems to make their research and development work more efficient.

Table 1 shows the present status of informatics being developed in various countries.

5-1 Present status in the U.S.A.

Most materials research using the combinatorial method is found in the U.S.A. By expanding the use of combinatorial materials research, many research organizations are now attempting to establish databases integrating data on materials design, synthetic methods, and data collection into a single data set. Commercial companies, in particular, are developing systems to discover new materials and the importance of informatics in processing large amounts of data is increasing.

(1) Research and development in commercial companies

General Electric Company (GE) is one of the U.S. companies that are actively utilizing combinatorial methods for materials development. GE Global Research has been using combinatorial methods for the development of various materials for use as heterogeneous catalysts, structural materials, and for biochemistry[10]. GE Global Research has two researchers in charge of the development of materials informatics, one of whom controls the data and establishes the database. In order to implement efficient materials design, they are attempting to develop effective experimental design schedules and to automate the data collection process. The software they use includes Oracle and Visual Basic for building the databases. They aim at more efficient materials development by visualizing the data taken from the combinatorial library.

Symyx Technologies Inc.[11] is one of the most successful venture companies which use combinatorial methods for developing new materials. This company also sells equipment for developing materials and software for building informatics systems. This company also commissions new materials development projects, and is considered to be a successful business model by other venture companies.

(2) Research and development at a national research institute

The National Institute for Standards and Technology (NIST) has, under the Advanced Technology Program, been supporting commercial companies that conduct research on combinatorial materials since 1999. In 2001, the Combinatorial Method Center (NCMC) was established within NIST[12]. At the Center, an informatics system is now being established that actively focuses on organic polymers. To accelerate research on materials development by rationalizing the combinatorial research work, a system called Laboratory Research Informatics (LRIS) has been designed. This system implements the automatic control of various combinatorial facilities, collection and storage of data, and the creation of databases. SQL is used as the language format, and the databases are made available on the Web so that outsiders can access the data.

(3) Research and development at universities

The Combinatorial Sciences and Materials Informatics Collaboratory (CoSMIC) is a research organization involving collaboration between the Rensselaer Polytechnic Institute, the University of Maryland, and Florida International University[13], at which materials informatics is being studied.

Table 1 : Present status of informatics being developed in various countries

Country		Organization, university	Field of research	Remarks
U.S.A.		NIST	Organic polymers, catalysts	Supporting many venture companies in the field of combinatorial materials research under the ATP Program since 1999. Building an informatics system related to organic polymers. Also has databases relating to inorganic materials and a center of research on informatics in the U.S.A.
		General Electric Company	Metals, catalysts, etc.	Has established a unique informatics system, developing a wide range of materials.
		Symyx Technologies, Inc.	Catalysts, various materials, evaluation	Licensing its own software to other companies.
		Accelrys Software Inc.	Computation science for catalysts	Developed software for informatics. Also has bases in the EU.
		University of Maryland	Dielectrics, thin films	Carrying out the CoSMIC Project as part of NSF's IMI.
		Massachusetts Institute of Technology	Catalysts	Computation science method for informatics.
		University of Delaware	Catalysts	Development of heterogeneous catalysts and informatics.
		Rensselaer Polytechnic Institute and Iowa State University	Informatics theory	Cooperative development of data mining software under CoSMIC. (Due to a change in the position of the researcher part-way through)
EU	Germany	hte Company	Catalysts	Development of high throughput screening equipment and software for catalyst development.
		Saarland University	Catalysts	Promotion of catalyst development using a new algorithm.
	Netherlands	Eindhoven University of Technology	Organic materials, thin film materials, catalysts	Cooperating with the Dutch Polymer Institute. Has developed a unique informatics system.
	France	TOPCOMBI	Catalysts	Led by CNRS, with the participation of 22 national institutes, universities, and private companies in the EU. The research base is in Lyon.
	United Kingdom	University of Southampton	Organic materials, polymers, catalysts	A COE organization. The research base is in the United Kingdom.
Asia	Korea	Korea Advanced Institute of Science and Technology (KAIST)	Catalysts, various electronic materials	Aiming to become a research base in Korea for combinatorial methods and informatics.
	China	Accelergy Corporation	Development of catalysts	The research bases are in Palo Alto (California, U.S.A.) and Shanghai.
	Japan	Asahi Kasei Corporation	Organic polymers, etc.	Has built a unique informatics system. Has a laboratory in the University of Southampton.
		National Institute for Material Science	Semiconductor-related materials	COMET Project (1999 to 2005)
		National Institute of Advanced Industrial Science and Technology	Catalysts	Informatics using software available on the market.
		Tokyo Institute of Technology	Catalysts, fluorescent materials	Research under the CREST Project (1995 to 2000).
		University of Tokyo	Thin film materials, measuring techniques	Proposed an international standard for informatics.
		Tohoku University	Oxides, thin films, computation science	Application to oxide electronics. Combinatorial computation science.

CoSMIC obtains research funds from the National Science Foundation (NSF) as part of the International Materials Institutes (IMI).

The most important activity in CoSMIC relating to materials informatics is the data mining of existing databases to predict new materials. To implement practical data mining, a method that compares the results obtained from the combinatorial methods with existing phase diagrams is used. Saxena, at Florida International

University, plays a central role in establishing massive databases relating to materials research. A group led by Rajan of Rensselaer Polytechnic Institute (now at Iowa State University) is carrying out a project to develop various types of analysis software relating to data mining. Rubloff, Takeuchi, et al. of the University of Maryland are conducting research on establishing a materials informatics system using the data obtained from combinatorial libraries by developing a data handling tool that provides feedback for combinatorial synthesis. For example, they are developing software that enables stereoscopic visualization of several hundred X-ray diffraction spectra simultaneously by visualizing data using a simple visualization technique in order to accelerate the research and development of new materials. CoSMIC now aims to develop a Web port that would allow global data exchange among collaborators using the Internet.

Research on materials informatics is also being conducted at other universities in the U.S.A. For example, a group led by Lauterbach at the Chemical Engineering Department of the University of Delaware is carrying out an active program of combinatorial research into heterogeneous catalysts, involving the use of informatics. At the Massachusetts Institute of Technology, Morgan et al. at the Department of Materials Science and Engineering are conducting research on the application of the first-principles calculation to combinatorial materials synthesis and data mining. In this research, crystal structures and physical properties are calculated for all chemical compounds, and the calculation results are verified by comparing them with experimental results and existing databases. The massive database of calculation results is then used for the prediction of new materials. Such a screening technique for materials based on the use of computation science may become one of the standard methods for materials development in the future.

5-2 Present status in Europe

Since the research and development of catalysts has been actively pursued in Europe, combinatorial studies on catalysts and organic polymers are quite common and the importance of informatics has long been recognized.

(1) Research and development in commercial companies

The German company, hte, has been developing catalysts using a screening technique called the “virtual library” based on computation science [14]. Recently, the company proposed the term “MatInformatics”, meaning materials informatics, and is now preparing an operating environment and developing software for MatInformatics in cooperation with the Accelrys Software Inc. They have developed Descriptor Property Relationships (DPR) as an analytical tool for exploring data relationships based on an algorism similar to the genetic algorism.

(2) Research and development at universities

Maier et al. at the Saarland University in Germany are actively developing new catalysts using flow charts (experimental design charts) for combinatorial materials research. They are attempting to build a materials informatics system and implement data mining in order to select optimal compositions for the highest catalytic activity from more than 500 candidate compositions by adopting an evolutionary algorism. Schubert et al. at Eindhoven University of Technology in the Netherlands established the Dutch Polymer Institute (DPI) as an industry-go vernment-academia research organization[15] in order to build a materials informatics system for shared use within the organization.

(3) Measures taken by the EU

In 2005, a multilateral project called “TOPCOMBI” was initiated by the European Commission, involving combinatorial materials development and materials informatics. Twenty-two companies, universities, and research institutes from 11 countries of the EU participated in “TOPCOMBI”[16]. “TOPCOMBI” is led by CNRS of France, whose representative is Mirodatos of CNRS. Its budget is said to be about ¥4.5 billion. Although the main aim of this project is to promote catalyst development based on the use of combinatorial methods in the EU, the building of a materials informatics system is also included.

5-3 Present status in Asian countries

The Accelergy Corporation is a Chinese company that makes use of materials informatics[17]. This company has business bases in Palo Alto (California) and Shanghai. The company receives orders for materials development in the U.S.A. and carries them out in a large-scale research and development center located in Shanghai. This business model enables research and development costs to be reduced and results in the quick delivery of results. Its main business is to sell combinatorial materials synthesis systems for catalysts and software for use in materials informatics, and it also develops electronic materials. The company is also active in purchasing related venture companies established in the U.S.A.

In Korea, there is growing interest in informatics as research on combinatorial materials becomes more popular. Although the Korea Advanced Institute of Science and Technology does not possess materials informatics technology at present, it is very interested in the technology and frequently participates in international conferences on combinatorial materials in order to collect information.

5-4 Present status in Japan

(1) Research and development in commercial companies

There are many companies in Japan that are involved in organic molecular synthesis and pharmaceuticals discovery using combinatorial chemistry, and research websites on combinatorial chemistry are found on the Internet[19]. Unfortunately, however, only a few companies are attempting to build combinatorial materials science or materials informatics systems. Asahi Kasei Corporation is one Japanese company that is enthusiastic about combinatorial materials synthesis and the building of an informatics system[20]. The company established a laboratory in the University of Southampton to promote new materials development and the building of a unique informatics system. Moritex Corporation, Hitachi High-Technologies Corporation, and Pascal Corporation all sell equipment for combinatorial materials synthesis systems. The portable combinatorial materials synthesis equipment of Pascal Corporation, in particular, has now become an industry standard for the combinatorial materials synthesis of thin films[21].

Although Ryoka Systems Inc., Teijin Systems Technology Ltd., and Sumisho Electronics Co., Ltd. (now Sumisho Computer Systems Corporation) sell computation science systems for use in combinatorial materials science, most of these companies currently just represent overseas software companies.

(2) Research and development at universities and public research institutes

The Tokyo Institute of Technology was the first to start research on combinatorial materials science in Japan and the basic concept was demonstrated in 1995. Among the organizations that have conducted research on materials development using combinatorial methods since then are the National Institute for Material Science, the Kansai Branch of the National Institute of Advanced Industrial Science and Technology, the Tokyo Institute of Technology, the University of Tokyo, and Tohoku University. The combinatorial materials research project "COMET", which is a joint project involving the National Institute for Material Science, the University of Tokyo, Tohoku University, and the Tokyo Institute of Technology, cooperates with "CoSMIC" in the U.S.A. and their servers are mutually linked in order to complement each other's data.

In Japan, however, research activities still remain within the project confines of each organization, whereas overseas countries have established research bases for combinatorial materials science so that research on materials informatics is promoted from a long-term perspective.

6 International Conferences on Materials Informatics

It has been pointed out that both international competition and cooperation are needed for the development of materials informatics using combinatorial methods. To discuss the orientation and development of materials informatics, a workshop was co-hosted by NIST (the National Institute of Standards and Technology) and CoSMIC-IMI (the Materials Institute for the Combinatorial Sciences and Materials = Informatics Collaboratory) in January 2005. In this workshop, the concept of "Data Driven Materials Research", combining materials science and informatics, was introduced. The Boeing Company, for example, provided specific examples of informatics showing the history of aluminum alloy development. New areas requiring the international sharing of massive amounts of data in other research fields were also introduced. For example, it was pointed out that in the field of astronomy the amount of data obtained in a year would reach the order of magnitude of a petabyte by 2010 and acquiring information from such a massive database would become a field of scientific research in itself. During the conference, problems facing the future of materials informatics, particularly problems of sharing data based on different degrees of accuracy and data obtained using different models, were also discussed.

In "The First International Roadmap Conference on Materials Informatics" subsequently held at the University of Maryland, the above-mentioned Associate Professor Lippmaa of the University of Tokyo introduced the concept of a data and informatics structure based on XML, and the possibility of using XML as the standard format for informatics in the future was also discussed.

7 Issues to be Addressed in Building a Materials Informatics System in Japan

Materials informatics aims at the rapid development of new materials by organically linking information on different processes for materials synthesis with materials data. In the course of materials development, complex measurement results are represented visually wherever possible, and the future direction of materials science will be significantly affected by developments in materials informatics. In overseas countries, ever since combinatorial methods were adopted in certain fields such as catalysts by commercial companies and the methods were industrialized, there has been a trend towards the establishment of central research bases around which an informatics system can be built by linking these bases with each other. However, the application of informatics to the development of inorganic materials is still in the initial stages, worldwide.

Compared with such rapid advances in foreign countries, it is unfortunate that the importance of informatics has not yet been sufficiently recognized in Japan. Although materials development using combinatorial methods is listed in "Strategies by Fields, Second Basic Policies for Science and Technology" as an example of a technical target, the need to expand this to include informatics has not been recognized. Furthermore, the most serious problem in Japan is that much research and development is kept within the confines of each project by different research organizations.

Taking account of the fact that all manufacturing industries are based on materials, we must recognize the importance of materials informatics in enabling innovative materials development and start the systematic accumulation of data related to the research and development of inorganic materials in particular. To promote research and development in this field in Japan, the following measures must be taken.

(i) A central research base for materials informatics should be established in Japan, to look at the subject from a long-term perspective. Multiple research institutes and universities should cooperate with this research base to establish an informatics system for promoting the development of new materials by exchanging information on the Web using a standard data format based on XML. The central research base should be equipped with foundry facilities and databases so that it can provide external organizations, including commercial companies, with the space for materials development based on materials informatics and the preparation of prototype devices.

(ii) Since building a materials informatics system cannot be done by a single organization, it requires long-term domestic and international cooperation. As for the standardization of data format, Japan should promote the use of the XML format for databases by actively proposing it internationally.

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Dissemination of Nanosimulation Techniques to Promote the Development of Nanotechnology

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1 Introduction

"Nanotechnology" generally refers to technology involving materials and components ranging in size from 1 to 100 nanometers ("nano" means a billionth) [1]. Such materials and components consist of 10 to several million atoms and exhibit properties quite different from those found in conventional bulk materials. They show characteristic electronic properties associated with specific atomic arrangements, establishing an essential source of new technology. At the same time, they bring about previously unencountered technical problems. For instance, the typical size of semiconductor CMOS has become as small as 65 nanometers [2], causing significant problems due to increased leak current. Hence, intensive development of dielectric films with high dielectric constant, which remedies this problem, is underway. In addition to CMOS, there are many other issues of great interest in nanoscale science, such as nanotubes for conductor wires, monomolecular devices with a switching function, spintronics (using electron spin to represent information), and nano-catalysts based on nanoscale atomic clusters.

Computer aided design (CAD) is now common in many industrial fields, contributing to more efficient development. These simulation techniques are built on modeling of appropriate basic science. How, then, should simulation techniques for materials/device design for nanotechnology be constructed? In the nanoscale region, the wave characteristics of electrons become prominent, which is the basis for the new functions. Due to the tiny size, however, manipulation by conventional contact techniques is impossible. Electronic states and atomic configurations must therefore be controlled by light and by electric and magnetic fields. Analysis and prediction of these properties must be based on quantum mechanics. Furthermore, since it is difficult to accumulate a large amount of data through experiments, "accuracy" in modeling becomes an important factor.

Such highly accurate simulation techniques based on quantum mechanics are not entirely new. They have already been used in theoretical and computational science for physics, chemistry, and materials science. Therefore, one may consider that using those calculation techniques and codes (programs) would be sufficient. In fact, there are many projects in which experimental scientists and engineering developers collaborate with researchers in computational science for this purpose.

However, the development of nanotechnology is remarkably fast. If such simulation techniques remain only in the hands of researchers in computational science, the situation will be insufficient for the rapid development of nanotechnology. Environments must therefore be developed in which simulation techniques can be widely used not only by specialist researchers but also by researchers in other fields. It is still a fresh memory that dissemination of technology, such as the transfer of semiconductor technology from military to civilian use and the spread of internet technology that was originally a tool for researchers, brought about drastic technological revolutions. The U.S. government has recognized the importance of such dissemination and is taking measures to promote it. Because Japan aims to be a technology-oriented nation, it should take similar measures as quickly as possible.

Mere transfer of advanced simulation codes from nanoscience (basic science) researchers to nanotechnology engineers will not work well without transfer of basic principles and the meaning of results. In fact, there is a gap between the two groups with respect to the scales they deal with, leading to another gap in the way they view phenomena. This causes many nanotechnology engineers to doubt the effectiveness of the simulation techniques developed by researchers in nanoscience. In order to disseminate nanotechnology, it is therefore essential to close these gaps. To achieve this, it is important for nanoscience researchers to develop techniques for calculation of larger sizes as well as for computation of more observable physical quantities, and for nanotechnology engineers to understand fundamental theories and modeling mechanisms in order to absorb knowledge obtained by the calculation of smaller sizes. It is therefore very important for both parties to interact with each other.

This report discusses essential conditions to realize desired outcomes from the perspective that the dissemination of advanced simulation (nanosimulation) techniques will promote the development of nanotechnology. First, this report surveys what are nanosimulation techiniques and what kinds of infomation they can give. Next, it analyzes trends of dissemination in the U.S.A., Europe, and Japan. Finally, it recommends measures that Japan should take.

2 Present Status of Advanced Simulation (Nanosimulation) Techniques in Nanoscience

Figure 1 summarizes nanosimulation techniques related to the development of nanotechnology. The most important items in the chart are the quantum chemical calculation and the first-principles calculation based on the density functional theory, which in principle do not require empirical data and allow for highly accurate calculation. Many software products for these types of calculations are already available. The

Figure 1 : Outline of advanced simulation techniques in nanoscience

Objects: electron (spin), nucleus

Input:
Number of electrons; nuclear configuration; atomic number; interaction between electron and electron, electron and nucleus, and nucleus and nucleus

Output:
○Electron (spin) density, wave function
○Total energy ○Various optical spectra
○Internuclear force
→stability of structure, dynamics

Calculation technique	Objects of calculation/characteristics
Quantum chemical calculation	Electron and nucleus. A wide range of methods is available from rough approximation to ultra-precision calculation. Suitable for handling atoms and molecules.
First-principles calculation (density functional theory)	Electron and nucleus. A wide range of methods is available from rough approximation to high-precision calculation. Suitable for handling solids, surfaces, and solutions.
Empirical (TB) Calculation of electronic state	Electron and nucleus. Significant approximation of electron regions is implemented using empirical parameters. Applicable to the calculation for relatively large sizes.
Classical molecular dynamics (MD)/molecular mechanics (MM)	Nucleus only. Accuracy depends on the estimation of mutual interaction. Applicable to calculation for fairly large sizes.
Quantum dot and wire calculation	Electron only. Approximation is made by taking a coarse-grained viewpoint for the nuclei.
Lattice model	Electron only. Nucleus is fixed. Suitable for describing magnetic state and super conductivity state.

