CRDS-FY2018-RR-02

Beyond Disciplines

JST/CRDS focuses on 12 transdisciplinary research themes (2018)

Center for Research and Development Strategy
Japan Science and Technology Agency

Preface

The accumulated scientific discoveries of our forebearers has seemingly transformed all things of heaven and earth from myth to reality. Yet the benchmark of science must always be "Socratic ignorance," the ability to recognize that we know nothing. The creation of new knowledge opens up new worlds of the unknown. In every age, it is the young who venture to explore these frontiers, and we must be patient as they make their way.

The Science Map published by MEXT's National Institute of Science and Technology Policy (NISTEP), gives some indication of the relationships among, and degrees of activity and development of, various fields of scientific endeavor (Fig. a). The effect is like that of a large continent with numerous peninsulas extending in different directions and islands, large and small, floating in the middle of a great ocean. But this fluctuating geographical map with its constant ebb and flow is only one expression of recent research activity based solely on citation indices; under the deep waters of the hypothetical ocean, all are connected. "Science is one." There are no boundaries in exploring the universal principles of the natural world, and yet universities, academic societies, and even researchers themselves turn their backs on this truth, go out of their way to create academic boundaries, and stubbornly defend those barriers. A crucial issue today is how to co-create new value that will add to

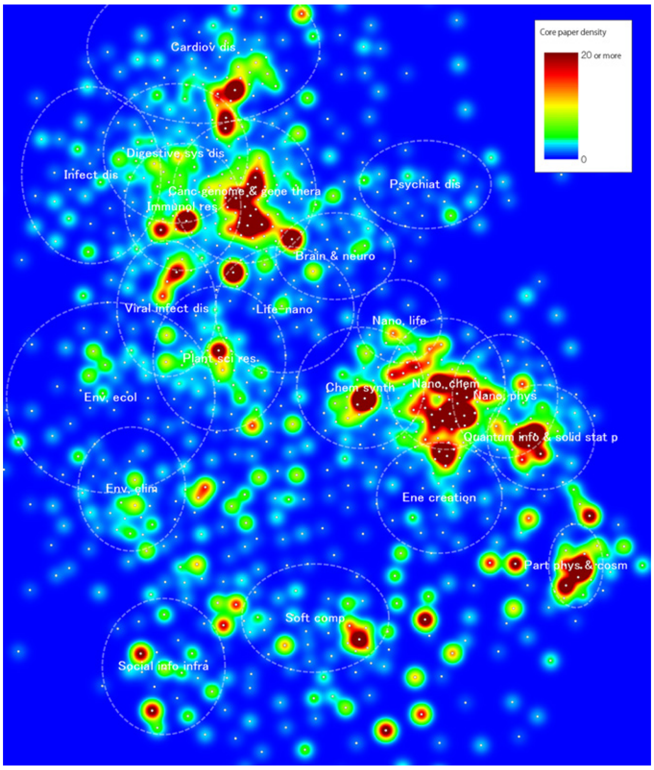


Fig. a Science Map 2016
Source: National Institute of Science and Technology Policy

individual, original research. Could it be, perhaps, a deficiency in the systems of modern science that is hindering this process? To correct the map I alluded to above, we must begin by building bridges connecting the already existing land masses and providing ships and planes to facilitate the movement of people back and forth. Also important will be the thorough implementation of rapidly evolving information technology.

In our efforts to enhance our communal welfare, humanity has drawn on elements of politics, economics, education, medicine, food, transportation, etc., to build its social infrastructure. Maintaining and ensuring healthy conditions is not possible without continuing development of science-based technology. Furthermore, sustaining the critical “planetary boundaries” is crucial for the survival of human civilization (M. Leach et al., 2013). In recent years, however, nonlinear and irreversible changes are posing a very real threat to our continued existence. These changes in the conditions for sustainability arise not only from massive natural disasters but also from excessive human activity leading to the disruption of natural resources, pollution of the atmosphere and oceans, and greenhouse gas emissions. The question arises: Is comprehensive and sustainable economic development even possible in the context of a vulnerable space for existence defined by diverse social and global environmental conditions? Regardless of country or region, our current generation has a responsibility to reassess our ethical perceptions and integrate our knowledge for the benefit of future generations. Those in the world of science and technology must strive, not only for our own benefit, but to enter into constructive and broad-ranging dialog and mature debate on how best to tackle and overcome the unprecedented problems confronting the diverse societies of our world.

CRDS is dedicated to preparing and nurturing the soil for such endeavors, and I am hopeful that the several concrete proposals set forth in this report will become milestones in our journey forward.

Ryoji Noyori

Director-General
Center for Research and Development Strategy
Japan Science and Technology

References

- Science Map 2016, National Institute of Science and Technology Policy (NISTEP REPORT No. 178), October 2018. (in Japanese)
- M. Leach, K. Raworth and J. Rockström, "Between social and planetary boundaries: Navigating pathways in the safe and just space for humanity," *World Social Science Report 2013: Changing Global Environments*, (Paris: OECD and UNESCO, 2013)

【Contents】

1 Summary

1.1 Why we speak of going “Beyond Disciplines”

Today, the more the world is said to be in the Volatility/Uncertainty/Complexity/Ambiguity (VUCA) era, the more we enter a rapidly changing, complex, and unpredictable era. Proceeding in one direction with only one method is risky in an era that demands diversity and adaptability. In a society that is diversifying and becoming more complex, many phenomena required, or regarded as problematic, by humankind and society—SDGs are a prime example of such phenomena—are becoming increasingly difficult to tackle head-on by a single research field, which is deeply specialized and subdivided based on historical academic and scholastic systems. In order for science and technology to address various problems and issues of modern times, it is required that new fields transcending academic systems that have conventionally developed independently be defined and research activities carried out in such fields, and that new integrated fields be created through coordination among multiple research fields, and research be carried out in these new fields. Doing so can be expected to induce new discoveries and advancements in existing fields.