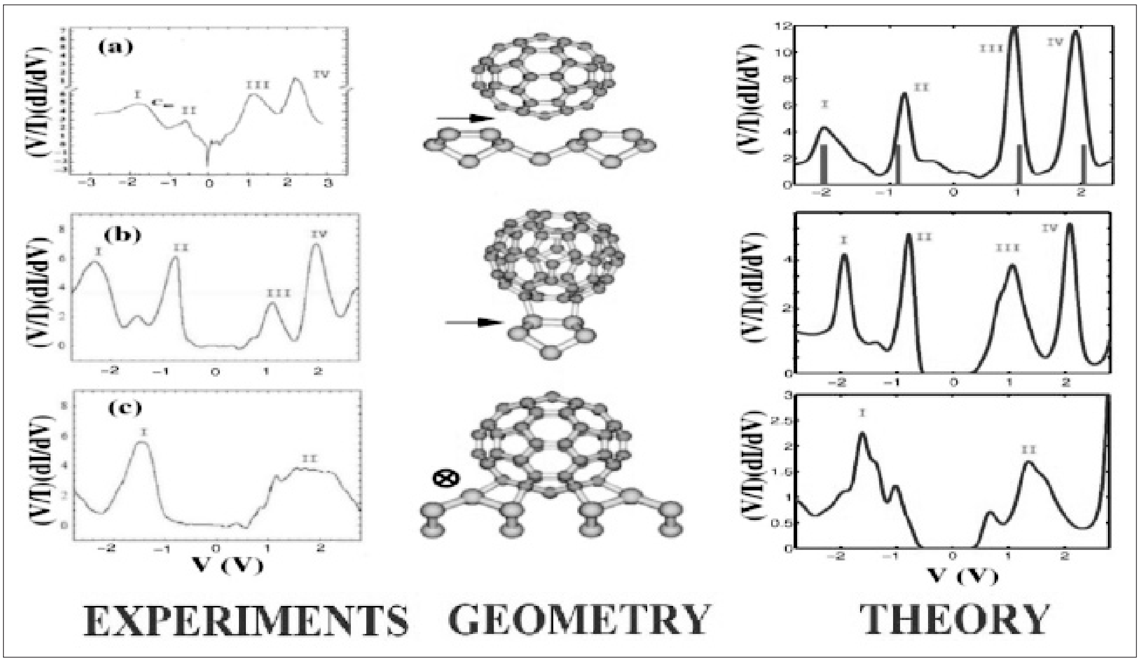
Quantitativity: High ↕ Low

most popular are Gaussian and GAMESS for the former, and CASTEP and VASP for the latter. These software products have been already used for the development of nanotechnology. For instance, a domestic chemical manufacturer has achieved some success in materials design by analyzing the structure of solid acid catalysts using a first-principles calculation software product [3].

While the above-mentioned software products are very useful, some issues remain. For instance, (i) introduction of cutting-edge calculation techniques tends to be delayed and is sometimes never done at all; (ii) since codes are generally published in binary form, users cannot customize the software; (iii) it is therefore difficult for users to introduce calculation techniques appropriate for their objectives. Such a situation is undesirable for application to fast-evolving nanotechnology. Another possible problem is that the development centers for such software products are located mainly in the U.S.A. and Europe. This dependence on foreign software is undesirable in terms of competing against these countries in the fields of both nanoscience and nanotechnology.

In fact, many state-of-the-art calculation techniques have not been incorporated into these software products. One example is the nonequilibrium Green function (NEGF) method [4]. It was recently demonstrated that this method can quantitatively predict electrical conductivity by studying the quantum transport properties between fullerene (C60) and a silicon surface as shown in Figure 2 [5], although it is uncertain whether the method has reached a level at which it can contribute to the development of nanotechnology. Since quantum chemical calculations and first-principles calculations are generally based on the assumption of absolute zero temperature (-273°C), they sometimes fail to explain phenomena at room temperature (25°C). To address this problem, a method that enables efficient calculation of “free” energy for discussing structural stability and reactions at “finite” temperatures has been proposed [6]. Recently, the author and coworkers have developed a first-principles calculation technique for standard redox potential, which is a crucial quantity in electrochemistry [7]. The promotion of independent development of calculation techniques, codes, and software products for domestic researchers is essential in order to promptly incorporate such new calculation techniques.

Figure 2 : Comparison of the results of electrical conductivity simulation for monomolecular devices using NEGF method (resistance to the applied voltage) and experimental values [5]



Source: Reference[5]
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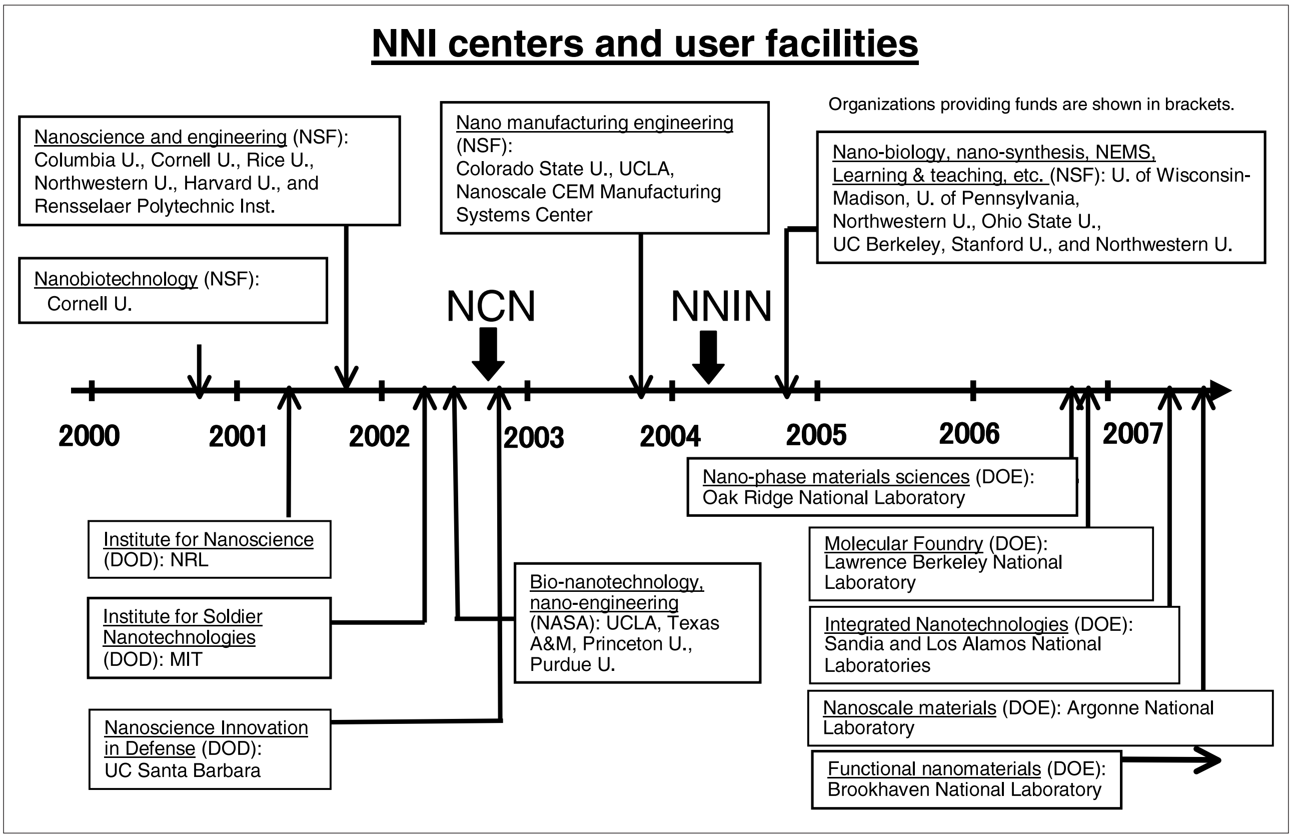
3 Trends in the U.S.A. in the Dissemination of Nanosimulation Techniques towards the Development of Nanotechnology

3-1 Overview of trends in the U.S.A. in the development of nanotechnology

In the U.S.A., the National Nanotechnology Initiative (NNI), a federal-level R&D project related to nanotechnology, is underway [8,9]. In this project, 23 federal agencies including the National Science Foundation (NSF) and the Department of Energy (DOE) are active in nanoscale science, engineering, and technology. The objectives of the NNI are to: (i) maintain research and development programs relating to nanotechnology on a global level; (ii) support the transfer of new technologies to commercial products; (iii) develop educational resources, skilled labor, and support bases for future nanotechnology; and (iv) address social issues expected to arise from the development of nanotechnology. It is notable that three of the four items are related to technology transfer and dissemination. In fact, support is being given to the construction of R&D facilities in universities and national research institutes and to the establishment of user networks for general (non-specialist) users. Figure 3 outlines the R&D centers and user facilities of the NNI.

A typical network established by the NSF is the National Nanotechnology Infrastructure Network (NNIN)[10]. The NNIN began in March 2004 as a five-year project, taking over the support services of the National Nanofabrication User Network (NNUN, 1994 to 2003). The NNIN is a collective entity comprising experimental facilities from 13 universities. It provides students, engineers from small companies, and startup companies with opportunities for experiments, together with support for use of the facilities. The NNIN/C (computational drive) is the computation department of the NNIN [11]. The NSF has established another network focusing on computation called the Network for Computational Nanotechnology (NCN), with the objective of facilitating the dissemination of nanosimulation techniques [12]. In this manner,

Figure 3 : Outline of R&D center, user facilities, and networks of the U.S.A. National Nanotechnology Initiative (NNI)



Prepared by the STFC based on NNI Strategic Plan (December 2004)

Table 1 : Software groups of NNIN/C

Category	Characteristics	Software name (developer)
First-principles calculation	Plane wave basis, standard	ABINIT* (Belgium)
	Plane wave basis, standard	CPMD* (Switzerland, Germany)
	Real space, pseudo-potential	PARSEC* (Minnesota)
	Real space, anisotropic mesh	HARES
	LMTO method, excitation, quantum transport	LM Suite* (Arizona)
Quantum chemical calculation	Standard	NWChem* (Washington)
TB method	Quantum transport of CMOS	SEMC-2D
Classical MD method	Environment-dependent potential	EDIP (Harvard)
Quantum wire & dot		SETE (Harvard)
Others	Transition state search, NEB method	ANEBA
	Band structure of photonic crystals	MIT Photonic Bands* (MIT)
	CV calculation of silicon MOS	UTQUANT (Texas)
	Two-dimensional particle transport	TOMCAT (Texas)
	Neutron transport	UT-MARLOWE (Texas)

The * mark indicates secondary publication of software products that have been published elsewhere.

in addition to COE (center of excellence) type facilities, the NSF carries out network projects focusing on expanding the population in the field of nanotechnology and raising the level of their skills.

The DOE is setting up five user facilities called Nanoscale Science Research Centers (NSRCs), which focus on the synthesis, processing, and manufacture of nanoscale materials in existing national research laboratories[13] (see Figure 3). Some of the NSRCs focus on theory, modeling, and simulation. In these centers, users must first apply for collaborative research projects with NSRC researchers. If their proposals are accepted, they can use the NSRCs' facilities and receive support from their technical staffs. This indicates an emphasis on pioneering studies conducted by high-level collaborative research groups consisting of computational science researchers. It is very important to enhance the combination of dissemination activities and pioneering research as described above.

3-2 Present status of NNIN/C [11]

The activities of NNIN/C can be analyzed as follows. As described above, the NNIN itself is a collective entity of 13 sites, each of which specializes in a unique field. General users can select a site relevant to their objectives through advice from consultation services. Usually, users can access facilities within two weeks. Anyone can apply, and certain fees are charged for use. Since the technical staff of the NNIN devotes its entire attention to technical support, collaborative research is not carried out in this framework. Instead, various types and levels of seminars and training programs are prepared for users with different skills.

The NNIN/C is the computation division of the NNIN. Its objectives are: (i) creation, accumulation, and maintenance of software for nanoscale technologies; (ii) preparation of manuals that enable non-specialists in nanotechnology to swiftly address problems, provision of technical support and seminars, and setting up an online site for simulation on the internet; and (iii) maintenance of feedback paths from users. These objectives indicate an emphasis on support activities after software is published.

Users are assumed to include: (i) experimental researchers and engineers, (ii) computational science researchers and students who cannot access the most advanced software, (iii) researchers who need software that provides the basis for code development and extension, and (iv) computational science researchers who intend to provide their own codes. This list indicates the expected participation of a wide range of researchers, from beginners in nanotechnology to experts in code development.

The participation of code developers, in particular, is considered very important in order to obtain high-quality software.

Table 1 shows the NNIN/C's software as of December 2005. The software includes a balanced range of participants, from first-principles calculation to device design. Explanations and manuals are provided on the internet for all software products, along with contact information for technical services. In addition, the NNIN/C provides hardware. It has several cluster machines with about 1,000 CPUs in total, which users can access by remote operation. This level of hardware is enough for standard simulations. Researchers from Harvard and Cornell Universities administer the entire operation of the NNIN/C, and try to provide environments in which general users can quickly undertake simulations.

Potential weaknesses of the NNIN/C are: (a) there are no clear-cut portal sites; (b) there are no seminars and tutorial systems; and (c) most of the software products for device design have been developed originally, but many of those for first-principles calculation are merely redistributions from the sites of the original developers. (a) and (b) are probably caused by the fact that the NNIN/C has just begun operation, and whether they can be achieved is an important issue. On the whole, however, the activities of the NNIN/C provide a useful reference.

3-3 Activities in the NCN [12]

The NCN began in 2002 as the first network of the NSF, before the NNIN/C. The objective of the NCN is to link theories, experiments, and calculations to promote the development of nanotechnology. Nanoscience researchers who develop new calculation techniques and code are at the center of the administration of the NCN. It is noteworthy that the intention is to provide the newest simulation techniques that are not yet available in software products. In particular, nanoelectronics, nanoelectromechanical systems (NEMS) and nanobioelectronics are the main targets, and software for leading-edge calculation techniques such as quantum conductivity calculation is already in development.

In addition, the dissemination activities of the NCN for general users through seminars and educational resources on the internet are remarkable. The NCN holds summer school courses, including basic theory and simulation workshops, with the course recorded on video and released over the internet. Users who do not attend the course can therefore still derive some benefit from the course over the internet. The NCN already has an internet portal site called "nanoHUB" to provide nanosimulation software products and hardware computers to general users [14]. Users can run simulations on nanoHUB and check the results. NanoHUB provides detailed explanations and manuals for software products so that non-specialist users can quickly run simulations without worrying about software installation or other initial set up. Published statistics show about 1,600 users in the previous year. A cluster machine with 200 CPUs is provided as the hardware. System size appears adequate for initial trials. The full range of support provided after software publication is highly regarded.

The NCN's software includes everything from first-principles calculation (GAMESS, ABINIT, CPMD, etc.) to simulation software for device design (TBGreen, etc.). As with the NNIN/C, most of the simulation programs for first-principles calculation are republications of software products developed elsewhere, while more of the simulation programs for device design are independently developed. In particular, the quantum conductivity calculation software [5] based on the NEGF method described in the preceding chapter is one of the most advanced in the world, and it was developed by an NCN researcher. This lineup of state-of-the-art simulation techniques is an attractive characteristic of the NCN.

The NCN also began collaboration with TeraGrid, part of the Grid Project in the U.S.A., in 2005 [15]. This collaboration enables the NCN to respond to users who require a more practical calculation scale. It is unclear, however, whether NCN software is tuned at each node (platform) for full performance. When software is opened to public use, tuning for different platforms is also an important aspect. In any event, there is an interesting contrast between the NCN, which began as a software project and was joined by Grid, a hardware project, and projects in Japan, which almost always begin with hardware.

4 Trends in the Dissemination of Nanosimulation Techniques in Europe

4-1 Overview of trends in Europe in the development of nanotechnology

This section focuses on measures taken in Europe as a whole. There is no powerful initiative focusing on nanotechnology in Europe like those in the U.S.A. Instead, the European Commission, which oversees science and technology policies for Europe as a whole, plays that role.

The European Commission is taking measures under the "European Research Area (ERA) Initiative" to eliminate barriers to research and development among various European countries so that they can function as a single unit[16]. The basic research investment plan for the establishment of the ERA is the Framework Program (FP). The Sixth Framework Program (FP6) is operating through 2006[17]. Among its seven top-priority programs, there are two programs related to information and nanotechnology, "Information society technologies (IST)" and "Nanotechnology and nanosciences, knowledge-based function materials, new production processes and devices (NMP)." Several projects on nanosimulation techniques are being carried out under these programs. The Seventh Framework Program (FP7) is to start as a seven-year program in 2007[18]. In this program, two projects focusing on research and development to meet the needs of European industry, "Technology Platforms" and "Joint Technology Initiatives," are to be added to the existing FP6 projects. FP7 is therefore expected to accelerate the linkage between nanoscience and nanotechnology.

Below, this report briefly describes a software hub called PHANTOMS, whose development began in FP5, and the development status of other simulation codes for first-principles calculation in physical science fields.

4-2 PHANTOMS Computational Hub [19]

A notable project for promoting the development of nanotechnology by the dissemination of nanosimulation techniques in Europe is the "PHANTOMS Computational Hub." This software hub was constructed as part of the FP5 projects "Nanotechnology Computer Aided Design (NANOTCAD)" (January 2000 to April 2003) and "Network of Excellence on Nanoelectronics (PHANTOMS)" (December 2000 to November 2004) and released to the public in April 2002. In other words, the PHANTOMS Computational Hub began before the NCN. The objectives of the hub were collection of software useful for the design of nanoscale electronic devices, evaluation of its accuracy, and calculations for verification. In addition to fostering human interaction in workshops and providing information over the internet, it also brought in industrial users and established a forum for opinion exchange.

In the software PHANTOMS released, there was an emphasis on nanoelectronics, with 15 device-oriented products, than on first-principles calculation, with only 2 or 3 products. In this case as well, programs for first-principles calculation were re-releases, while most other programs were developed independently. A check of internet portal sites found that the explanations of the software are passable. There are several shortcomings, however, including (a) lack of information on accuracy; (b) no explanations of what can be done after registration on the portal site; (c) inadequate contacts for further information; and (d) no updates to the website for three years. It is therefore difficult for users to utilize the hub with confidence. This is in marked contrast to the NCN, but perhaps the problems stem from the difference between a project currently running and one that has been completed. The situation confirms how important it is to continue support activities after software is published in order to maintain the achievements of open-software projects.