There is, however, a historical background of the government bodies responsible for formulating policies related to science and technology devising and implementing policies in concert with existing fields and existing industrial sectors. For modern society—which, as mentioned above, is rapidly changing, complex, and unpredictable—it is difficult to adapt in order to resolve problems, and experts have even been heard to say that society is rigidifying. Of course, the raison d'être for existing fields and industries is recognized and is not itself being denied. However, these problems and issues are difficult for any field or sector to address head-on; that is to say, a structure have been created in which existing specialized fields and existing industrial sectors all shut their eyes to the problems, saying, “That has nothing to do with me.” For example, has not this structure always enabled a researcher in a certain specialized field to say, “I'm not an expert regarding this issue,” or for many traditional organizations to say, “We're not the department responsible for that”? It may be that we may frequently not realize the problems that such statements contain. That is to say, such statements arise when the “diminution of requirements due to personal convenience,” for both individuals and organizations, becomes structurally pervasive.

The term “integration” as used in this report is not limited to either integration between horizontal fields that arise as the result of horizontal or vertical collaboration between different fields, or integration between vertical layers (although in the care of vertical integration, “synthesis” may be a more accurate term). The term includes various other forms of integration, such as integration between different stakeholders and integration between different types of industry. Nowadays, use of related terminology—such as “transdisciplinary” and “convergence”—is increasing in countries and international forums around the world. In the United States, for example, beginning with the “Facilitating Interdisciplinary Research” report published by The National Academies in 2005 and the “Convergence - Facilitating Transdisciplinary Integration of Life Sciences, Physical Sciences, Engineering, and Beyond” report published by The National Academies in 2014, transdisciplinary research is being considered from the perspectives of how it can be created, how it can generate value, and how it can be promoted. In Japan, the term “integrated research” is often used, but this report has been entitled "Beyond Disciplines" based on expectations for creating new integrated fields that transcend existing "disciplines". However, this term is not necessarily strictly defined within this text. In this report, the term "integration" has been used as a word that incorporates all these concepts rather than being limited to any one of them. In other words, there are cases in which it is necessary to bring about integration for a certain purpose, such as a social issue; cases in which it is necessary to go beyond existing disciplines in order to achieve that purpose; and cases in which it is necessary to proactively go beyond existing disciplines without there being a certain purpose. Furthermore, there are cases in which integration is born beyond the transcending of disciplinary boundaries. However, it is essential to understand that integration for a certain purpose and the integration of disciplines are not necessarily the same. Moreover, integrated fields do not suddenly come into being overnight; rather, they are created through the mixing of different fields and specialties over periods of time spanning years to form a new outline. This new outline does not exist to begin with. In contrast, in the case of "collaboration" between different disciplines or experts, it is possible for the parties to join hands and begin their joint activities immediately if the decision to collaborate has been made. Collaboration involves joint activities to achieve certain results by parties that join hands while maintaining their original disciplinary or expertstructures—that is, maintaining their boundaries. Integration is not necessarily the correct path is all situations, and there are cases in which collaboration is more effective (Fig. 1-1).

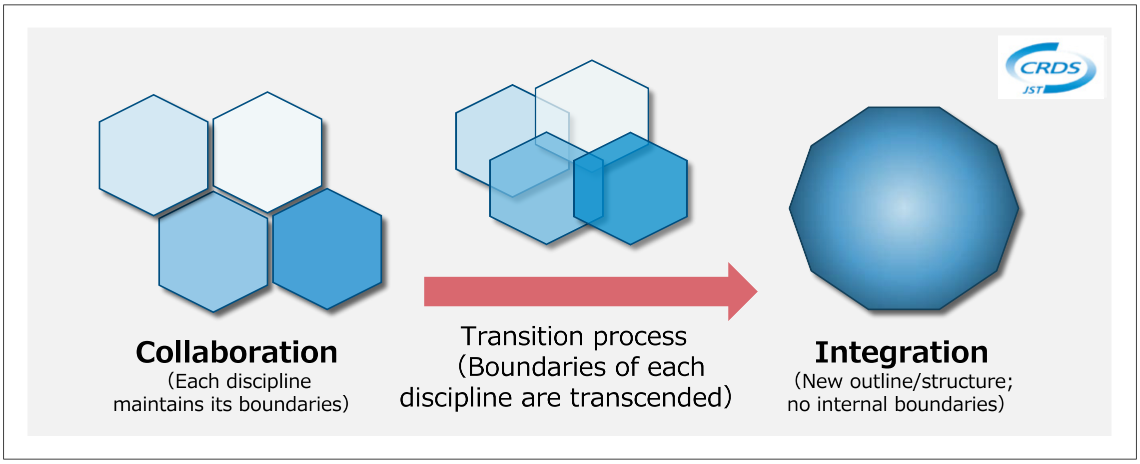


Fig. 1-1　Collaboration and Integration

Based on awareness of this background, CRDS believes that, in order to induce or provide momentum for initiatives in which research activities is carried out through collaboration beyond multiple existing research fields, or initiatives that create transdisciplinary fields, as a first step it is important that several concrete examples be presented and broadly disseminated regarding specifically what kinds of transdisciplinary research themes are required and gradually being identified. It goes without saying that not only individuals but also organizational structural changes, new experimentation, and system design innovations are essential for inducing later action as well.

This report identifies and introduces 12 transdisciplinary research themes that CRDS recognizes and is focusing on as of 2018. The 12 themes shown were selected from among themes following recent R&D using broad-ranging bird's eye view processes; themes for which CRDS has issued recommendations in recent years; themes for which CRDS is promoting the formulation of recommendations; and other themes incorporating a certain awareness of issues or that promote surveys and analysis (Table 1). Here it is necessary to understand that an approach that attempts to systematically cover transdisciplinary research themes is inappropriate. Such themes are born and change against the background of the current social situation and stage of scientific development and are included to a certain extent in various spheres and structures. However, while they influence each other, their formulation is based on different standards. Accordingly, these themes are not necessarily linearly correspondent and cannot be neatly categorized. This report presents research themes that, as of 2018, CRDS is focusing on within the process of endeavoring to obtain a broad bird's eye view of trends in society and science and technology. In doing so, the report endeavors to present these themes as plainly and simply as possible with a view to a broad readership comprising not only certain expertsand specialist organization but also members of the general public as well.

Table 1 JST/CRDS focuses on 12 transdisciplinary research themes (2018)

No.	Transdisciplinary research themes	Specialized disciplines which must be gone beyond for transdisciplinary research	People and organizations which work together for social implementation
1	Information science and technology for decision-making in a complex society	Systems and Information Science, Sociology, Behavioral Economics, Political Science, Psychology	Entrepreneurs/ companies/ business operators, lawyers, financial institutions, medical institutions, farmers/agricultural legal persons, administrative bodies, NPOs/NGOs, schools/educators, designers/artists, diverse citizens, etc.
2	R&Ds for solving social issues by data science 2.1 Future energy network using IoT 2.2 Promoting the integration of Bio-Medical Things (IoBMT)	2.1 Systems and Information Science, Materials Science and Engineering, Architecture, Electrical Engineering, Mathematics, Economics, Sociology, Psychology, Medicine, Dwelling Environment 2.2 Life Sciences, Medical Science, Systems and Information Science, Health Economics, Medical and Hospital Management	
3	Advanced design and manufacturing with Digital Twins and Cyber Physical Systems in future industries	Systems and Information Science, Mechanical Engineering, Physical Engineering, Materials Science and Engineering, Chemical Engineering, Metallurgical Engineering, Fluid Dynamics, Electrical Engineering, Measurement Science	
4	Robotics as integration technology	Robotics and Control Engineering, Mechanical Engineering, Systems and Information Science, Measurement Science, Materials Science and Engineering, Psychology	
5	Data-driven innovations in Materials and Life Sciences	Systems and Information Science, Life Sciences, Materials Science, etc.	
6	Cutting-edge analytical instrumentation for deciphering biological phenomenon	Measurement and Analytical Science, Systems and Information Science, Life Sciences	
7	Bioproducts and Biosystems Engineering	Life Sciences, Systems and Information Science, Agriculture, Botany, Pharmacy, Materials Science	
8	Nexus approach for water, energy, and food security	Environmental Science, Energetics, Engineering, Agriculture, Ecology, Social Science, Law, Economics, Systems and Information Science	
9	Science and technology for sustainable use of critical resources and materials	Chemistry, Engineering, Agriculture, Environmental Science, Ecology, Materials Science	
10	Innovations in Separation Engineering: Separation science and technology for a sustainable society	Chemical Engineering, Metallurgical Engineering, Biotechnology, Mechanical Engineering, Fluid Dynamics, Energy Engineering	
11	Next-generation Biomaterials Engineering: Controlling interaction between materials and biological environment	Life Sciences, Medical Science/Clinical Medicine, Materials Science, Mechanical Engineering	
12	Structural reforms of research systems/ laboratories; nationwide research infrastructure/platform for promoting transdisciplinary research	Systems and Information Science, Robotics, Industrial Engineering	

For convenience's sake, the figure on the right shows the distribution and positional relationships among the 12 research themes presented in this report. It is necessary to understand that the data lacks a certain rigor because essentially the nature of transdisciplinary research fields is that "if this field is related to that field, then it must also be related to that field over there." For the sake of simplicity, the themes have been plotted in quadrants: on the horizontal axis, whether or not the content has a greater impact on nature/the environment or business or other artificial entities; and on the vertical axis, whether or not the content has a greater impact on industry or humans. As mentioned above, it is impossible to broadly classify types of transdisciplinary research fields, but the diagram provides one means of understanding the spread and variation among the research themes presented.

Of these 12 themes, the first 11 correspond to actual research themes, while the 12th theme examines aspects related to common foundations and mechanisms in research activities. For each item, the report lists points regarding integration/collaboration as well as issues and orientation.