4-3 Other measures for the dissemination of simulation techniques

FP6 projects include many that involve

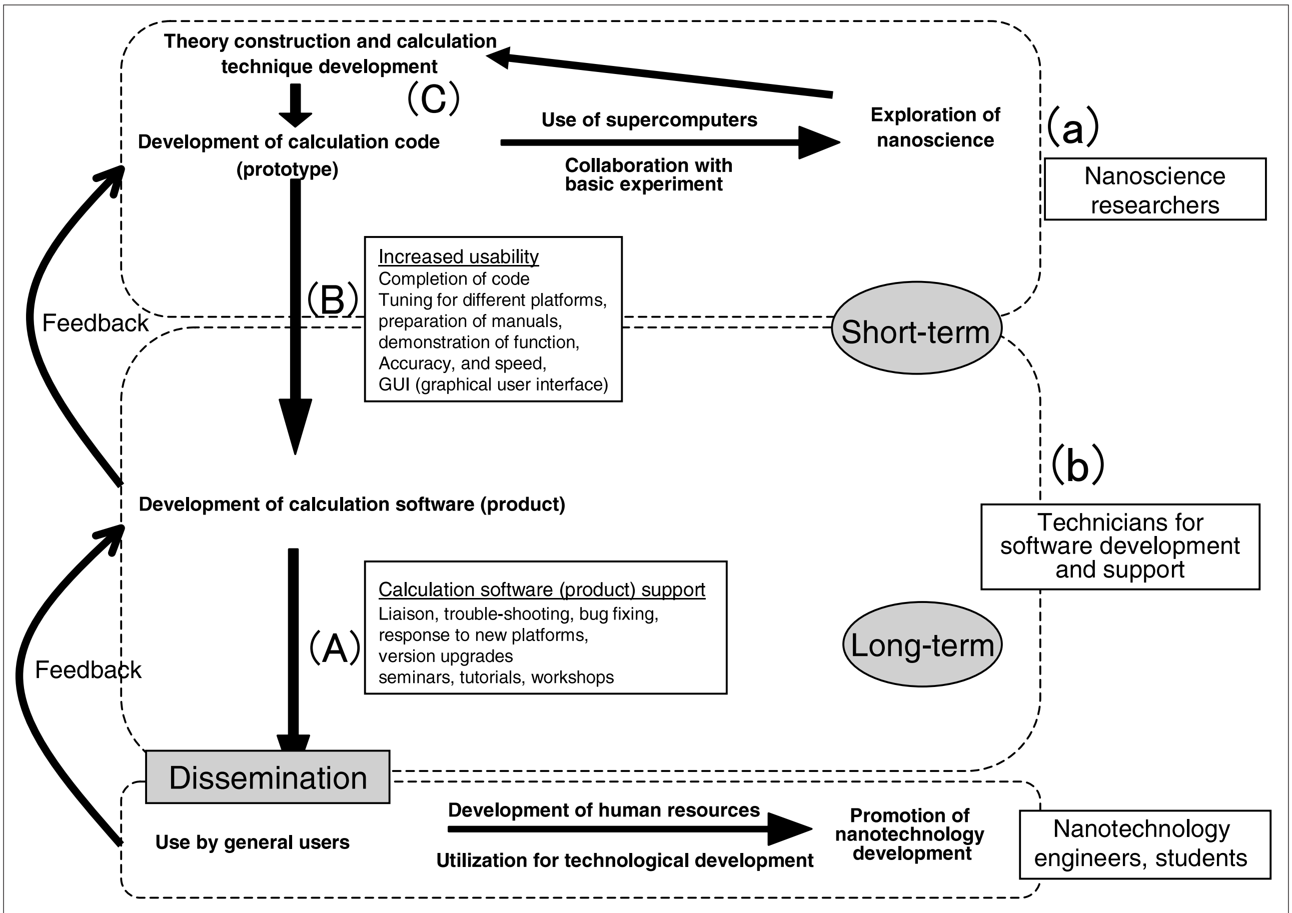
nanosimulation. For instance, theoretical and computational scientists working on first-principles calculations manage the "Nanoscale Quantum Simulations for Nanostructures and Advanced Materials (NANOQUANTA)" project of FP6-NMP (June 2004 to May 2008) [20]. This project, in which the development group for ABINIT software (see Table 1) participates, looks very powerful from a nanoscience viewpoint. It has achieved appreciable results in the expansion of the population through the traditional European approach of organizing seminars. Furthermore, the establishment of a common facility for theoretical research has been proposed. It would be called the European Theoretical Spectroscopy Facility and would provide a site for collaborative research among basic scientists and industrial engineers.

"Towards Atomistic Materials Design (Psi-k)" is a program sponsored by the European Science Foundation (ESF)[21]. This program is a gigantic network consisting of many European researchers in the field of first-principles calculation. Psi-k sponsors many seminars and workshops, and researchers belonging to the network have developed various creative simulation codes including the above-mentioned CASTEP, VASP, ABINIT, CPMD, SIESTA (using the Order N method), and TranSIESTA for quantum conductivity calculation. Although a software hub assembling these codes has not been established, each developer group provides active support and maintenance on its own site, creating a well-served and practical system. The situation in Europe suggests the importance of maintaining a high level of theory construction and development of calculation techniques at the nanoscience level.

5 Model Flow for the Dissemination of Nanosimulation Techniques

This analysis of the present situation in the U.S.A. and Europe suggests conditions and a model flow for the effective dissemination of nanosimulation techniques to promote the

Figure 4 : Design for effective dissemination of advanced simulation techniques in nanoscience



development of nanotechnology. There are three key points, which are summarized in Figure 4.

(A) Enhancement of support activities after software release

It is no exaggeration to say that the most important aspect of dissemination is long-term support activities after the public release of software. Conditions necessary for the maintenance of software assets are setting up a highly active technical consulting service (liaison), sequential bug fixing and response to new platforms, periodic version upgrades, education in theory and modeling through seminars and tutorials, and enhancement of practical simulation training.

(B) Improvement of necessary conditions before software release

To achieve productive dissemination, it is also important to create software products that are easy to use. To achieve this, it is necessary to make software products from prototype simulation codes by tuning them so that they are useful for general purposes and applied to different platforms. Preparation of usable manuals and provision of information on the verification of accuracy and validation of speed are also indispensable. Development of a graphical user interface (GUI) and appropriate handling of copyrights related to prototype codes or previously published primary software products are also needed.

(C) Improvement of skills for construction of leading-edge theories and development of simulation technique

Activation of development of prototype codes that are seeds for the software products is also important. To this end, it is necessary to establish skill promotion projects, in which researchers in nanoscience theory and computational science can devote themselves to the development of new basic theories and calculation techniques. For instance, pioneering research toward a grand challenge problem using a supercomputer would be a good candidate.

6 Present Status of the Dissemination of Simulation Techniques in Japan

6-1 Research and Development for Applying Advanced Computational Science and Technology (ACT-JST) [22]

There have been many Japanese projects targeting the promotion of materials design based on the dissemination of simulation techniques. The ACT-JST project played a pioneering role among these projects. It began in 1998 to focus on development and release of simulation software for use in industrial fields. This was an epoch-making experiment at the time. In FY 1998, 50 research projects on this process were selected for intensive short-term examination (one year). Subsequently, the research period changed to three years. Seventeen research projects were selected in FY 1998, 4 in FY 1999, 4 in FY 2000, and 21 in FY 2001. That concluded the entire enterprise. The ACT-JST website states that the JST publishes the results of research and development in the hope of contributing to the creation of new business and that the results of software development are made public (as of December 2005).

However, there are various barriers for users to overcome in order to actually use the published software products. There are no support activities to encourage practical use, no periodic version upgrades, and no seminars to promote dissemination. Furthermore, descriptions of the contents of the software, basic principles, accuracy, and speed are inadequate. This makes it difficult for general users to actually reach the stage of downloading the software and compiling it in their computer environments. It is important to learn from the problems encountered in such pioneering projects and to construct new viewpoints for future improvement. Vigorous follow-up on the question of whether the requirements for published software packages are satisfied is essential. In projects whose objective is to make and provide open-source software, it is necessary to assess the status of dissemination and also to undertake long-term assessment of

Table 2 : Examples of Revolutionary Simulation Software (RSS21) software groups

Category	Description	Software name
Quantum chemical calculation	Based on density functional theory	Protein DF
	Based on density functional theory	Protein MD
	Fragment molecular orbital method	ABINIT-MP
First-principles calculation	Plane wave basis, standard	PHASE
	Production of pseudo-potential	CIAO
	Expanded plane wave basis	ABCAP
	Dielectric constant calculation	UVSOR
	Quantum and classical physics combined multiscale method: PHASE + TB calculation + classical MD	CAMUS
TB calculation	Standard	FXZTX
	NEGF method, quantum transport	ASCOT

software support activities after the software is made public. Software that is genuinely useful for general users can only be maintained by assigning long-term responsibility to the proposer of the project.

6-2 National Research Grid Initiative (NAREGI) [23]

NAREGI began in 2003 with the goal of developing grid infrastructure software for practical use. The project aims to develop hardware and middleware, but demonstration research on application software in grid environments is organized with the cooperation of industry, universities, and national research institutes. The NAREGI website says, "In particular, computational methods are to be used to clarify the structures of nanomaterials as well as the natural principles of functional manifestations of nanomaterials. An academic base will be built for next-generation nanomaterials design by new technique and software, which has been dependent solely on experimentation in the past, with the aim of developing devices for industrial applications." This statement indicates that the intention of the project is to publish demonstrated software together with grid environments to promote the development of nanotechnology.

The project is in its third year, and various types of information will be disclosed from now on. Of particular concern, however, is the fact that it is unclear at this time how the demonstrated software packages will be dealt with at the end of the project and how they will be supported after that. Furthermore, it is questionable to what extent the resultant software packages will be optimized and tuned to grid environments. The six fields of nanoscience addressed in the demonstration research are distinct, and one hopes that useful software products will be developed in each field. When the development and dissemination of software are part of projects whose primary aim is to develop hardware, underestimation of software often results because its importance is not sufficiently appreciated. This is why it is necessary to have projects such as the NCN that focus on software.

6-3 Revolutionary Simulation Software (RSS21) [24]

While most Japanese projects focus on hardware, some that focus on software have been started in the last few years. Two examples are the "Frontier Simulation Software for Industrial Science (FSIS)" project[25], which began in 2002 as part of the IT program sponsored by the Ministry of Education, Culture, Sports, Science and Technology, and its successor, the "Revolutionary Simulation Software (RSS21)" project[24]. In RSS21, simulation software packages in a variety of fields including chemistry, biology, nanotechnology, fluids, and structures are being independently developed, verified, and published free of charge. The project is led by the Collaborative Research Center of Frontier Simulation Software for Industrial Science, Institute of Industrial Science, the University of Tokyo.

Because this project does not have its own hardware, sufficient emphasis appears to be placed on use on different platforms. The software download site is well established and manuals and explanations of content are well prepared. The software lineup (see Table 2) covers a wide range of useful calculation techniques, from chemical and biochemical calculations to first-principles calculation and quantum transport calculation.

Furthermore, software support is remarkable in that RSS21 has established an independent company to provide ongoing support. Corporate organization is a workable option in order to maintain software quality of independent of budgetary fluctuations. Opinions are sought from industrial users and reflected in actual development. Seminars on how to use the software are held a few times each year. The seminars last several hours and the average number of participants is about 20. Software products are upgraded periodically so that general users can use the software with confidence.

A key point of the project is the staffing of support technicians in the support company to mediate between general users and code developers (researchers). These technicians contribute to reducing the gap between nanoscience researchers and nanotechnology engineers. However, there appear to be too few people capable of covering the entire spectrum from the role of developing software products from prototype codes through upgrading of the software to giving seminars for the users. In order to secure such outstanding human resources, it is necessary to improve the skills of technicians as well as to take measures to advance the status of technicians and to stabilize their professional status.

A problem with this project is neglect of technical consultation and support for users who have downloaded the free software. In addition, disclosure of information on the speed and accuracy of the software is inadequate. Enhancement of softwares for device design is also desirable. However, the project is the most promising so far among domestic software development projects.

6-4 Computational Materials Design (CMD) workshop [26]

The CMD workshop also is worthy of attention as a project aiming only for dissemination of simulation techniques. The CMD workshop was started around 2004 by several research groups centered around Osaka University on first-principles calculations. The eighth workshop is scheduled for March 2006. The workshop is a residential seminar over three days and two nights, involving practical experience with nanosimulation codes owned by the organizing groups and lectures on basic theory. Such residential education and technical transfer deepens human interaction and is far superior to the training over several hours offered by the RSS21 project.

The fact that seven workshops have already been held is also important. Such continuity provides the users with a congenial atmosphere and reduces costs to the organizer as experience is accumulated, benefiting both users and organizers. In the past seven seminars, 118 students and 143 members of the general public have participated. Of the 143 general participants, 75 were from businesses, demonstrating that the workshop is enhancing industry-academia collaboration. From the viewpoint of education in computational science and simulation techniques, the project is a success.

From the perspective of promoting of nanotechnology development, the emphasis on first-principles calculations and the limited variety of software are problems. Because information is not made available to the public, users who encounter difficulties must directly contact the researcher who developed the code, increasing the work on both sides. The current situation, however, is probably the best the present staff can do. In order to expand the scope of activities, staffing support technicians who can liaise between the code developers (researchers) and general users are necessary.

7 Proposals

Based on the necessary conditions for publishing and disseminating software described in Chapter 5 and the present state of such efforts in Japan described in Chapter 6, this report proposes the following measures for effective dissemination of nanosimulation techniques to promote nanotechnology development.

(1) Improvement of assessment procedures for software publishing projects

Appropriate assessment of published software is essential to gain the trust and confidence of users. Therefore, this report recommends that projects aiming at publishing software introduce assessment procedures including the evaluation of long-term support activities and the results of usage. For instance, it might be productive to increase budgets as a bonus for successful achievements after publishing. Measures that allow only reliable software products to survive will contribute to the effective development of nanotechnology.

(2) Establishment of the status of technicians for the development and support of software

It is practically impossible for researchers in nanoscience to develop completed software products from prototype codes and then support the products. Specialist technicians should therefore be staffed as shown in Figure 4 (b). The establishment of job security is particularly necessary in order to insure “long-term and consistent” support. In this sense, setting up support divisions in appropriate organizations would be an effective measure. In order to secure outstanding human resources, skill upgrades through technical and personal exchanges among nanoscience researchers and leading-edge program developers is also an important factor.

(3) Maintenance of the linkage among researchers, technicians and users; the development of domestic programs

Progress in nanotechnology is remarkable. To keep pace with the speed of development, it is necessary to maintain a good relationship among the nanoscience researchers who take charge in the development of computational techniques and prototype codes (Figure 4 [a]) and the technicians who take charge of dissemination activities (Figure 4 [b]). Otherwise, it is difficult to reflect feedback from users in the development of new calculation techniques and codes, resulting in falling behind in the development race. From this viewpoint, it is important to establish domestic programs, based on national policies, that promote linkages among researchers, technicians, and users.

(4) Creation of software hubs

To raise the general level of nanotechnology, diversified software groups must be fostered. In Japan, because simulation techniques (particularly for devices) appear to be behind those of foreign countries, improvement in this field is necessary. This report therefore recommends construction of software hubs. Each project may prepare such a hub site accumulating resultant software, as in the case of the NCN. Another possibility is for a collective organization to form a hub by including multiple software lineups from the viewpoints of longevity and continuity. In the latter case, the technicians described in (2) may be employed there.

(5) Expansion of projects focusing on the development of prototype codes

Although this is not directly related to dissemination, because most projects nowadays involve software publication, nanoscience researchers often cannot concentrate on the development of leading-edge calculation techniques because they must perform tasks necessary for software publishing. To mitigate this problem, expansion of projects focusing on the portion up to the development of prototype codes for leading-edge calculation methods (Figure 4 [c]) should also be considered.

While it is not certain that the measures described in (1) to (5) will have immediate effects on nanotechnology development, at least they will be effective for the dissemination of advanced simulation techniques in the long term. Enhancing the linkage between theory and experiment as well as between nanoscience and nanotechnology with these measures will surely contribute to the future development of nanotechnology in Japan.

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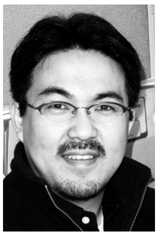

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6

Trends in Technical Developments for the Exploration, Development, and Production of Petroleum and Natural Gas Resources

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1 Introduction

According to Japan's projected energy supply (Table 1), in 2010, the supply of oil (including LPG) and natural gas in crude oil equivalent will be 277-253 million kl and 91-81 million kl, respectively, accounting for 46-44 percent and 15-14 percent of all energy. In 2030, these figures will reach 256 million kl and 108 million kl, accounting for 42 percent and 18 percent of all energy. Oil and natural gas are expected to account for the majority of the entire primary energy supply.