CRDS has in the past conducted repeated deliberations related to this topic and has published several reports, but already ten years have passed since these past deliberations were carried out. Considering the changes that are currently occurring, both in Japan and overseas—global financial crises, expanding gap between wealth and poverty all over the world, the rise of giant IT platformers, increasingly frequent natural disasters—in a world that is changing more and more, becoming even more complex, it is our hope that both our deliberations this far and this report will provide helpful for considering transdisciplinary integration methodology while grasping concrete images.

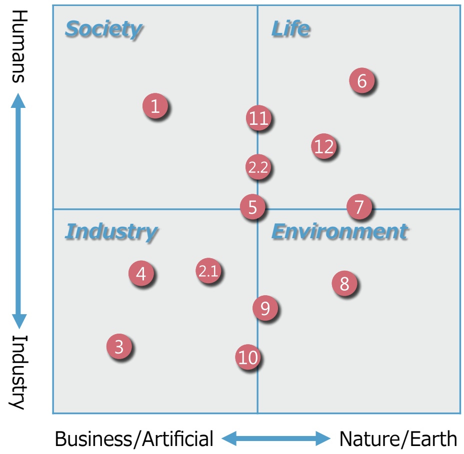


Fig. 1-2 Spread and distribution of presented themes

References

- Committee on Facilitating Interdisciplinary Research, Committee on Science, Engineering, and Public Policy. *Facilitating Interdisciplinary Research.* (Washington, DC: The National Academies Press, 2005)
- National Research Council. *Convergence: Facilitating Transdisciplinary Integration of Life Sciences, Physical Sciences, Engineering, and Beyond.* (Washington, DC: The National Academies Press, 2014)

2 12 transdisciplinary research themes

2.1 Information science and technology for decision-making in a complex society

(1) Overview

In modern society, which is becoming increasingly complex, realization of better mechanisms utilizing information science and technology to enable individuals and groups to make decisions autonomously and persuasively is required. Within human activity, decision-making is a fundamental action that can even influence survival, but as the social environment today grows increasingly complex, cases in which people face difficult decision-making situations and the risk of making mistakes in decision-making are increasing. One reason for this is related to the advancement of information science and technology. The information explosion and borderlessness of societies generate a multitude of possibilities for factors and effects related to decision-making that are so broad that it is impossible for humans to think about them in their heads. Moreover, it is becoming easier for information (media) manipulation with the intent to cause harm or incitement to influence the decision-making of others, with fake news spread via social media and behavior known as "digital gerrymandering" influencing public opinion formation and election results, creating a social problem.

In the process of spreading rapidly advancing technology throughout society, usefulness (the "bright side") is always accompanied by adverse effects (the "dark side"). The vision of society to which Japan aspires, Society 5.0[1], is supported by information science and technology, but it must not be forgotten that countermeasures to the "dark side" are necessary for achieving the healthy development of information science and technology. There is also a strong need for countermeasures to the problems mentioned above related to human decision-making, and as information science and technology, especially artificial intelligence (AI) technology, evolves, movements to create countermeasures are being formed through collaboration with humanities and social science. Another point to bear in mind is that enabling humans to make decisions autonomously and persuasively rather that leaving everything to AI will lead to the realization of a human-centered Society 5.0. Accordingly, current issues and solutions to reach for are shown in Fig. 2-1-1.

1 Society 5.0 is defined as a human-centered society that balances economic advancement with the resolution of social problems by a system that highly integrates cyberspace and physical space. It was proposed in the 5th Science and Technology Basic Plan as a future society that Japan should aspire to. It follows the hunting society (Society 1.0), agricultural society (Society 2.0), industrial society (Society 3.0), and information society (Society 4.0).