As shown in Figure 1, although worldwide confirmed and recoverable oil reserves*1-2 are increasing annually due to discovery and development of new oilfields, deep exploration, and the integration of heavy crude oil, as well as projected improvements in recovery rates, at

Table 1 : Projected primary energy supply

unit: million kl

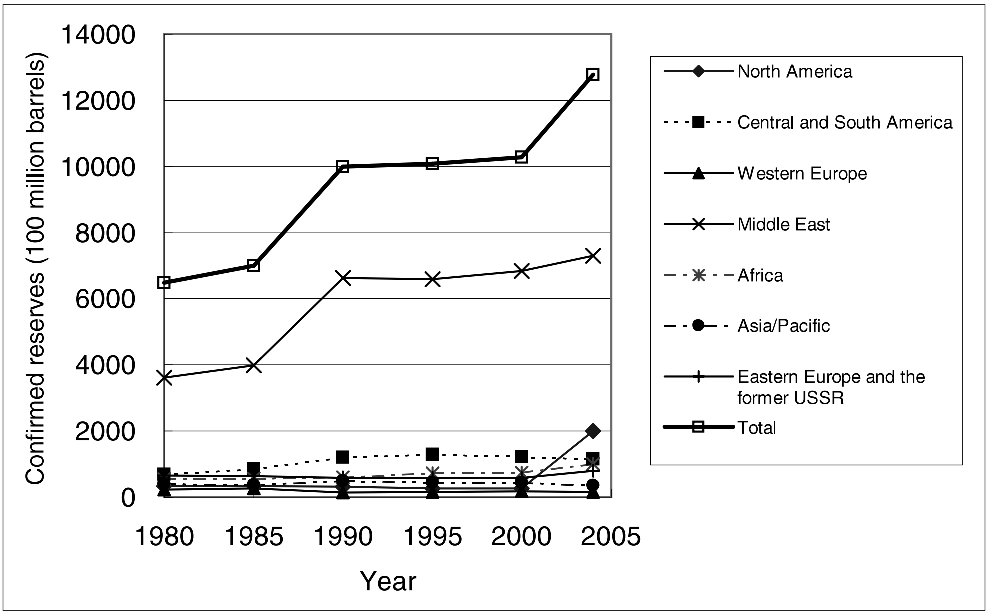
	FY 1990		FY 2002		FY 2010						FY 2030	
					Reference		Under current promotion measures		With additional measures		Reference	
Domestic supply of primary energy	512		576		602		585		569		607	
By energy type	Actual number	Percentage distribution	Actual number	Percentage distribution	Actual number	Percentage distribution	Actual number	Percentage distribution	Actual number	Percentage distribution	Actual number	Percentage distribution
Oil	271	53%	263	46%	258	43%	247	42%	About 236	About 41%	233	38%
LPG	19	4%	19	3%	19	3%	19	3%	About 17	About 3%	23	4%
Coal	86	17%	111	19%	111	18%	105	18%	About 101	About 18%	106	17%
Natural gas	53	10%	80	14%	91	15%	86	15%	About 81	About 14%	108	18%
Nuclear energy	49	10%	69	12%	85	14%	85	14%	About 87	About 15%	90	15%
Hydropower	22	4%	19	3%	21	3%	21	4%	About 21	About 4%	20	3%
Geothermal	0	0%	1	0%	1	0%	1	0%	About 1	About 0%	1	0%
New energy, etc.	12	2%	14	2%	16	3%	22	4%	About 27	About 5%	27	4%

Note 1: Please note that the energy balance sheet was revised in FY 2003 through the elimination and consolidation of some statistics beginning in FY 1990, so the actual values for final energy consumption and primary energy supply differ in some places from the previous (2001) long-term energy demand projections.
Note 2: In the previous (2001) long-term energy demand projections, the energy category "oil" under "primary energy supply changes and projections" included LPG. LPG is not included in "oil" this time.
Note 3: "New energy, etc." includes blast furnace top gas pressure recovery power generation and other forms of waste energy in addition to new energy.
Source: Reference [1] (p. 17)

current consumption rates the reserve life index is estimated at less than 50 years. By region, the integration of Canadian ultraheavy crude oil has greatly increased North American reserves, but the reserve life indexes*3 for Western Europe, Asia/Oceania, and Eastern Europe/former Soviet Union are all below 20 years.

Meanwhile, world primary energy consumption reached 9.74 billion tons in crude oil equivalent in 2003, with oil and natural gas accounting for 61 percent. Oil consumption, as seen in Table 2, also deserves attention. Consumption in Western Europe and Japan is down slightly, while it is up sharply in China and elsewhere in Asia, and up slightly in the USA and Russia. These statistics do not include India, which has become a major world consumer of oil and natural gas as its economy has grown rapidly. In 2003, India's daily oil consumption was 2.42 million barrels, competing with Germany and Russia for fourth place in the world behind the USA, China, and Japan. India's energy demand in 2030 is projected to reach 1 billion tons in crude oil equivalent. Along with China's 2.5 billion

Figure 1 : World confirmed and recoverable oil reserves



Prepared by the authors from OGJ (2004 final issue)

Table 2 : World oil consumption by country

units: 1,000 barrels/day (%)

Country/region \ Year	1985	1990	1995	2000	2003
Japan	4,435 (7.6)	5,305 (8.1)	5,784 (8.4)	5,576 (7.4)	5,451 (7.0)
China	1,810 (3.1)	2,255 (3.4)	3,390 (4.9)	4,985 (6.6)	5,982 (7.7)
Asia (not including Japan and China)	3,535 (6.1)	5,360 (8.2)	8,014 (11.6)	9,406 (12.5)	10,174 (13.0)
USA	15,170 (26.0)	16,305 (24.9)	17,725 (25.6)	19,701 (26.2)	20,071 (25.7)
Germany	2,670 (4.6)	2,710 (4.1)	2,882 (4.2)	2,763 (3.7)	2,664 (3.4)
France	1,790 (3.1)	1,910 (2.9)	1,893 (2.7)	2,007 (2.7)	1,991 (2.5)
Italy	1,730 (3.0)	1,930 (2.9)	1,987 (2.9)	1,956 (2.6)	1,927 (2.5)
UK	1,630 (2.8)	1,760 (2.7)	1,757 (2.5)	1,705 (2.3)	1,666 (2.1)
Russia	4,910 (8.4)	5,015 (7.7)	2,934 (4.2)	2,474 (3.3)	2,503 (3.2)
Middle East	2,980 (5.1)	3,395 (5.2)	4,028 (5.8)	4,320 (5.7)	4,480 (5.7)
Other	17,765 (30.4)	19,535 (29.8)	18,766 (27.1)	20,361 (27.1)	21,203 (27.1)
World total	58,425 (100.0)	65,480 (100.0)	69,160 (100.0)	75,254 (100.0)	78,112 (100.0)

Sources: BP "Statistical Review of World Energy 2004" and Reference [1] (p. 20) tons, this will account for 25 percent of projected world energy demand. Because of the large rapid increase in oil and natural gas consumption that is accompanying economic growth in these populous countries, the reserve life index shown in Figure 1 cannot be regarded with optimism.

Japan's policy is to reduce energy consumption. However, until renewable energy becomes available in terms of both price and volume, Japan must have agile overall policies to secure the primary energy supply necessary to maintain its economic growth and the livelihood of its people. Therefore, along with the development of renewable energy, Japan should adopt balanced policies that secure fossil resources. Japan must make careful and thorough preparations in the event of a sharp jump in the prices of crude oil and oil products and avoid the current overexcitement regarding the securing of rights to oil and natural gas resources. Obviously, securing primary energy supplies reflects a country's overall power. In Japan's case, strategies based on its technical and industrial expertise must be reviewed and strengthened adequately. Japan is internationally competitive with regard to industry, technology, and human resources in oil and natural gas resource exploration (mineral exploration), development, and production, so cooperation with resource-rich countries to secure economic and stable resources is an important strategy.

Exploration, development, and production of oil and natural gas are carried out today through international collaboration and division of labor. This is led by upstream and downstream businesses with national policy companies in oil-producing countries and the world's major oil companies (the majors described in Chapter 5 form the core, with an increasing number of national or large corporations from various countries) as project owners. Exploration, development, and production work are generally carried out with companies specializing in various technical areas, civil engineering and construction companies, and local service companies forming contracting teams dominated by two major service companies (Halliburton[*4] and Schlumberger[*5]) for projects. In other words, projects are divided into owner companies that obtain the rights to resources and lead projects, project participant companies that expect some rights, and service companies that cooperate to move projects forward with advanced upstream technologies. The owner companies judge the economics and politics of resource acquisition, development, and production, and orchestrate the knowledge of the service companies. The service companies develop highly reliable upstream technologies and provide various development services under the leadership of the owner companies. Verification and implementation of technologies is completed during the projects. At the same time, owner companies must have international project experience and the ability to effectively organize service companies with comprehensive advanced upstream technologies in order to acquire highly profitable economic rights.

Due to the recent international situation, bidding on and participation in overseas projects by Japan's trading companies and oil development, refining, and engineering companies is increasing, but in terms of leadership, scale, and economics, they cannot be considered powerful in comparison with the activities of the major oil companies or emerging nations. Japan also needs a strategy to utilize its outstanding industrial expertise to develop and apply advanced upstream technologies. Japan must pay attention to the increasing number of emerging industrialized nations and major consuming nations utilizing huge national owner corporations and acquiring upstream technologies to apply to new developments.

Against this background, this report takes an overview of the exploration, development, and production technologies that are considered the upstream sector of resource technology and the status of development. It clarifies the position of Japan, and offers proposals to prepare for the near future. Looking at these technologies and current technical developments, the advanced nations of Europe and the USA with their major oil companies and very specialized technologies, resource-rich emerging nations with their remarkable technical growth and major consuming nations must all be kept in mind.

2 Overview of Exploration, Development, and Production Technologies

Table 3 shows an outline of the workflow from the beginning of an oil or natural gas project through production and abandonment. Each step, including mineral exploration, test drilling, development, production, and abandonment proceeds over a long period of decades. Various technologies at each stage advance in parallel, and work advances sequentially to the next major stage of investment based on evaluation of each preceding stage.

As depicted in Table 3, various fundamental technologies are developed, verified, used, and implemented at each stage. All technologies are adjusted to the geological conditions in the development area, oil and gas deposit conditions, and distance to market. They are tested for effectiveness, improved, and finally completed as the optimum technologies for specific oilfields. In order to maintain technical superiority, it is therefore necessary to have considerable experience and a record of achievements in oilfield development. At the same time, continual challenge of the latest technologies is also essential to securing superiority. Currently, most established and applied technologies are operated by the above-mentioned Halliburton and Schlumberger. They have even adopted and commercialized technologies developed in Japan. In the long-term, Japan needs to consider always the challenge of participating to this international system and becoming competitive to them. In fact, efforts in that direction can be seen in emerging oil producing countries.

2-1 Mineral exploration

Table 4 summarizes typical mineral exploration technologies. Mineral exploration methods utilizing the characteristics of each type of technology are used to determine sites for test drilling. Seismic explorations using artificial earthquakes, technology for the final stage of determining sites, are particularly important. Improvement and advancement in both hardware and software aspects of the technology are underway.

2-2 Drilling

Currently, rotary-type drills are used for test and production well drilling. Table 5 describes

Table 3 : Oil and natural gas project flow

	Process	Technology	Costs
Year 0	Mineral exploration	Regional geological survey Remote sensing Preliminary survey of subject area Application for mining rights, negotiation and bidding, acquisition of mining rights Aerial geological survey Geophysical exploration Geochemical exploration Seismic exploration Comprehensive analysis of all explorations	Mineral exploration investment
3-5 years	Test drilling	Determination of test well locations Test well drilling Analysis of source rock and reservoir rock data Analysis of logging and well data Overall assessment, examination of profitability, renunciation of mining rights	Test drilling investment
	Develop-ment	Oilfield development plan Drilling of development wells Placement of production equipment	Development investment
6-10 years	Production	Production/sales	Operating costs Reinvestment to expand production competence
	Abandon-ment	Abandonment and equipment removal	Abandonment costs

Prepared by the authors

Table 4 : Overview of mineral exploration technologies

Preliminary survey	Assessment of geology through literature surveys and purchased materials Political and economic site survey
Resource exploration	Detection of sedimentary land from surface condition through remote sensing using exploration satellites
Geophysical exploration (gravity, magnetism)	Estimation of underground geological structures through measurement of gravity and magnetism over a wide area to obtain an overview of land with sedimentary layers differing from surroundings in gravity and magnetism
Seismic exploration	Artificial earthquakes are generated and the seismic waves reflected back from strata surfaces are captured by seismographs to examine the depth and shapes of the boundaries between underground formations. Earthquakes are generated using vibrations from compressed air in oceans and from gunpowder or steel plates on land. The observed reflected waves are digitized and processed by computer.

Prepared by the authors from Reference [2]

Table 5 : Drill mechanisms

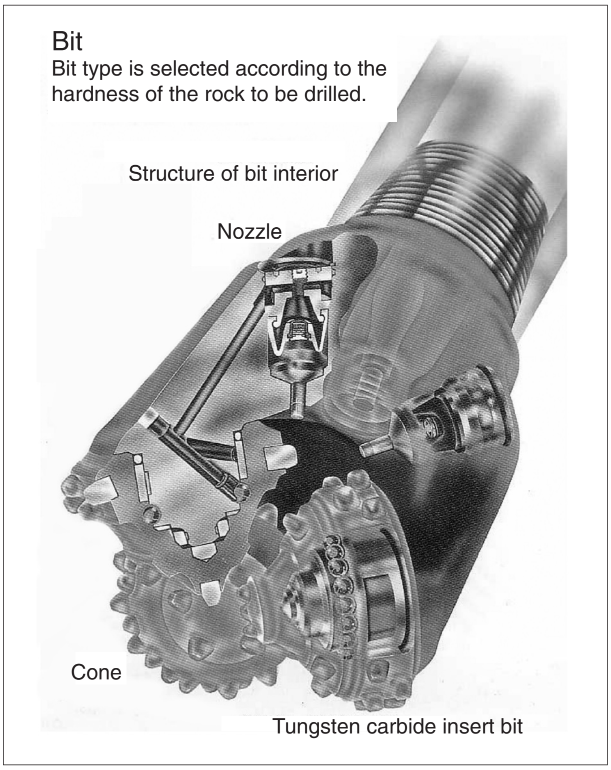
Drill mechanisms	Mechanisms for raising and lowering drill and casing pipes
Rotary mechanisms	Mechanisms to rotate drill pipe and drill bits using a rotary table
Mud circulation mechanisms	These mechanisms provide a liquid seal to resist underground pressure, preventing oil and gas blowouts while also preventing well walls from collapsing. Circulation of mud brings cuttings to the surface.
Safety/blowout prevention mechanisms	Mechanisms to seal off pressure inside wells that could cause gas or oil blowouts

Prepared by the authors based on Reference[2]

their mechanisms. As depicted in Color Chart 1, a bit is located at the tip of the drill. Optimum control of bit drilling direction and speed in accordance with the strata is important, while the bit materials and construction are important for drilling precision, efficiency, and life. Bits have a complex structure, so materials development technology and precision machining are both necessary.

Drilling circulates mud along a drill pipe. The mud is slurry water composed of water, bentonite, a viscosity regulator, a filtration regulator, a lubricant, an ion regulator, a pH regulator, and a density regulator (barite). This serves to bring the drill cuttings to the surface, thereby transmitting underground data. This facilitates geophysical exploration. In this case, the muddy water prevents the stratum from collapsing and the gushing of liquid inside the stratum, cools the bit, and lubricates the drill stem. The development of mud therefore played an important role in making deep drilling possible. Along with land drilling and marine platforms, the pipes that link bits with the surface are also the culmination of advanced technologies in materials and structures, including their operation, data transmission, and strength. Fundamental technologies include civil engineering technology such as that used to stabilize the walls of the hole.

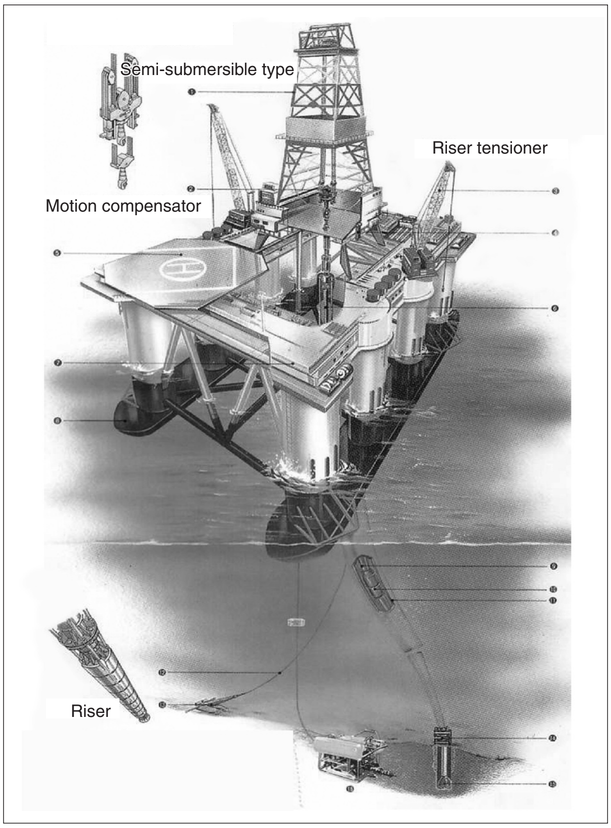
Color Chart 1 : Drill bit structure



Source: Reference [3] (p. 20)

Color Chart 2 shows the typical structure of a marine oil drilling rig. The chart shows a semi-submersible rig. The floating area is kept relatively small, lessening the impact of wave action so that stable drilling is possible even in heavy seas. Position is maintained with anchors

Color Chart 2 : A typical marine oil drilling rig



Source: Reference [3] (p. 24)

Figure 2 : Reservoir assessment methods

Mud logging
- Detection of oil/gas reservoirs

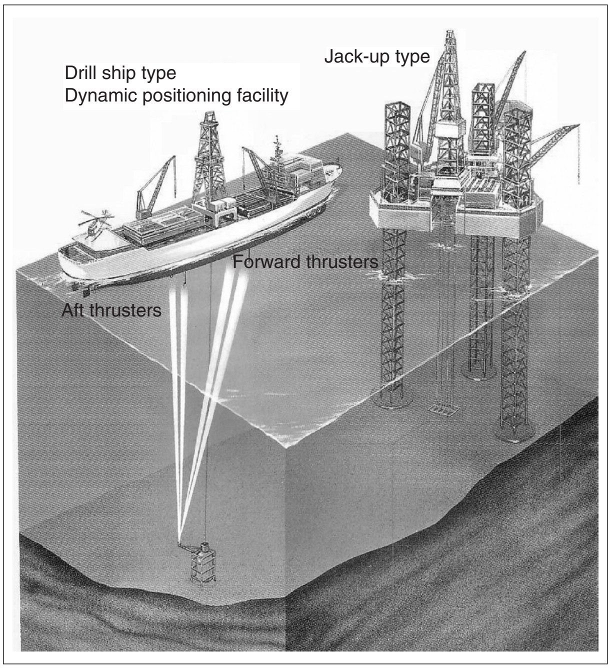
Core cuttings
- Detection of oil reservoirs
- Lithofacies survey (sandstone, mudstone, volcanic rock…?)
- Fossil survey (determination of geological age) (determination of deposit environment)
- Survey of reservoir rock competence (porosity, permeability, oil saturation)
- Survey of source rock competence (quantity, quality and maturity of kerosene)

Wireline logging
- Survey of strata depths and lithofacies
- Survey of geological structures (strata slope)
- Survey of reservoir rock competence (porosity, oil saturation, permeability)

Test oil/gas from reservoir
- Type of fluid (oil, gas, water?)
- Production capacity survey (fluid pressure, permeability, obstacles to completion)
- Component analysis of extracted fluid

Source: Reference [3] (pp. 28-29)

Color Chart 3 : Other drilling equipment



Source: Reference [3] (p. 25)

and mooring cables.

The types of marine drilling equipment depicted in Color Chart 3 have also been put into practical use. Equipment with high cost-performance in accordance with the site's topography, ocean conditions, climate, environment, and so on can be selected. Large surface, submerged, and ocean bottom structures are the fruits of ocean civil engineering.