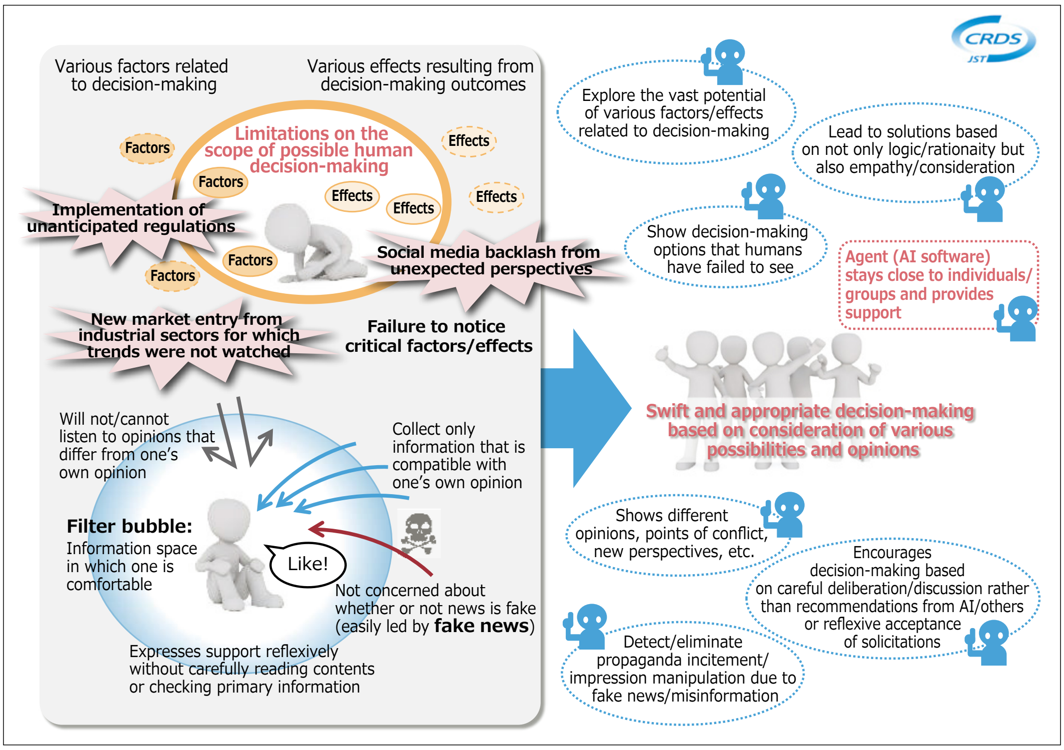


Fig. 2-1-1 Advancement of information science and technology and decision-making: current issues and solutions to reach for

(2) A transdisciplinary approach

We undertake decision-making in various situations on a daily basis. Mistakes in decision-making in critical situations worsen the status of the individual person or group and may even threaten their survival. For example, a decision-making mistake in corporate management may cause the company's performance and competitiveness to decline, and a decision-making mistake in national policy-making or social system design may lead to stagnation of the country's economy and a decline in citizens' living standards. Furthermore, insufficient judgement skill or deliberation in an individual person's decision-making may not only increase various risks in that person's life but also even influence the direction of society in the form of groupthink in public opinion formation and voting.

Such fundamental issues for individuals, organizations, and society in the decision-making of individual people and groups are issues that have long been studied mainly in the humanities and social science fields (for example, the research of Herbert A. Simon, a recipient of the Nobel Prize in Economics). Today, however, due to the advancement of information science and technology and increasing complexity of society as discussed in (1) above, it has become impossible to address these issues as integrated/transdisciplinary themes in the fields of information science and technology and humanities and social science.

From the perspective of information science and technology, the U.S. research and advisory firm Gartner, Inc. has categorized the development of problem-solving based on themes into four stages: (1) Descriptive Analytics (What happened?), (2) Diagnostic Analytics (Why did it happen?), (3) Predictive Analytics (What will happen?), and (4) Prescriptive Analytics (What should I do?). The fourth stage clearly pertains to decision-making, and Gartner, Inc. further divides the fourth stage into two types of prescriptive analytics: “Automatic decision-making” whereby a computer decides what should be done and automatically does it; and "Decision-making support" whereby a computer provide options and information pertaining to each option, and humans carry out the final decision-making and implementation. These categories are divided according to differences in the nature of issues. For reducing costs, increasing sales, shortening timescales, improving accuracy, and other cases in which the evaluation axis is clearly set, "Automatic decision-making" is possible if an optimal solution can be found within the evaluation axis and this solution is automatically selected. In contrast, in cases where no clear evaluation is set or the evaluation axis differs from person to person, "Decision-making support" whereby the final decision-making is left up to humans is the appropriate choice.

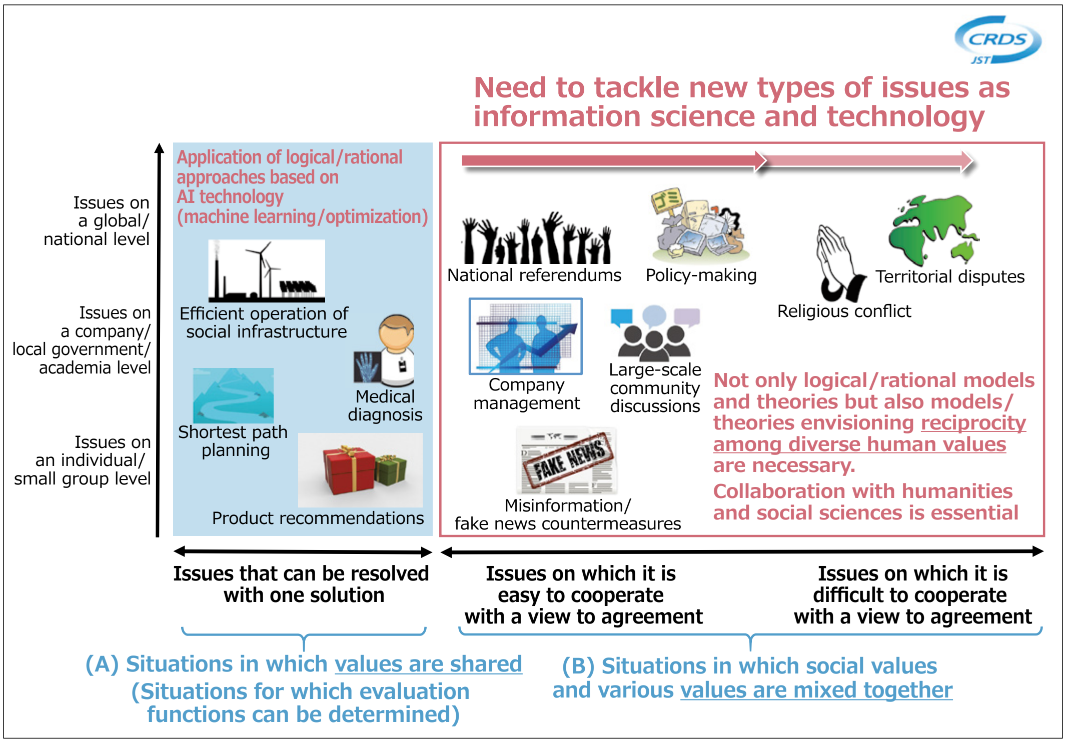


Fig. 2-1-2 Categorization of decision-making issues

Here the evaluation axis corresponds to human values related to decision-making. Categorization of decision-making issues from the perspective of human values related to decision-making is shown in Fig. 2-1-2. The (A) type issues are decision-making issues for which one solution can be selected in situations where values are shared. "Automatic decision-making" is possible for the (A) type decision-making issues, and currently it is mainly the (A) type issues for which the practical application of AI technology is being advanced. In contrast, the (B) type issues are decision-making issues in situations where social values and various human values are mixed together and for which "Decision-making support" is appropriate. The (B) type issues require not only AI logical/rational models and theories but also models/theories envisioning reciprocity (for example, empathy, consideration) among diverse human values. Accordingly, collaboration with humanities and social science is essential.

(3) Issues and directions

As discussed in (1) above, the problem of the increasing difficulty of decision-making (increased risk of decision-making mistakes occurring) is becoming more and more serious, and therefore to counter this there is a need for promoting R&D aimed at "realizing good mechanisms utilizing information science and technology that enable individuals and groups to make decisions autonomously and persuasively as modern society becomes increasingly complex".

Initiatives aimed at realizing this vision are shown in Fig. 2-1-3. The current issues and future visions are as discussed above, while the main causes that have generated the current issues, as mentioned in (1) above, are regarded as being the "exploding potential of various factors/effects related to decision-making" backed by the advancement of information science and technology (Cause 1) and "increasing ease of manipulating information (media) with the intent to cause harm or incitement to influence the decision-making of others" (Cause 2). Two R&D themes that have been identified for directly addressing these two causes are: "Technology to explore the vast potential of various factors/effects related to decision-making and quickly identify candidate solutions" and "Technology for countering information manipulation with the intent to cause harm or incitement (avoidance, increased enhanced resistance)".

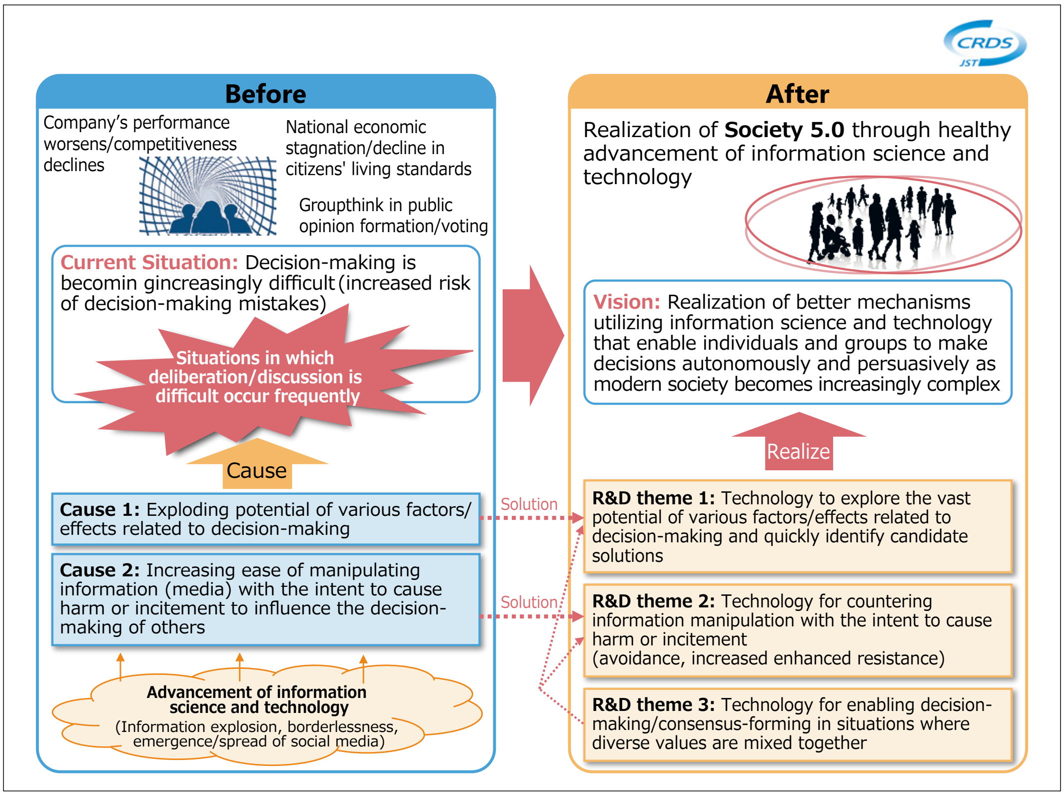


Fig. 2-1-3 Visions and R&D themes

Furthermore, a third research theme is also important for including the aspects mentioned in (2) and Fig. 2-1-2: "Technology for enabling decision-making/consensus-forming in situations where diverse values are mixed together".