2-3 Logging technology

Test drilling allows various types of logging within wells, enabling the detection or prediction of oil and gas reservoirs. Logging technologies are summarized in Figure 2. Table 6 briefly describes logging technologies. Mud, core, and wireline logging are used. There are companies that specialize in the various logging technologies. When a reservoir is struck, test oil or test gas is brought up, and production capacity is estimated from the type and density of the liquid, as well as liquid pressure, permeability, and flow speed.

2-4 Production

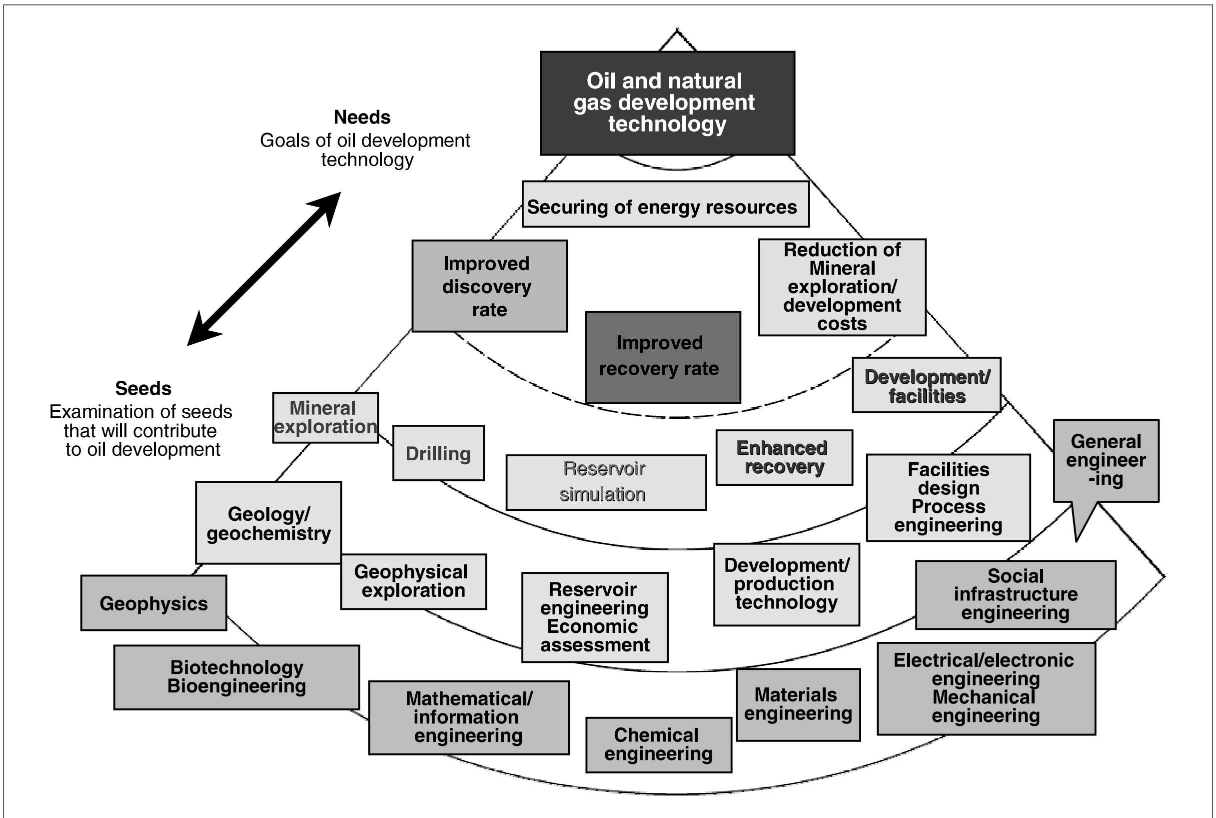
Oil and natural gas extracted from underground are separated into oil and gas, and then further refined by removal of water and salt. Crude oil or gas is allowed to flow into production wells drilled into the reservoir and flows through

Table 6 : Logging and test oil

Mud logging	Cuttings brought up from the well bottom by mud circulation are examined, and oil and gas are chemically detected.
Core logging	Rock and other content are extracted from strata and chemically analyzed.
Wireline logging	After completion of drilling, wirelines are lowered and the physical properties of strata are sequentially measured. Reservoir porosity and oil saturation rates are sought with electrical radioactivity logging.
Drill stem logging	Strata judged hopeful through the above logging are isolated with rubber packers and oil and gas are brought to the surface.
Collection of oil, gas, and water from test wells	Pressure within the test well casing is lowered, causing oil, gas, and water to come to the surface for collection, enabling well bottom pressure and production capacity to be ascertained.

Prepared by the authors

Figure 3 : Overview of oil and natural gas development technology



Source: Reference [4]

steel oil well pipes to the surface, where control equipment at the well mouth called a Christmas tree sends it to separating equipment and storage tanks. Control at the well mouth uses valves and flow controllers comprising thermometers and pressure gauge chokes.

Flowing wells, pumping wells, and gas lift wells are different types of production wells. Flowing wells are those where gas and water pressure in the reservoir cause the oil to flow naturally. This pressure declines during production, so methods such as drawing out the crude oil with a pump, or injecting gas to lighten the oil's specific gravity to assist flow are used to extract the oil.

3 Advances in Technologies for Mineral Exploration, Development, and Production

Chapter 2 provided an overview of mineral exploration, development, and production technologies. In light of the direction of current and future technical advances, it will be worthwhile to take a look at the engineering and basic science that links those needs and seeds. Figure 3 is an overview of technology provided by Professor Kazuo Fujita of the Shibaura Institute of Technology. Along with the integrated nature of science and technology in this area, it is necessary to continue a cycle of ideas, demonstration, application, and commercial improvement and verification that can be established based on proper understanding of their advanced nature and future direction.

3-1 Latest technologies for mineral exploration

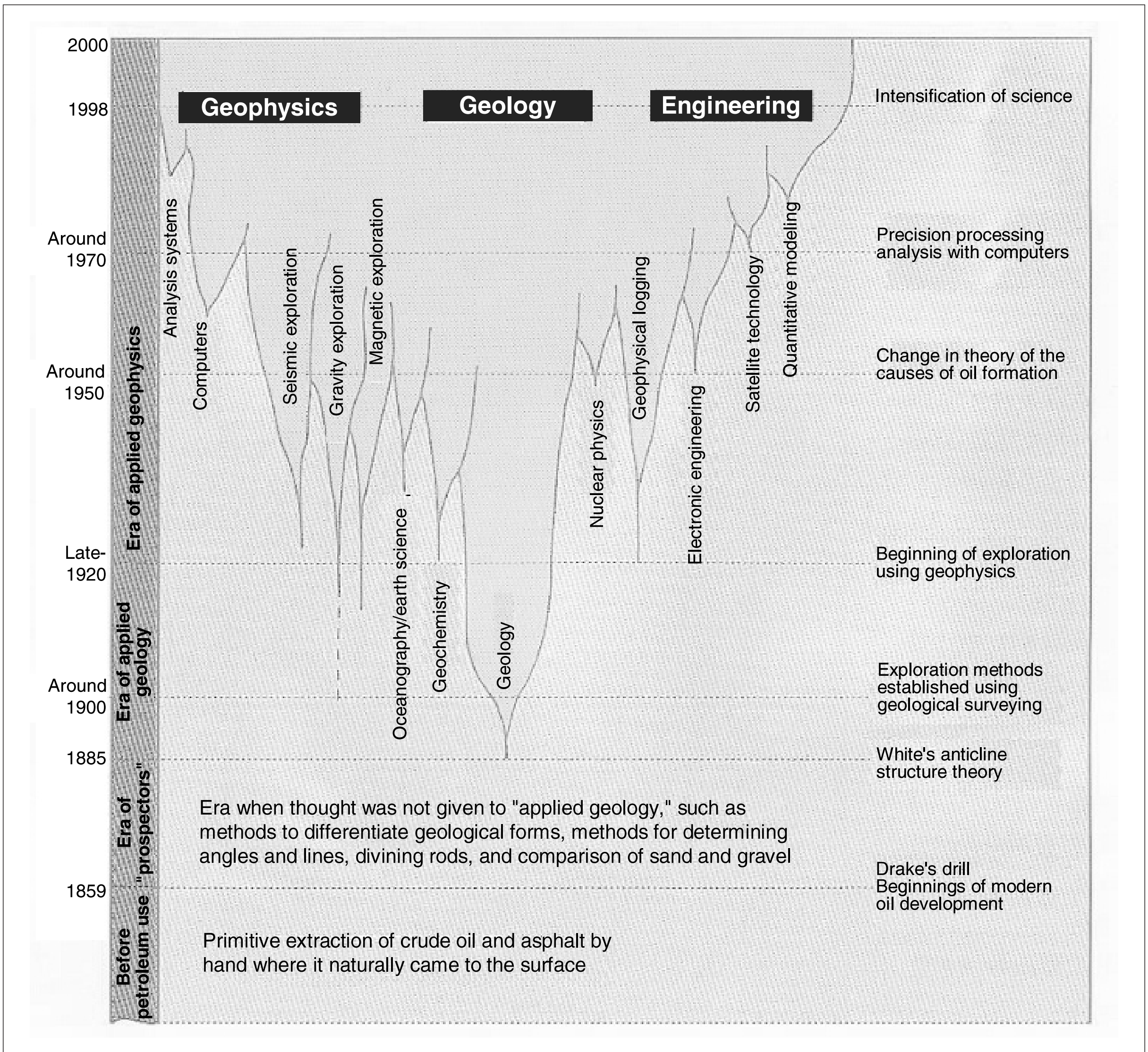
Figure 4 shows the development of mineral exploration technology. Based on geology and other sciences, mineral exploration technology began in the early 20th century. Since about 1930, geophysics has been used to survey subsurface structures. Recent advances in computer performance, the accumulation of vast amounts of data, and the use of analysis systems and quantitative modeling simulations have enabled the precise description of geological conditions and oil reservoirs, enabling the projection of future resource production.

As for seismic exploration, which was touched on in 2-1 above, closely linking the locations of epicenters and receivers and measuring multiple reflected waves with different phases allows three-dimensional imaging of geological formations. Precision measurement enables the estimation of gas reservoirs with large differences in density sandwiched between other geological formations.

3-2 Advanced drilling technology

With regard to deep drilling to extract resources from deep underground, in 1985 the former Soviet Union reached a depth of 12,000 m in the Arctic. Currently, deep drilling technology is being developed with the goal of reaching 15,000 m.

Figure 4 : History of mineral exploration technology



Source: Reference [3] (p. 9)

To avoid surface obstacles or to extract resources from oil reservoirs spreading horizontally from vertical wells, inclined wells and long horizontal wells are in development and being used. Multilateral well systems combining one vertical well with multiple horizontal wells are already in use, increasing the economic viability of resource extraction.

This kind of drilling requires accurate drilling control to precisely determine the underground position. Therefore, MWD (measurement while drilling) that obtains bottom hole data at the point of drilling and feeds it back to surface control systems is now in use. Positioning using satellite data, quick collection of drill head data, control programs, automatic control of databases that need to be compared and other developments are constantly evolving.

Furthermore, in addition to obtaining bit load, torque, and other drilling parameters at the drilling point, systems that use sensors to obtain data on geological conditions (such as specific resistance and gamma-ray absorption) and send them to the surface have been developed, enabling the application of the so-called LWD (logging while drilling) method that simultaneously performs drilling and logging.

Improving the transmission speed of large amounts of data is another area of development. Advances are also being made in the development of mud pulse, mud siren, and pipe transmission methods and systems that use mud as a medium.

3-3 Advances in oil reservoir evaluation technology

The acquisition, analysis, and interpretation of data on liquid pressure and movement from rock, oil, gas, and stratum water obtained from wells can be combined with information from geological exploration, well building, logging, and oil reservoirs to create quantitative models of oilfield shapes and conditions. Predictive simulations have also been created, and these are being developed as a method for assessing oil reservoirs at the point of drilling. The flow of liquid within oil reservoirs can also be modeled, and outside forces (e.g. changes in flow when water or carbon dioxide is injected from the surface) can also be simulated. This is expected to improve recovery rates.

Samples obtained from oil reservoirs are being used for measuring physical properties deep underground to estimate the physical properties of deep oil reservoirs. When these analyses are collected from multiple wells on a site, they can be used to create a detailed image of geological and oil reservoirs in an area.

In the process of production work, repeated three-dimensional seismic exploration and oil reservoir evaluation that tracks changes over time allows so-called four-dimensional monitoring and simulation. Extending this over time may yield remarkable improvements in the accuracy of predicting oil reservoir productivity and reserves.

3-4 Pursuing the limits of development

The limits of resource development are reaching towards the Earth's mantle, at ocean depths exceeding 2,000 m, and expanding mining areas in the Arctic. Not only must exploration and development be started under harsh natural conditions, but production and transport must also be continued. Protection of the environment in such cases is also an important issue. Complete technical development for exploration, development, and production technologies suited to the natural environment together with appropriate materials and systems will be needed.

3-5 Enhanced oil recovery (EOR) technology

The amount of oil that can be recovered through natural pressure or pumping (primary recovery volume) is usually 20-30 percent of the resources in an oil reservoir. In order to continue recovery beyond that point, water (steam) and gas may be injected, raising pressure in the oil reservoir. This secondary recovery raises the rate of recovery to 30-40 percent. In addition, insertion of steam and surfactants to lower oil viscosity, injection of carbon dioxide to separate oil from rock, and dilution with chemicals or solvents can raise the recovery rate to 40-60 percent. Experiments are also underway to raise the rate by growing microorganisms in oil reservoirs to depolymerize oil into lighter components or to perform underground gasification reactions.

Improvements in such recovery methods are a major reason that recoverable reserves are now increasing.

Over time, production is accompanied by changes in oil components. Production can also be reduced or halted by obstacles in geological formations. Technologies using water pressure or explosives to remove such geological obstacles are being developed. In complex geological formations containing faults, oil reservoirs are broken up, so such technologies will be an important means of improving recovery rates.

3-6 Noteworthy Japanese technologies

The Japan Oil, Gas and Metals National Corporation (JOGMEC) is developing the following technologies, aiming to apply and demonstrate them in domestic and overseas developments. It is working with Halliburton and Schlumberger on the commercialization of oil reservoir analysis.

(1) Imaging of subsurface structures

Accurate depiction of the complex underground geological structures of steep slopes and the faults, fissures, and salt domes that accompany them is difficult to carry out with analysis of ordinary strata exploration. However, a program combining multiple seismic exploration analysis programs to portray complex underground geological structures is being developed. This technology uses parallel processing in small workstations while linking multiple sites to analyze subsurface structures. Its effectiveness is now being verified.

(2) Logging technology

In logging technology, improved technology for analysis of core rock is expected. Observing the flow of oily water inside the rock core with an X-ray CT scanner allows analysis of the dynamic behavior of liquid in the rock. With this technology, the status of water accumulation in Middle East oilfields from improvements in extraction using the water flooding method was clarified. This in situ analysis is an important means of accurately measuring the current status of oil reservoirs. In the future, one can imagine that the technology will progress to comparisons of the chemical and physical structures of rocks and to the modeling of entire areas.

Detection of hydrogen atoms using the emission of gamma rays by hydrogen atoms irradiated with neutrons is used as means of logging to measure the characteristics of geological formations in the vicinity of well walls and liquids within them. This technology can detect water. Radioactive material had been used as the pulse neutron source, but pulse neutron sources that generate neutrons electrically have been developed as an LWD tool. Verification testing with Schlumberger for the commercialization of the technology is progressing.

(3) Drilling and drilling tools

Multistage fracturing of low-permeability lithofacies more than 5,000 m deep to release gas reservoirs, which can increase natural gas productivity six-fold and allows precise and accurate underground work, is the subject of much attention. For re-access to multilateral horizontal wells and horizontal drilling, drilling equipment (multilateral tieback and remote directional control system) with a drive system that can be controlled in any direction is being developed. Demonstrations are being conducted along with Sperry-Sun and Halliburton, and commercialization is expected.

In addition, large amounts of dense corrosive gases such as hydrogen sulfide and carbon dioxide are generated, so highly durable materials must be selected and cost reduction is necessary. This requires corroborative testing over long periods of time. Selection tests that reproduce actual conditions such as water content, temperature, pressure, are underway, and cost reductions are being pursued.

4 Resource Developments in the Near Future

Because of today's strong demand and concerns about future supplies, attention is turning to oil and natural gas in areas where extraction was considered economically or technically difficult. In some cases, development for extraction has begun, while in others preparation for the future is underway.

4-1 Technology to utilize ultraheavy crude oil

The appearance of ultraheavy crude oil, which has a small amount of distillable oil components, on international markets would appear to be feasible. Arabian heavy, Kuwait heavy, Marlim crude, Orinoco tar, and tar sand bitumen are types of ultraheavy crude oil. With the aim of raising prices in oil-producing countries, stable production and appropriate up-grading are the subjects of technical development. One of the types of ultraheavy crude oils, tar sand bitumen, is extracted along with silica through opencast mining. Oil is extracted and collected, and distilled oil is obtained from distilled residual oil through coker cracking. This oil undergoes light hydrotreating and appears on the market as synthetic crude oil. In the future, as opencast mining becomes more difficult as the depth of reserves increases, new recovery methods such as underground steam injection, partial burning, and underground gasification will need to be introduced. Meanwhile, for today's markets in developed countries, the development of high-quality refining technology is necessary. Therefore, integrated development of recovery and refining that unites upstream and downstream processing is required. This integrated development is a topic that Japan can address now and in the future. International participation has already begun, and now is probably the last chance to guide joint development with an eye to the future of oil-producing countries.

4-2 Technical development accompanying the development of small and medium gas fields

Long-distance transport of natural gas is based on pipelines and LNG transport. In both cases, massive investment is required to prepare infrastructure. Utilization of small and medium gas fields with limited production volume for other than local consumption is therefore difficult, retarding development. However, if economic means of long-distance transport can be developed, they can be commercialized. Technologies that could make this possible include:

(1) Transport utilizing storage in high-density adsorbents or methane hydrate slurry
(2) Transport after conversion from natural gas to compounds that liquefy under low pressure, such as dimethyl ether (DME) and light hydrocarbons.

4-3 Consideration of methane hydrate

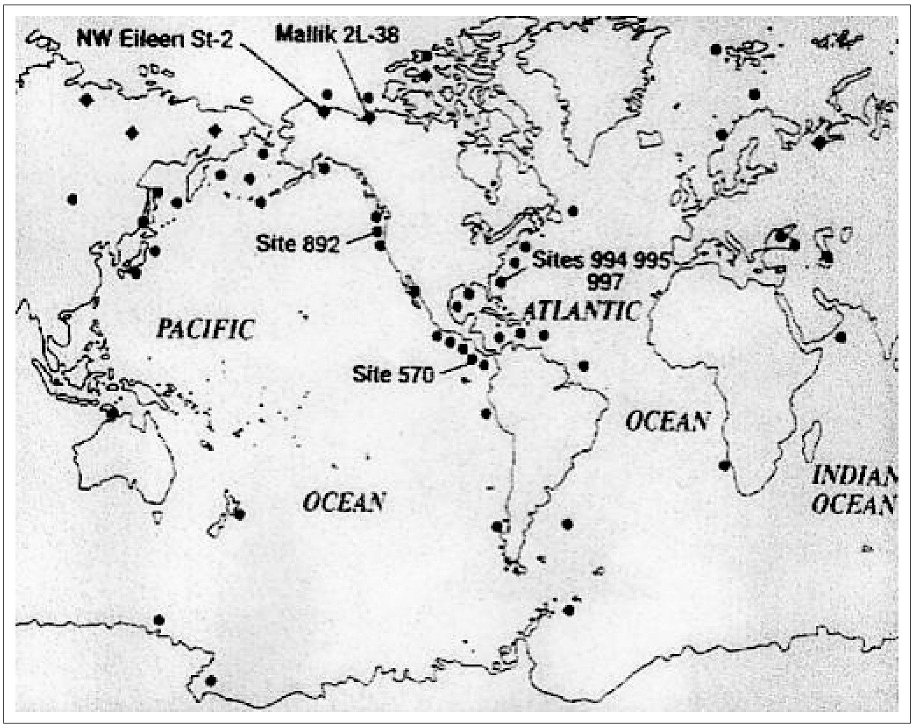
Combined with water in specific proportions, methane gas forms the sherbet-like substance methane hydrate. It is found in large quantities in geological formations under deep oceans. Because it exists in large amounts in deep oceans all over the world, including in the vicinity of Japan, it is seen as a future natural gas resource. Figure 5 shows locations around the world where the existence of undersea methane hydrate has been confirmed.

However, technology that can efficiently recover methane alone from methane hydrate without melting ice and consuming large amounts of energy to transport solid hydrate has yet to be developed. In addition, extraction of methane hydrate, which is abundant in the deep ocean and polar regions, is practically difficult. Furthermore, methane that is released into the atmosphere has an enormously large impact on the environment, so great care must be taken in its collection in order not to increase the burden on the environment. Basic research on methane hydrate should be carried out rationally from scientific and economic perspectives, without believing that it is some sort of dream resource.

5 The Status of World Resource Development and Japan's Activities

World resource development has been led by the major oil companies, ExxonMobil (USA), Shell (Netherlands/UK), BP (UK), Total (France), ConocoPhillips (USA), and Chevron (USA) and various other companies known as quasi-majors. Although recently there has been talk that investment is stagnant, mineral exploration and development costs in 2004 still reached an overwhelming $4-10 billion.

Figure 5 : Areas where methane hydrate exists



Source: Reference [5] (p.31) and Kvenbolden 1999

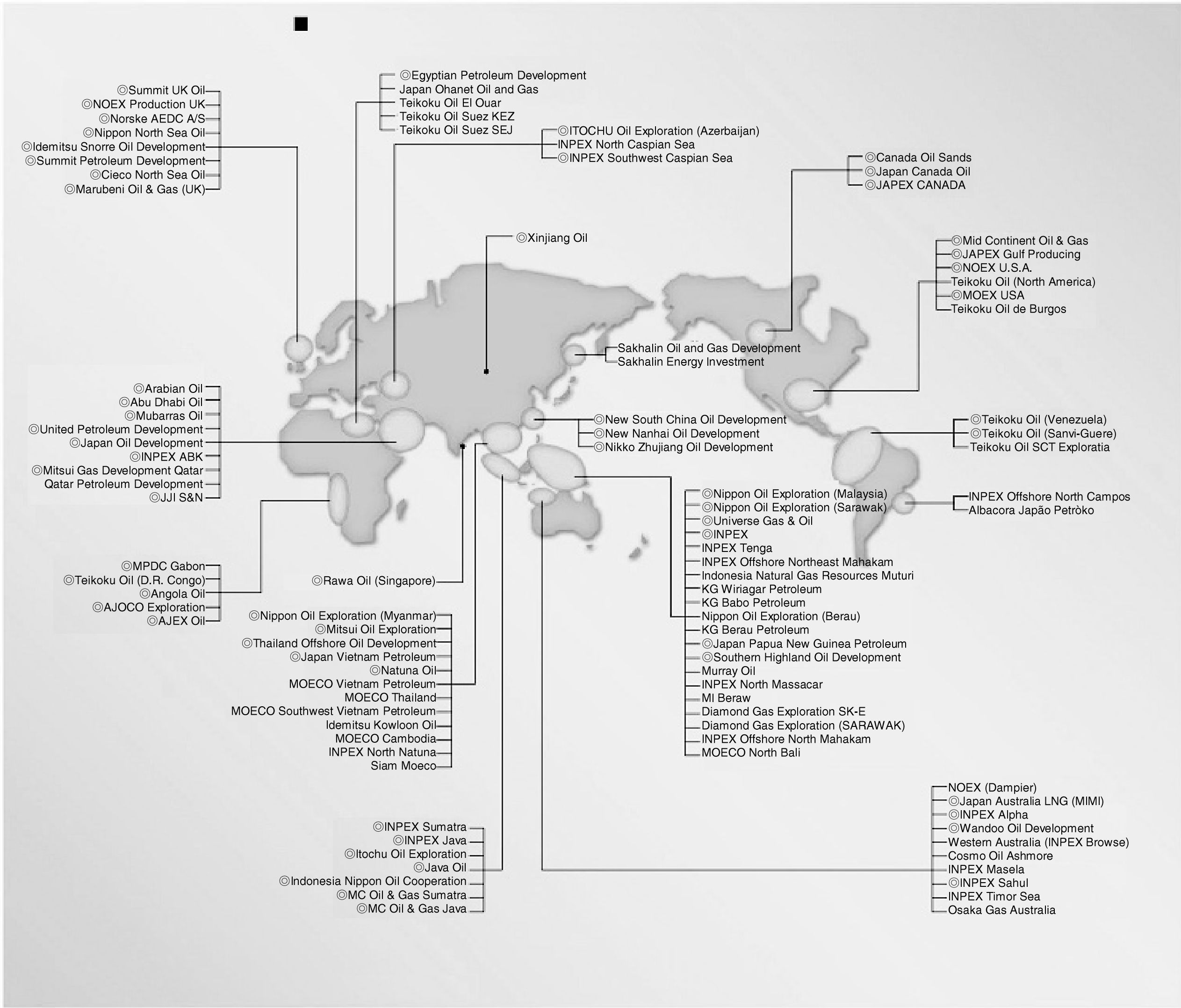
Based on the Energy Independence Plan, the USA's Department of Energy (DOE) is also working to develop upstream technologies. It has announced a policy of promoting developments at underwater depths greater than 1,500 m. At the same time, it has set aside a large amount of funding to support research that will form the basic infrastructure for development. Areas for technical development include recovery of natural gas from sandstones and coal seams, gas recovery from depths below 5,000 m, and boring with low environmental impact.

Meanwhile, China National Petroleum Corp. has invested as much as $8 billion in domestic and foreign development, taking its place among the above-mentioned majors. It is active in foreign development in the seas around Japan, in the ocean off Vietnam, and in countries such as Kazakhstan, Algeria, Nigeria, and Brazil. It is now making the transition from acquiring technologies to developing its own. In addition, two more companies, China Petroleum and Chemical Corp. and China National Offshore Oil Corp. are close behind. In 2004, the 20 major resource and environment topics of the Ministry of Science and Technology of China included deep sea oil and gas exploration and key technologies, theories of exploration of the geological conditions of gas, liquid, and coal resources and their technologies, and security technologies for ocean oil and gas resources development. This indicates the effort that the state is putting into this type of research.

Along with its rapid economic growth, demand for oil and natural gas in India has skyrocketed. Indian national and municipal companies such as Oil and Natural Gas Corp., Indian Oil Corp., and Reliance Industries Ltd. are engaged in natural gas development around their own country and have obtained development rights all over the world. They are also active in oilfield development. At this time, joint ventures are the mainstay of their business, but if the example of the steel industry is followed, it will not be long before they begin to master upstream technologies and to carry out their own technical development and applications. Intense competition with China can already be predicted.

The growth of national oil companies and oil development technology companies such as Thailand PTT Public Co., Singapore's Keppel Corp., Indonesia's Bumi Resources, and Malaysia's Petronas has also been remarkable. The scale of these companies is already comparable to that of Japan's Nippon Oil Corp. and INPEX Corp., and they are accelerating their overseas activities.

Figure 6 : Major overseas oil development projects by Japanese oil development companies



Note: Those marked with a circle are in production

Source: Reference [1] (p. 28)

Brazil is South America's second-largest oil-producing country, producing more than 500 million barrels of crude oil annually. The national company Petrobras monopolizes that country's upstream sector and is carrying out deep sea development at a depth of 1,400 m off Rio de Janeiro. Average production cost is expensive at \$10-\$14/barrel, but it is said to already have development and production systems using its own technology. In 2005, Brazil became 100 percent self-sufficient in oil. It is expected to begin exporting oil and is accelerating development of upstream and downstream technologies.

Based on guidance from the national government, Japan has also used its technical expertise and large market as tools to increase its presence in the upstream sector. As shown in Figure 6, Japan has aimed to acquire crude oil from all over the world. Japan is strong in technical areas such as deep underground production technology and the application of advanced technologies, but it has a limited record as a main operator in the development of major oilfields. Its ties with the governments of oil-producing countries are not strong, so it seems to lack power in the face of the vast size of the major oil companies and the energy of emerging nations. A lack of human resources needed to fully develop Japan's strength is also a concern. Under these circumstances, the Committee for the Strategic Examination of Oil Development Technology (chair: Kazuo Fujita, Professor Emeritus, the University of Tokyo) of the Information Center for Petroleum Exploration and Production was commissioned by JOGMEC

Table 7 : Development goals for oil and gas development technology

Theme	Individual topics
1. Improved exploration success rate	(a) Integration of oil data
	(b) Advanced geological modeling
	(c) Precision geological exploration technology
	(d) Precision geophysical exploration technology
	(e) Development of methods for direct hydrocarbon detection
2. Improved recovery rates for already-discovered oilfields and gas fields	(a) Precision reservoir assessment technology
	(b) Productivity-raising technology
	(c) Recovery-improvement technology
3. Cost reduction	(a) Reduced cost of three-dimensional self-submerging exploration
	(b) Reduced drilling costs
	(c) Reduced production costs
	(d) Development of new drilling and production systems
4. Effective use of gas	(a) Reduced LNG and natural gas costs
	(b) Technology to convert gas to liquid fuel
5. Development of unconventional oil resources	(a) Oil shale development technology
	(b) Ultraheavy crude oil development technology
	(c) Methane hydride exploration development technology
	(d) Technology for optimal development of water-soluble natural gas
6. Conservation of the global environment	(a) Technology to reduce environmental impacts
	(b) Technology to assess environmental impacts
	(c) Oil spill response technology

Source: Committee for the Strategic Examination of Oil Development Technology of the Information Center for Petroleum Exploration and Production (commissioned by JOGMEC)

to establish goals for oil and gas development, as shown in Table 7. Unfortunately, to date no policies that strongly promote the achievement of these goals have been set. The authors hope that debate on the proper form of science and technology in this sector, and the industries that apply and commercialize them, will advance.

6 Proposals

In Japan, the pessimistic argument that this country can never match the American and European majors in terms of industry and technology in the upstream sector of oil and natural gas has been pervasive. In the face of the remarkable growth of emerging nations and their shift to their own technologies, some believe there is nothing to do but wring one's hands in self-deprecation. However, Japan has a national policy of being a science and technology oriented nation. In order to thrive in the first half of the 21st century, Japan must secure oil and natural gas and maintain its technological capability. For both the upstream and downstream sectors of oil and natural gas resources, Japan should vigorously develop technologies and the supporting science that it can pass on to the rest of the world. At the same time, it is essential to strengthen the industries that can lead the way. The intelligence and fortitude of the Japanese people are other keys. In addition to including oil and natural gas in a comprehensive energy policy, the authors offer the following three proposals.

(1) Strengthen industrial expertise

Currently, there is a trend for companies in the oil refining and production fields to form businesses on a scale large enough to integrate upstream and downstream sectors. Japanese society must recognize the importance of doing this, and assemble the capital, technology, and bargaining power to have a global impact. The national government and the people of Japan, who will be the investors, should think seriously about building a powerful oil industry infrastructure that can pass on competitive upstream technology to the world by demonstrating and applying exploration, development, and production technologies.

(2) The importance of continued progress in upstream technologies

Against the background of Japan's broad range of advanced science and technology, it is necessary to further the development of upstream technologies as an integrated science. In particular, Japan should tackle technology for deep underground and deep sea development. The development of ultraheavy crude oil should also be made a priority.

Japan should aggressively promote technical development of robots, communications, control, sensing data processing, and precise and durable machinery and materials. This could develop into remote sensing technology for oil resources.

Furthermore, geophysics, geochemistry, surface chemistry, chemical engineering related to upstream technologies should be strengthened and their active contributions to practical technology should be promoted. These new sciences must be introduced into mineral exploration, development, and production. The recently completed deep sea drilling vessel Chikyu is one of the world's best exploration vessels. It is to be hoped that the Chikyu's research into the geological structures under the deep sea around Japan can be integrated into the complete description of underground resources with research on mantle drilling, which has never been carried out before. Such information is of the highest value for our nation not to be easily released.

(3) Fostering and retaining human resources

The training of people who can be active anywhere in the world where oil and natural gas resources exist is an urgent task for Japan. In corporate and university research institutions in Japan and abroad, Japanese people who possess scientific and technical knowledge, development expertise, and business-oriented minds and who are able to converse with a range of ethnic groups are needed.

Therefore, Japanese universities and corporations should collaborate in a program in which each year about 100 creative and vital college graduates with a broad education in science and engineering will be trained as human resources with international value. The goal should be the fostering of strong-minded people who want to face international challenges and who can not only develop advanced technologies from a background of accumulated experience and accomplishments, but can also deal with ethnic conflicts and competition to acquire international rights in development work. In so doing, Japan must recognize that it will need the assistance of universities, research institutes, and corporations in various countries that have already achieved international recognition. In this field, Japan needs to abandon its self-satisfied stance of offering its favors to developing nations and be prepared to learn from the rest of the world. Preferably, it will be Japanese companies that accept these human resources, but the goal should be the fostering of people with broad visions who will be internationally active. Preparing graduate schools and research institutes that enable Japan to be a place that produces the human resources needed by the world is a task for industry as well as educational institutions and the national government.

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Glossary

*1 Confirmed reserves

Reserves confirmed by seismic exploration, logging, etc.

*2 Recoverable reserves

Reserves that can be economically recovered at a specific point in time. Recoverable reserves increase through price rises and advances in extraction methods. Recoverable reserves increase even without the discovery of new oilfields when economic changes or price rises make subsidized extraction or drilling under difficult conditions economically viable.

*3 Reserve life index

Reserve life index = Recoverable reserves / Production (annual)

*4 Halliburton

Halliburton was established in 1919 in Texas, USA. It has 85,000 employees and is active in over 100 countries. It has two main divisions, ESG, which provides oil and natural gas upstream services, engineering, and construction, and KBP, which provides oil and natural gas upstream and downstream services, engineering, and construction. It also provides advanced measurement while drilling (MWD) and logging while drilling (LWD) technology/underground imaging, production, and disaster management. It is renowned for putting out 320 oilfield fires in Kuwait during the Gulf War in 1991. (Taken from the company's web site.)

*5 Schlumberger

Schlumberger was established in 1912 in Paris, France. It specializes in electric logging. In 1940, it relocated to Texas, USA. It has 58,000 employees and is active in 80 countries. First to adopt LWD, it is renowned for wireline measurement. Its corporate arsenal consists of drilling, geophysical exploration, and logging.

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Technology Foresight surveys in China

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1 Introduction

In February 2006, the Chinese government announced its National Guidelines for Medium- and Long-term Plans for Science and Technology Development, which set forth the direction of science and technology promotion for the next 15 years[1]. Under the guidelines, research and development expenditures across the entire spectrum of society are to be raised to at least 2.5 percent of GDP by 2020, the contribution rate of science and technology to GDP growth is to reach at least 60 percent, dependence on foreign technology is to be reduced to 30 percent or lower, and China is to move into fifth place in the world in terms of patents obtained and science and technology papers cited. Additional goals to be achieved by 2020 include the following: (1) Enhancing China's innovation capacity in order to strengthen the country's ability to use science and technology to promote economic and social development and safeguard national security, supporting the building of "a little well-off (xiaokang) society. (2) Stronger overall capabilities in basic science and frontier technology research, producing results of international importance, making China one of the innovation-oriented nations, and laying the foundation for China to become a world science and technology power by mid-century. Meanwhile, progress is being made on setting the 11th Five-Year Plan. At the National People's Congress held in March, adjustment of industrial structure and development that is balanced among different regions were discussed and adopted.

In line with this movement to firm up plans, the Ministry of Science and Technology and the Chinese Academy of Sciences[2] since 2002 have carried out technology foresight survey and published a series of reports. The Ministry of Science and Technology occupies a position similar to that of a ministry in Japan, while the Chinese Academy of Sciences is an operational department that reports directly to the State Council. It is China's largest scholarly organization in the natural sciences as well as a comprehensive research center. The Chinese Academy of Sciences incorporates six academic divisions, about 90 research institutions, and 12 branches. It has around 700 members (academy members) and 46,000 employees (according to its 2005 annual report). Technology foresight survey had been carried out in the special administrative regions of Beijing and Shanghai, and also in Wuhan, but this was the first time it had been carried out at national level in connection with planning for the development of science and technology.

Both the Ministry of Science and Technology and the Chinese Academy of Sciences adopted the method of examining concepts of future societies (or needs) and using Delphi analysis with questionnaires on technological development. Delphi analysis is a survey method involving repeated identical surveys of many experts to draw out a consensus of respondents' opinions. It has been used in Japan about every five years since 1971 (The National Institute of Science and Technology Policy has administered the program since the 5th survey.)[3]. The Delphi questionnaires are modeled on the Japanese method and have many similarities, including the method of carrying out the survey twice in order to obtain a consensus of opinions, question categories, and evaluation methods.