Such social issue resolution cannot be achieved through the use of specific technological seeds; rather, it is necessary to promote "problem-solving-oriented fundamental research" whereby concurrent testing of multiple technological approaches is carried out to identify those that are suitable, with suitable technologies combined to create solution strategies. Naturally, such R&D falls under the scope of transdisciplinary research themes.

2.2 R&Ds for solving social issues by data science

Systems and information science is a general-purpose fundamental technology, and it produces various effects in diverse fields as well as accelerating innovation in different areas. It will improve social systems in terms of social infrastructure such as energy, traffic administration and civil services, and realize more efficient and higher value added industries. Moreover, not only is this technology an indispensable R&D tool in life sciences, nanotechnology, materials, and a range of other fields, but is also contributes to R&D activities in various forms as a driver generating new transdisciplinary research themes.

As computers have become smaller, lighter, and increasingly high performance, devices have become smarter and increasingly digitalized, and the spread of IoT has made collection and analysis of large quantities of data possible. Smart devices play the role of edge computing device while communicating with other smart devices connected to the Internet, making possible the creation of systems providing real-time control. There are also various types of systems that enable big data utilization methods to be viewed from a technological perspective. One of these is a large-scale knowledge-intensive system type that accumulates and structures large quantities of big data as knowledge and guides actions based on judgements and reasoning combining this knowledge. A representative example of this system type is IBM's Watson question-answering/decision-making system. In 2016 it was reported that when medical institution treatment methods were implemented based on WATSON diagnostic support results for patients whose recovery was poor, the patients' recovery improved.

Below we introduce two examples of R&D aimed at solving social issues by data science. The first of these is the "Future energy network using IoT", represented by electrical power, in which expectations are held for the real-time collection, utilization, and control of data through the penetration of IoT. The second example introduces "Promoting the Integration of Bio-Medical Things (IoBMT)" used in R&D on big data and AI. In addition to the examples presented here, acceleration of R&D as well as various transdisciplinary research aimed at resolving social issues are expanding and advancing at a rapid pace.

2.2.1 Future energy network using IoT

(1) Overview

An energy network such as an electrical power network is a system structured to supply energy from large centralized suppliers to multitudes of consumers. By implementing this system with the IoT, network devices and sensors can be connected over an information network to yield a variety of benefits. In particular, the following benefits are anticipated when utilizing the IoT in power networks that deliver energy in real-time.

- Improved efficiency and lower costs for balancing power supply and demand, known as grid management, through adjustments coordinated with demand-side energy equipment (demand response)
- Creation of entirely new businesses utilizing information acquired by correlating consumer data, and particularly data from the vast number of household devices

When envisioning power networks around the year 2050, one anticipates an enormous increase in distributed power generating systems for common households that include photovoltaic (PV) systems and fuel cells, as well as electric vehicles (EV) and other devices that utilize rechargeable batteries. This vision assumes not only that households currently only consuming electricity will be converted to producers that can also generate electricity, but also that a much larger number and more diverse variety of energy equipment than today will be present on networks of low-voltage (100/200 V) distribution systems. Future challenges are lowering cost, improving efficiency and enhancing robustness (avoiding power outages) for the entire network by coordinating energy equipment for households through utilization of the IoT, and developing a revolutionary, flexible network capable of producing new value; for example, creating new businesses, such as low-cost direct trading of surplus power from home PV systems to neighboring households (peer-to-peer transactions).