This report provides an overview of both

Chinese foresight surveys and highlights notable statements and data in order to provide a reference for those involved in science and technology policy planning and implementation.

2 Technology Foresight survey by the Ministry of Science and Technology

The Ministry of Science and Technology has been carrying out technology foresight survey since 2002. The research itself is conducted by the National Research Center for Science and Technology for Development, which is affiliated with the Ministry of Science and Technology. The purpose of the survey is to "clarify major technologies for China's socioeconomic development for adoption in the National Guidelines for Medium- and Long-term Plans for Science and Technology Development and the 11th Five-Year Plan," making clear its relationship to both plans.

The survey has a three-stage structure. The first stage comprises analysis of socioeconomic needs and science and technology trends, together with design of the Delphi survey sheets. The second stage is analysis of the Delphi questionnaire and its results. The third stage comprises selection of nationally important technologies and the creation of reports.

2-1 Survey target fields and questions

First, a survey covering the three high-tech fields of information and communications, biotechnology and life science, and new materials was carried out during 2002-2004. Next, a survey covering energy, resources and environment, and advanced manufacturing technology was conducted during 2004-2005. A survey of three more fields, agriculture, public safety, and population and health, began in autumn 2005. These cover most of the 11 major areas (energy, water and mineral resources, environment, agriculture, manufacturing industries, transportation, information services, population and health, urbanization, public safety, and national defense) found in the National Guidelines for Medium- and Long-term Plans for Science and Technology Development. In particular, the three areas now being surveyed fall within those major areas. To date, reports have been published for the six fields through to "advanced manufacturing technology." Separate internal documents have been created regarding "nationally important technologies."

Technologies targeted by the survey are organized into "fields, sub-domains, and technology topics." As shown in Table 1, there are 6 fields, with 42 sub-domains and 483 technology topics.

The questions regarding technology themes covered 17 items, including predicted time of

Table 1 : The 42 sub-domains set forth in the foresight survey of Ministry of Science and Technology

Field	Sub-domains
Information and communications (6 sub-domains, 75 topics)	Computers, computer network and information security, communications, software, integrated circuits, video and audio
Biotechnology and life science (4 sub-domains, 83 topics)	Agricultural biotechnology, life science, industry and environment, medicine
New materials (4 sub-domains, 64 topics)	High-performance structural materials, new functional materials, electronic information materials, nanomaterials
Energy (9 sub-domains, 83 topics)	Coal, oil and gas, electric power, nuclear energy, renewable energy, hydrogen energy and other new energies, building energy coservation, Industry energy conservation, transportation conservation
Resources and environment (6 sub-domains, 100 topics)	Ecology and environment, solid mineral resources, oil and gas resources, land resources, ocean resources, water resources
Advanced manufacturing technology (13 sub-domains, 78 topics)	Advanced manufacturing models, digital engineering for equipment, manufacturing flow automation, digital design, environmentally friendly manufacturing technology, micro-nano manufacturing technology, energy sources equipment, transportation equipment, process manufacturing, agricultural equipment, environmental protection equipment, household electrical appliances, marine engineering

Source: Reference [4]

realization, importance, effects, China's technical level, and government policies. A number of items concern application in society and industrialization. Among these are the potential for obtaining intellectual property rights, industrialization outlook and costs, and predicted time of realization (time for industrialization). Furthermore, 3 of the 5 items asking about results are industry-related (promotion of high-tech industrial development, promotion of the development of existing industry, and increased international competitiveness). In addition, it is notable that there are questions concerning national security, but the results are not included in the reports.

The forecast period varies according to field: 10 years for information and communications, biotechnology and life science, and new materials; 15 years for energy, resources and environment, and advanced manufacturing technology.

Respondents to the questionnaire (experts who responded to the second round) numbered 130-180 for each field, totaling 929.

2-2 Examination of science and technology needs

Examination of science and technology needs for China's economic and social development was undertaken from the 10 perspectives listed below. At the same time, analysis of China's internal and external environments for scientific and technical development was carried out. This contributed to the selection of technology themes.

(1) Optimization of industrial structure
(2) Development of agriculture
(3) Development of high-tech industry
(4) Pressure of international trade
(5) Urbanization
(6) Population and health
(7) Overall resource use and sustainable development of society
(8) Optimization of energy structure
(9) Environmental improvement
(10) National security

2-3 Notable survey results

(1) Self-assessment of China's technical levels

Respondents assessed China's technical levels as being five years behind those of the leading countries for about 90 percent of technology topics. On the other hand, levels for about 10 percent of topics in the information and communications, biotechnology and life science fields are rated as being on a par with those of

Table 2 : Technologies in which China's level was assessed as being on a par with those of the leading countries

Field	Number of topics	Technology topics
Information and communications	6	• Chinese-language information processing technology • Regional networks • Broadband connection technology • Third-generation mobile phone systems (TD - SCDMA = Time Division - Synchronous Code Division Multiple Access) • DVD technology based on IP • Industrialization of multi-wavelength, multi-stage, high-density video disks
Biotechnology and life science	7	• Core technology for genome base sequencing • Technology for genetic engineering of plants • Technology for cloning animal somatic cells • Technology for adjusting the natural ingredients of medicines • Reagents for quick verification and diagnosis of serious and infectious diseases • Molecular markers and new species for major crops through biotechnology • New varieties of high-quality, mass-produced genetically engineered crops
New materials	6	• Technology for large-area, high-quality, artificial crystal materials and all-solid lasers • Shape-memory materials • Manufacture of nanocomposite materials • Manufacturing design and assembly on the nanometer level • Atom and molecular assembly through direct manipulation • Technology for nanomaterial performance characteristics and devices
Energy	2	• Development of watersheds for hydroelectric power • Ultralarge-scale electric power safety systems

Source: Reference [4]

the leaders. In the new materials field, 9 percent of topics were at the same level as the leading countries, while 14 percent were 6-10 years behind. The field of advanced manufacturing technology was assessed as being furthest behind, with 70 percent lagging 5 years behind and 30 percent 6-10 years behind. Themes seen as being at the same level as those of the leading countries are shown in Table 2.

For example, basic research in nanotechnology and nanomaterials is assessed as being at the same level as that of the leading countries. While China is at international levels in the compounding of nanomaterials such as carbon nanotubes, and matches the leading countries in R&D on nanocomposite materials, metal, ceramic, glass, and polymer nanomaterials, nano-oxides, single nanoparticles for semiconductors and metals, nanofilm layers, nano-functional materials, etc., it lags well behind in terms of their application to integrated circuits, etc.

As for genetic technology, technical levels in genome-sequencing analysis, research on human functional genomics, genetic engineering technology, molecular markers, cloning of animal somatic cells, etc., are seen as being at the same level as those of the leading countries.

In the information and communications field, third-generation mobile communications, optical networks, integrated switch routers, next-generation networks, and so on are said to be close to international levels. However, computers, software, and network and information security are seen as being five years behind the leaders, while research and development capability on integrated circuits is even further behind.

Regarding desirable research and development methods, autonomous research and development accounts for 60 percent of responses in all technology topics, but joint research accounts for 60 percent in the information and communications field and 50 percent in the biotechnology and life science field. In new materials, autonomous research and development accounts for 70 percent of the responses.

(2) Degree of importance

Looking at the 100 topics seen as most important, the information and communications and biotechnology and life science fields account for about half, with 26 and 22 topics, respectively.

In concrete terms, these include information security technology; network security technology; supercomputer system design; research on next-generation network architecture; low-cost, high-performance, leading-edge steel materials; reagents for the quick verification and diagnosis of serious and infectious diseases; Chinese-language information processing technology; systems for managing network computing environments; new-type and general-purpose IC production; and research and production of 64-bit high-performance CPU chips.

(3) Analysis of economic effects

The report includes analysis by question item as well as overall analysis. For economic effects in particular, an economic costs index is derived from three questions regarding industrialization outlook, international competitiveness, and industrialization costs. Technology topics are classified based on their characteristics in terms of economic effects × high-tech industry promotion effects / development and structural improvement of existing industry promotion effects / environmental conservation and resource development effects.

Technology topics with high promotion effects for high-tech industry may be either high or low in terms of economic effects, but technology topics with high promotion effects for existing industry have high overall economic effects. There is a tendency to promote high-tech fields in the future, but because China will depend on existing industries for the coming 5-10 years, their analysis holds that innovation in those fields must be accelerated.

(4) Breakthrough technologies with a high likelihood of realization in China

The information and communications, biotechnology and life science, and new materials fields are cited as offering breakthrough technologies with a high likelihood of realization

Table 3 : Breakthrough technologies with a high likelihood of realization in China in the coming 10 years

Information and communications	Next-generation mobile communications technology, next-generation network systems, nanochip technology, Chinese-language information processing technology
Biotechnology and life science	Human functional genomics, biomedical technology, bioinformatics, proteomics, technology for cultivating new crop species
New materials	Nanomaterials and nanotechnology

Source: Reference [4]

Table 4 : Core technologies with a high likelihood of dramatic industrial development in China

Information and communications	SoC (system on chip) technology, next-generation mobile communications technology, organic electroluminescence (EL) technology, digital communications, compression, Codec technology
Biotechnology and life science	Biotechnology for medicines and vaccines, technology for biocatalysts and genetic engineering, genetically engineered crops with high quality, productivity and resistance
New materials	Low-cost, high-performance, leading-edge steel materials; technology for manufacturing materials and measuring

Source: Reference [4]

in China in the coming 10 years (Table 3) and core technologies with a high likelihood of dramatic industrial development in China (Table 4). In the Japanese survey, the outlook for technical development in Japan alone is not considered.

3 Technology Foresight survey by the Chinese Academy of Sciences

The Chinese Academy of Sciences carried out technology foresight survey for four fields (information, communications, and electronics; energy; materials science; and biology and drugs) from 2003 through 2005. The survey was carried out by the Institute of Policy and Management of the Chinese Academy of Sciences. Surveys of another four fields (manufacturing technology, resources and environment, chemistry and chemical engineering, space technology) are now underway, with publication of results expected around the summer of 2006.

The report entitled “Technology Foresight for Future 20 Years in China”[5] distinguishes between “technology forecasting” and “technology foresight,” suggesting that recently “foresight” has been developed beyond the “forecasting” of the first half of the 20th century. The report argues that “foresight” obtains better results than “forecasting” by identifying future needs and preparing the capabilities required to address those needs. The following four reasons are given for the emphasis on “foresight.”

(1) It is a tool for determining areas that should take priority.
(2) It is a means of strengthening national innovation.
(3) It lowers the cost of creating proper investment strategies for small- and medium-sized businesses by enabling them to ascertain the direction of trends in future technology development.
(4) It enables early warning of negative social and environmental impacts of technologies.

Items of particular interest within the report are the “Six Visions for Chinese Society in 2020,” which were determined in 2003 and provided the basis for selection of technology themes, and the results of analysis of world technology levels, especially in relation to those themes in which Japan is seen as leading the world. Below, we discuss the report's content, with particular focus on those aspects.

3-1 Target fields and questions

In the Chinese Academy of Sciences foresight survey, the four fields (information, communications, and electronics; energy; materials science; and biology and drugs) incorporate 32 sub-areas and 409 technology topics. Aspects such as each theme’s importance, time of realization, potential for realization, the relative levels of leading countries and China,

Table 5 : The 32 sub-areas set forth in the Foresight survey of Chinese Academy of Sciences

Field	sub-areas
Information, communications and electronics (12 sub-areas, 150 technological topics)	(1) Computer technology, (2) software technology, (3) communications technology, (4) network technology, (5) broadcast and television technology, (6) man-machine and artificial intelligence technology, (7) information security technology, (8) bioinformatics, (9) microelectronic, photoelectronic, and micromachine technology, (10) information gathering and sensor technology, (11) information storage and display technology, (12) application of information technology
Energy (6 sub-areas, 72 technological topics)	(1) Coal, oil, natural gas, (2) electric power, (3) nuclear power, (4) hydrogen energy, (5) reusable energy, (6) thermal and mechanical energy
Materials science (6 sub-areas, 86 technological topics)	(1) High-polymer materials, (2) metal materials, (3) inorganic and ceramic materials, (4) functional materials, (5) photoelectronic materials, (6) nanomaterials
Biology and drugs (8 sub-areas, 101 technological topics)	(1) Bio-platform technology, (2) biomeasurement and bioengineering technology, (3) technology for promoting organism growth and improvement of species, (4) agricultural and environmental science, (5) disease prevention and cure, (6) new drug discovery and development, (7) stem cells and regenerative medicine, (8) cognitive and behavioral science

limits on development, etc. are analyzed. Table 5 shows the names of the 32 sub-areas. The 409 technology themes are listed in an appendix in order of their time of realization, from earliest to latest. The period examined is the 15 years ending in 2020.

The names of the 268 sub-area experts and the 975 respondent experts are also listed in an appendix at the end of "Technology Foresight for Future 20 Years in China." There is very little overlap between the two groups.

Not all the collected data are included in the report. Instead, only the top 10 items for each field and perspective are shown in most cases, so it is not possible to study the detailed results of the entire survey.

3-2 A picture of China's science and technology in 2020

Of note in the report are the following six visions set forth in Section 1, "Visions for an overall xiaokang society in China in 2020," in Chapter 3, "What is required of science and technology to build a little well-off (xiaokang) society." A little well-off society is a society in which "the people of China, who already number 1.3 billion, can live with a certain degree of happiness." In this technology foresight survey, Chinese society in 2020 is viewed as follows:

(1) Globalized society

World trends include an increase in the number of powerfully competitive multinational corporations, the globalization of production and finance using information technology, and other movements that ignore national borders. The flow of science and technology human resources and international cooperation are also progressing dramatically.

In accordance with this world trend, by 2020 China will have worked to expand its ability to absorb foreign investment and to invest in foreign countries, dramatically enhancing its "resource allocation ability" in a globalized society in terms of intellectual production, technology transfer, application capability, resource development and utilization capabilities, etc.

(2) Industrialized society

China's industrial structure currently has a high ratio of primary industries such as agriculture, unlike the advanced industrial nations. However, China's industrialization is already remarkable. The shift of workers from primary to secondary and tertiary industry will be promoted, lowering the share of primary industry to 6.75 percent by 2020, and raising the share of secondary and tertiary industry to more than 93 percent.

(3) Information society

Led by the major coastal cities in the east, China's use of information technology is rapidly expanding. China is now implementing measures that will enable it to become an information society, such as application of information technology, accumulation of information resources, preparation of information networks, the fostering of informatization human resources, and the establishment of laws and standards that accompany informatization. By 2020, China aims to have 40 computers, 7 network servers, 50 fixed telephone lines, 50 mobile telephones, 50 digital televisions, and 40 Internet users per 100 people.

(4) Urbanized society

In contrast to the progress of industrialization, the rate of urbanization is remarkably slow. By 2020, China will have transferred an excess rural population of 200 million people into the urban workforce, raising the urban proportion to 64 percent of total population.

(5) Recycling-oriented society

Against the backdrop of a natural environment that is deteriorating due to global warming, air pollution, etc. resulting from such impacts as industrialization, China is interested in developing a recycling economy, reuse of waste, etc. Aiming for realization of a little well-off society that efficiently employs science and technology to both utilize and conserve resources is the first step in building a recycling-oriented society.

By 2020, Chin's coastal area will be a vast model zone for a recycling economy, with energy consumption reduced by half from 2001 rates, and carbon-dioxide emissions per unit GDP reduced by 30-40 percent.

(6) Consumer society

As used in the report, a "consumer society" is one that aims for a more affluent, healthy, convenient, and safe life. At this point, China is pursuing realization of a consumer society by improving the quality and variety of its food and clothing, developing technology for healthcare and disease prevention, and improving public transportation. China projects a per capita GDP of at least $3,000 US (triple the 2002 figure) by 2020. The nation's wealthiest class now enjoys incomes up six times those of the poorest segment of the population (each accounting for 10 percent of all households), but the percentages of household budgets spent on food, clothing, housing, healthcare, light and heat, transportation, etc. do not differ to any great extent. For example, spending on healthcare is about 8 percent of household budgets for all income levels. National government investment in technical development for healthcare, pharmaceuticals, hygiene, etc. is expected to lower the percentage spent on healthcare at all levels of society. In addition, conservation of water resources, traffic safety, food safety, etc., are cited as areas requiring science and technology input in a consumer society.

3-3 Noteworthy survey results

(1) Japan's technical levels from the Chinese perspective

The following items are noted for each field: (i) an overview, (ii) the most important technology topics in the field, (iii) predicted time of realization for technology topics, (iv) China's research and development levels in those topics, (v) advanced countries in the technology topics (USA, EU, Japan), (vi) potential for realization of the technology topics, and (vii) elements constraining technical development. The results of comparisons between China's technical levels and those of the other countries are particularly interesting.

Research and development levels are shown on a scale of 0 to 1 point. If all respondents answer, "Leads the world," the score is 1.0; if all respondents answer "Close to world level," the score is 0.5; and if all respondents answer, "Trails the world," the score is 0.0. Looking at the assessment of China's research and development levels, the highest score is 0.31 for the information, communications, and electronics area; 0.56 for energy; 0.60 for materials science; and 0.53 for biotechnology. With the world number one in each area obtaining a score of at least 0.7, this is quite a low self-assessment.

The advanced countries in the technology topics are almost limited to the USA, the EU, and Japan (the only other countries appearing are Russia and South Africa). Japan is seen as number one in 1 technology topics in information, communications, and electronics; 5 in energy; 12 in materials science; and 6 in biology and drugs. Because it is of interest to note in which technologies China sees Japan as leading the world, these are shown in Table 6 (including some where Japan is at the same level as the USA).

The USA is seen as having by far the highest level in the information, communications, and electronics field, with Europe and Japan lagging well behind. It is notable that the only area in which Japan is seen as number one in the field - tied with the USA - is the topics of semiconductor white lighting technology, which was achieved based on technical development of blue LEDs. In the materials science field, Japanese technology in high-polymer materials did not beat the USA for any topics, but in the other five sub-areas, Japan was seen as first in one to four technology topics. In addition, Japan is seen as surpassing Europe in most topics in the materials science field. In the biology and drugs field, the existence of three technology topics related to Chinese herbal medicine is striking. Japan's technical level is seen as much higher than that of China, the

Table 6 : Technologies where Japan is seen as being in 1st place

Field	sub-area	Technology topics
Information, communications and electronics (1 topics)	Microelectronic, photoelectronic and micromachine technology	• All-solid semiconductor white lighting technology
Energy (5 topics)	Electric power	• New types of permanent-magnetic motors • Various energy-saving technologies
	Hydrogen energy	• Direct manufacture of hydrogen through highly efficient photolysis
	Thermal and mechanical energy	• Hybrid cars • Efficient, comprehensive handling of urban waste
Materials science (12 topics)	Metal materials	• Technology for environmentally friendly steelmaking without blast furnaces • Rolling technology that adds heat without oxidation • Development of high-quality, high-speed continuous-casting technology
	Inorganic and ceramic materials	• Ultralarge-scale integrated circuits using thin films with high or low electric constants • Application of lead-free piezoceramic materials to information technology • Technology for platform integration through low temperature co-fired ceramics (LTCC) • Thermoelectric conversion materials with a conversion efficiency of at least 10%
	Functional materials	• Flat information ceramic functional materials and devices • Functional materials from rare-earth elements
	Photoelectronic materials	• Full-color large-screen projection technology with all-solid lasers • Polishing and extension chips for 450-mm diameter silicon
	Nanomaterials	• Nanoenvironment purification materials
Biology and drugs (6 topics)	Agricultural and environmental science	• Countermeasure technology for red tides and other types of water eutrophication • Urban waste disposal using microorganisms • Healthy and efficient cultured production of sea life
	Disease prevention and cure	• Treatment with Chinese herbal medicine
	New drug discovery and development	• Technology for modernizing Chinese herbal medicine • Model identification methods for Chinese herbal medicine

Table 7 : Number of 1st- and 2nd-place topics

Field	No. of Topics	USA		Japan		EU		Russia		South Africa	
		1st place	2nd place	1st place	2nd place	1st place	2nd place	1st place	2nd place	1st place	2nd place
Information, communications and electronics	150	150	0	1	97	0	55	0	0	0	0
Energy	72	50	17	5	16	15	38	2	1	1	0
Materials science	86	73	11	12	68	2	6	0	1	0	0
Biology	101	94	7	6	23	1	74	0	0	0	0
Total	409	367	35	24	204	18	173	2	2	1	0

medicine's homeland.

Table 7 shows the number of topics in each field in which each country is ranked first or second.

(2) Method of assessing the importance of technology themes

The importance of technology is evaluated from three perspectives, which are combined in a comprehensive index for analysis. The three perspectives (three elements) are: (i) promotion of economic growth, (ii) improvement of quality of life, and (iii) protecting national security.

Responses are aggregated by combining and weighting degree of importance (four levels: very important, important, relatively important, not important) and respondents' degree of expertise (very well informed, well informed, relatively informed, not informed). For the "comprehensive judgment of the three elements," in other words, an overall degree of importance index, the root-sum-square (RSS) value of the "three elements" is used.

The report shows only the order of importance; nowhere does it describe the calculations used to obtain the results.

(3) Elements constraining development

There were six categories of constraints on the development of technology topics: (i) feasibility, (ii) potential for commercialization, (iii) regulation, policy, and standards, (iv) human resources, (v) investment of research and development funds, and (vi) basic infrastructure, with multiple responses possible. The report shows the results for only a few technology themes. The most common leading constraint is investment of research and development funds, with human resources or basic infrastructure often appearing in second place.

3-4 Development trend scenarios for important technology themes

The report of the Chinese Academy of Sciences was published in two parts. The second part is the above-described "Technology Foresight for Future 20 Years in China." In the first part, "Technology Foresight 2005,"[6] published in 2005, experts comment on the 44 technology themes regarded as most important at the time. They generally devote several pages to providing an overview of each technology and describing its significance, technical trends, issues, and China's strategies. Table 8 shows the result of comparing the 44 themes and authors with the results of the Delphi analysis. Looking at degree of importance according to the questionnaire, the energy field in particular has few high-ranked themes. The data for the level index are therefore also unclear.

Most of the experts who wrote the commentaries are specialists in the Delphi survey sub-areas or respondents to the questionnaire. Those marked with a ○ are experts in a sub-area, while those marked with a (are experts who responded to the survey. Some are included in both categories, while others are included in neither.

4 Conclusion

We have described technology foresight survey in China. Based on published reports, we have examined particularly noteworthy elements such as the six visions for a little well-off society that China is pursuing, technologies in which China is on a par with the leading countries, and Japan's technical level as seen from a Chinese perspective. From this, one can discern the direction in which China is moving and its self-assessment of its current status.

This recent technology foresight survey is the first research activity that China has carried out as background material for policy deliberation. Meanwhile, the "8th Science and Technology Foresight Survey"[3] conducted by the National Institute of Science and Technology Policy in Japan was the first survey to be carried out in close cooperation with Japanese policymakers. The necessity and importance of foresight surveys in policy deliberation will increase continuously. The major goal for foresight researchers will be to provide the information needed by policymakers in the most reliable and rational form possible.

China's technology foresight survey and Japan's foresight survey have many points in common, including questionnaire categories and technology classifications. They also share attempts to design research to supplement

Table 8 : Comparison of themes and authors from “Technology Foresight 2005” with questionnaire results from “Technology Foresight for Future 20 Years in China”

Field	sub-area	44 themes used in scenarios, authors and their affiliations			Time of realization	Index of Chinese level	Priority rank
		Theme	Author	Affiliation			
Information, communications and electronics	Computer technology	Tera FLOPS scale microprocessors	○ Zhi-min Tang	Institute of Computing Technology, Chinese Academy of Sciences	2017	0.05	41
		Grid computing	○ Yan-bo Han	Institute of Computing Technology, Chinese Academy of Sciences	2015	0.22	31
	Communications technology	Multifunction personal information terminal	○ Shao-qian Li	University of Electronic Science and Technology of China	2012	0.22	32
		Novel mobile communications providing moving pictures services	△ Jin-kang Zhu	University of Science and Technology of China	2012	0.25	24
		Fourth-generation mobile communication system	○ Shi-xin Cheng	Shanghai for Wireless Communications Research Center	2015	0.28	23
	Network technology	IPV6 networks	○ Zhong-cheng Li	Institute of Computing Technology, Chinese Academy of Sciences	2013	0.31	43
		Wireless sensor network	△ Song-lin Feng	Shanghai Institute of Microsystem and Information Technology, Chinese Academy of Sciences	2015	0.13	30
		Broadband access technologies	△ Xing-gang Wang Hua-shen Zeng	Institute of Computing Technology, Chinese Academy of Sciences Computer and Communication College, Southwest Jiaotong University	2010	0.27	50
	Man-machine and artificial intelligence technology	Speech technology in knowledge acquisition and information interaction	Yong-hong Yan	Institute of Acoustics, Chinese Academy of Sciences	2016		
	Information security technology	Large-scale anti-attack network security systems	Zheng-yue Wei Zhong-hui Wen	No.58 Research Institute of General Staff, PLA Beijing Science and Technology Information Association	2018	0.14	26
	Microelectronic, photoelectronic, and micromachine technology	Processing technology for 10-nm 1000G integrated density	○ Tian-chun Ye	Institute of Microelectronics, Chinese Academy of Sciences	2020	0.07	9
		MicroOptoElectroMechanical Systems (MOEMS)	○ Yue-lin Wang Tie Li	Shanghai Institute of Microsystem and Information Technology, Chinese Academy of Sciences	2016	0.15	59
Energy	Coal, oil, natural gas	Coal gasification and poly-generation	○ Zhen-yu Liu	Institute of Coal Chemistry, Chinese Academy of Sciences	2017	0.12	99
		Floating production technology in offshore oil fields	Xiang-an Yue Xiao-dong Wu	China University of Petroleum Beijing	2017		
		Development of marine gas hydrate exploitation technology	○ Qing-huan Jin △ Jia-qiang Zhang	Guangzhou Marine Geological Survey, Ministry of Land Resource Development and Research Center, China Geological Survey	2022	0.12	15
	Electric power	Ultralarge-scale electric power grids	○ Shu-yong Chen	China Electric Power Research Institute	2013	0.4	4
		Distributed power systems	Zhi-ping Qi ○ Li-ye Xiao	Institute of Electrical Engineering, Chinese Academy of Sciences	2016		
	Nuclear power	High-level radioactive waste disposal technology	△ Xiang-ke Wang	Institute of Plasma Physics, Chinese Academy of Sciences	2021	0.26	
	Hydrogen energy	Fuel cell vehicles	△ Bao-lian Yi △ Ming Hou	Dalian Institute of Chemical Physics, Chinese Academy of Sciences	2017	0.23	
		Distributed hydrogen fuelled generation system	○ Yun-han Xiao	Institute of Engineering Thermophysics, Chinese Academy of Sciences	2016		
	Reusable energy	Bioenergy technology	○ Jie Chang ○ Chuang-zhi Wu	Guangzhou Institute of Energy Conversion, Chinese Academy of Sciences	2015		
		Economical highly-efficient solar power technology	○ An-ding Li	Institute of Electrical Engineering, Chinese Academy of Sciences	2017	0.24	
	Thermal and mechanical energy	High-performance heavy gas turbines	○△ Xin Yuan	Department of Thermal Engineering, Tsinghua University	2016	0.09	

Field	sub-area	44 themes used in scenarios, authors and their affiliations			Time of realization	Index of Chinese level	Priority rank
		Theme	Author	Affiliation			
Materials	High-polymer materials	High-performance rubber	Bai-lin Lv	Beijing Research and Design Institute of Rubber Industry	2014	0.16	11
	Metal materials	Hydrogen energy materials	△ Ke Yang Man-qi Lv	Institute of Metal Research, Chinese Academy of Sciences	2017	0.19	25
		Light-weight high-steongth metallic materials	○ Li-kai Shi	Beijing General Research Institute for Nonferrous Metals	2014	0.22	3
	Inorganic and ceramic materials	Multifunctional and smart micro sensors	○ Wei Pan Qiang Xu	Department of Materials Science and Engineering, Tsinghua University	2016	0.12	39
	Functional materials	High-temperature superconductor technology	Qing Liu Zheng-he Han	Applied Superconductivity Research Center, Tsinghua University	2025	0.34	53
		Solar cells with a conversion efficiency of 50%	Da-ming Zhuang Gong Zhang	Research institute of Functional Membrane and nano-meter material, Department of Mechanical Engineering, Tsinghua University	2022	0.09	1
		Photocatalytic hydrogen production from water	Qi-yuan Chen Ya-hui Yang	Collage of Chemistry and Chemical Engineering, Central South University	2022	0.13	27
	Photoelectronic materials	Semiconductor white lighting	○ Zhan-guo Wang	Institute of Semi-conductors, Chinese Academy of Sciences	2016	0.28	12
		Ultrahigh-density magnetic data storage technology	Jian-wang Cai ○ Shao-hua Cheng	State Key Laboratory of Magnetism, Institute of Physics, Chinese Academy of Sciences	2016	0.16	29
		Ultra-broadband fiber amplifiers in all-optical networking	Wei Chen	Shanghai Institute of Ceramics, Chinese Academy of Sciences	—	—	—
	Nanomaterials	Controllable fabrication of nano-scale materials	Lei Jiang	Institute of Chemistry, Chinese Academy of Sciences	2015		
Biology	Bio-platform technology	Systems biology	Jia-rui Wu	Shanghai Institutes for Biological Sciences Chinese Academy of Sciences	2015		
		High throughput gene expression technology	Yu-yang Li	Institute of Genetics, School of Life Sciences, Fudan University	2015		
	Biomeasurement and bioengineering technology	Detection of pathogens, harmful and genetically modified ingredients in foodstuffs	△ Da-bing Zhang	College of Life Science and Biotechnology, Shanghai Jiaotong University	2011	0.24	7
	Technology for promoting organism growth and improving varieties	Practical technologies of bio-energy, biomaterials and biomass resource	○△ Ping-kai Ouyang	College of Life Science and Pharmacy, Nanjing University of Technology	2014	0.21	2
	Agricultural and environmental science	Microbial metabolic engineering (cell factory)	△ Zhu-an Cao Yin Li	Department of Chemical Engineering, Tsinghua University School of Biotechnology, Southern Yangtze University			
		Molecular design of plant cultivars and molecular breeding	○△ Ai-min Zhang Dao-wen Wang Xiang-qi Zhang	Institute of Genetics and Developmental Biology, Chinese Academy of Sciences	2017	0.36	28
	Disease prevention and cure Stem cells and regenerative medicine	Conquer multifactorial disorders	Jian-jun Gao	Shanghai Institutes for Biological Science, Chinese Academy of Sciences	2014	0.23	QoL 16
		Biodefence preparedness to ensure national safety and public health	Shun-qing Xu	Research Institute of Environmental Medical, Tongji Medical College, Huazhong University of Science and Technology	2012	0.16	10
		Technologies for the isolation, proliferation and differentiation of stem cells	○△ Xue-tao Pei	Institute of Transfusion medicine, Academy of Military Medicine	2022	0.11	
	Cognitive and behavioral science	Artificial intelligence resembling a brain (BAI)	○△ Yue-jia Luo	Key Lab of Mental Health, Institute of Psychology, Chinese Academy of Sciences	—	—	—

○: Expert in sub-area △: Responden —: Excluded from survey No priority rank: Rank is 100 or lower QoL: Rank from a quality-of-life perspective

Prepared by the STFC based on "Technology Foresight 2005" and "Technology Foresight for Future 20 Years in China" the limitations of Delphi analysis, such as examination of visions of future societies and needs and comments on development trends for important technologies. In addition, issues that must be addressed are the same for both: means of integrating various methods, handling of academic fields, and examination of methods to obtain useful data. Regarding the setting of technology themes, they have also taken steps to obtain contributions from outside experts, involve relevant research institutions and academic societies, and associate questionnaires and other methods. It would be beneficial for foresight researchers from various countries to exchange opinions based on their experiences.

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About SCIENCE AND TECHNOLOGY FORESIGHT CENTER

It is essential to enhance survey functions that underpin policy formulation in order for the science and technology administrative organizations, with MEXT and other ministries under the general supervision of the Council for Science and Technology Policy, Cabinet Office (CSTP), to develop strategic science and technology policy.

NISTEP has established the Science and Technology Foresight Center (STFC) with the aim to strengthen survey functions about trends of important science and technology field. The mission is to provide timely and detailed information about the latest science and technology trends both in Japan and overseas, comprehensive analysis of these trends, and reliable predictions of future science and technology directions to policy makers.

Beneath the Director are six units, each of which conducts surveys of trends in their respective science and technology fields. STFC conducts surveys and analyses from a broad range of perspectives, including the future outlook for society.

The research results will form a basic reference database for MEXT, CSTP, and other ministries. STFC makes them widely available to private companies, organizations outside the administrative departments, mass media, etc. on NISTEP website.

The following are major activities:

1. Collection and analysis of information on science and technology trends through expert network

— STFC builds an information network linking about 2000 experts of various science and technology fields in the industrial, academic and government sectors. They are in the front line or have advanced knowledge in their fields.

— Through the network, STFC collects information in various science and technology fields via the Internet, analyzes trends both in Japan and overseas, identifies important R&D activities, and prospects the future directions. STFC also collects information on its own terms from vast resources.

— Collected information is regularly reported to MEXT and CSTP. Furthermore, STFC compiles the chief points of this information as topics for “Science and Technology Trends” (monthly report).

2. Research into trends in major science and technology fields

— Targeting the vital subjects for science and technology progress, STFC analyzes its trends deeply, and helps administrative departments formulate science and technology policies.

— The research results are published as articles for "Science Technology Trends" (monthly report).

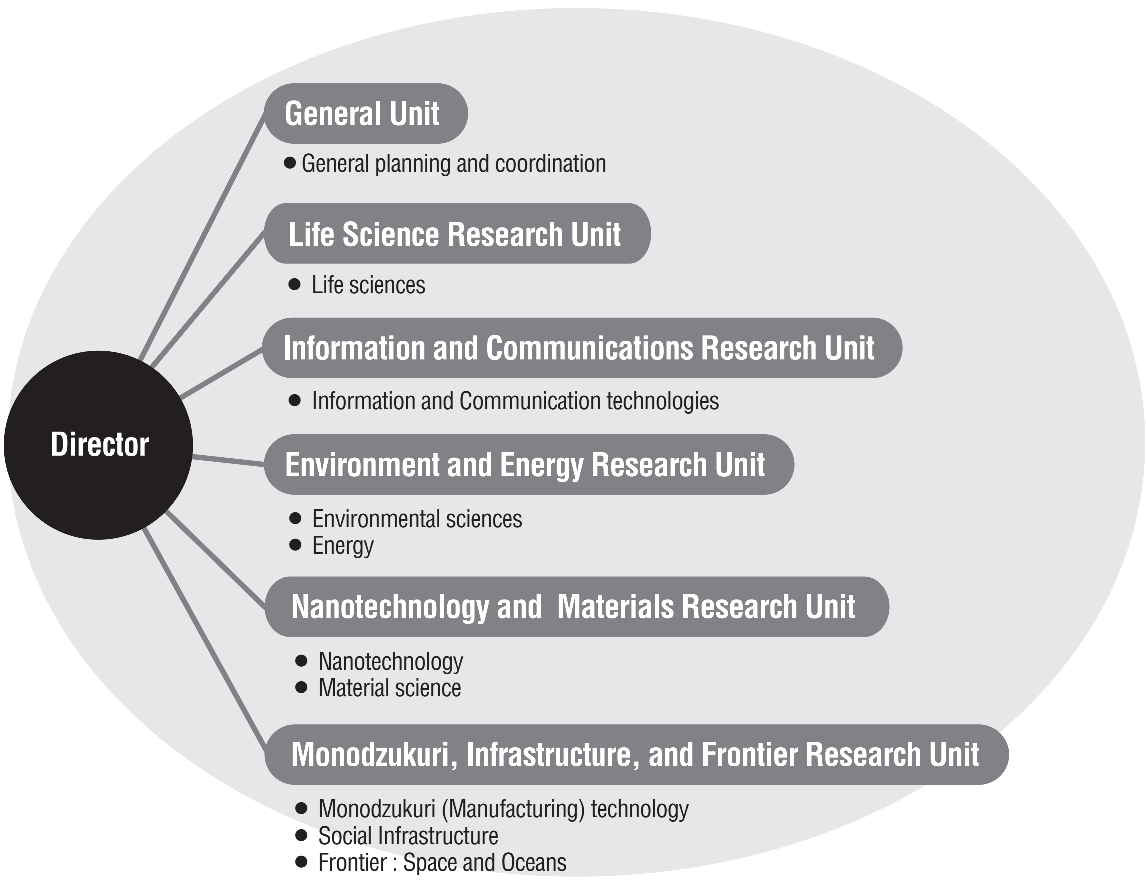
3. S&T foresight and benchmarking

— S&T foresight is conducted every five years to grasp the direction of technological development in coming 30 years with the cooperation of experts in various fields.

— International Benchmarking of Japan's science and engineering research is also implemented periodically.

— The research results are published as NISTEP report.

Organization of the Science and Technology Foresight Center



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