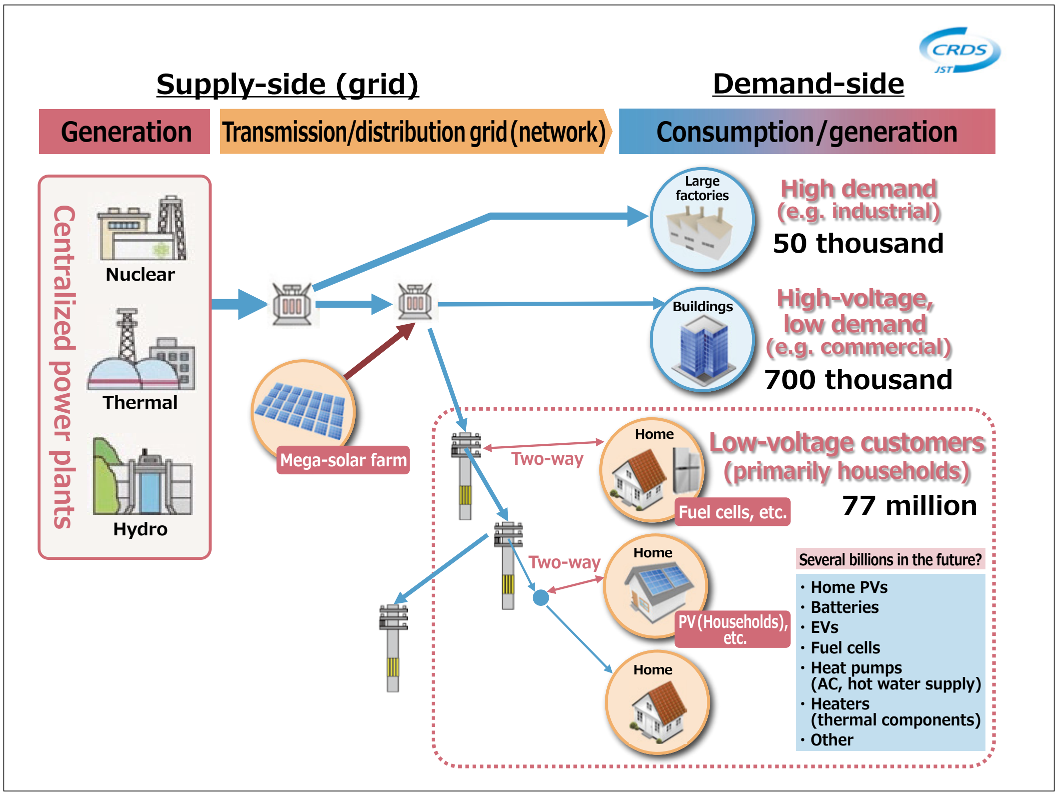


Fig. 2-2-1-1　Configuration of a power network

(2) A transdisciplinary approach

To avoid power outages, a power system must make adjustments (called "grid management") in near real-time in order to maintain the amount of consumed power (demand) equivalent to the amount of supplied power at all times. To perform this grid management, the network administrator (grid operator) traditionally has had to make a large investment to maintain the equipment and framework needed for continuously predicting power demand and adjusting power supply. The recent increase in distributed power generators, such as PV systems, is a significant factor in the increasing complexity of grid management. Consequently, a major challenge for the period around 2050 will be how to coordinate management and control of the diverse energy equipment present in households through a network, and particularly a low-voltage distributed network. It is important that such a network system be implemented by structuring the system in layers and conducting R&D at each layer. These may include a physical layer for controlling the actual equipment and power flow, a cyber layer that utilizes information represented in the IoT, and a service layer for constructing businesses and programs with incentives for coordinating the control of household appliances. R&D conducted on these layers must be transdisciplinary, involving not only information technology but also various other dissimilar fields such as systems engineering, materials science and technology, architecture, electrical engineering, mathematics, and economics. Further, energy demand is a derived demand and not a commodity for direct consumption like food. Electricity, for example, is consumed after being converted into another form such as light or information. Therefore, one must explore how human behavior is connected to energy use in order to extrapolate the essence of energy demand. For example, big data collected from smart meters detailing energy consumption at individual households would be analyzed to determine correlations with human behavior. Consequently, such analyses will require transdisciplinary collaboration among researchers in sociology, behavioral economics, psychology, medicine, and dwelling environment (Fig. 2-2-1-2).

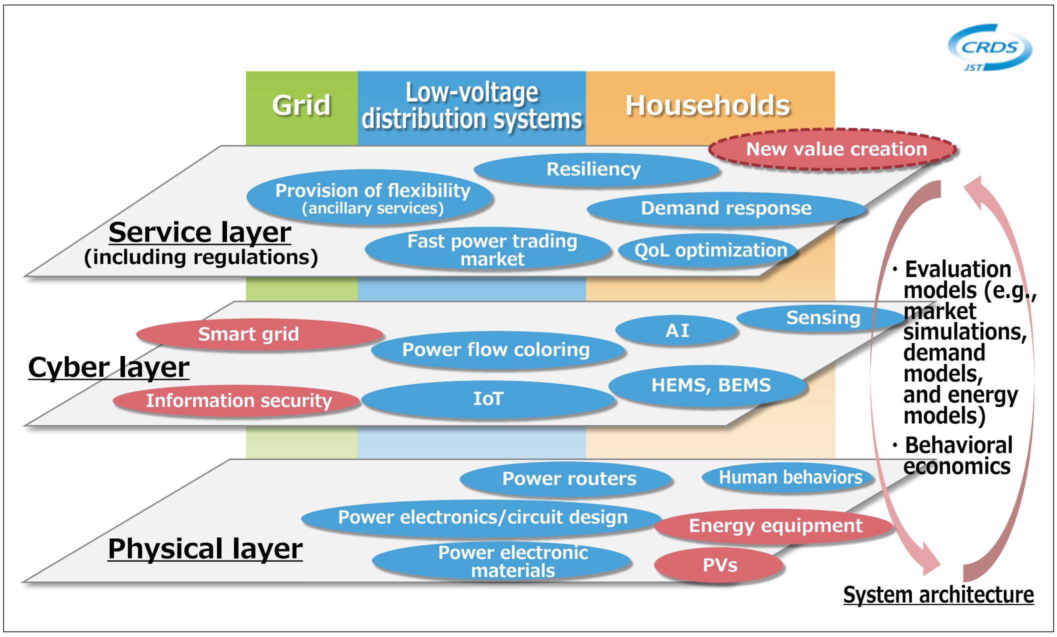


Fig. 2-2-1-2 R&D areas organized in three layers

(3) Issues and directions

R&D on future energy networks must go beyond various disciplinary boundaries. Here, the IoT will play a major role in ensuring that the individual parts function as a system. Patterns of power demand at ordinary households can be identified utilizing data obtained from individual households (e.g., data on power consumption received from smart meters). Analyses of these patterns can be used to take steps toward constructing efficient, inexpensive power networks with an autonomous distributed function, leading to more flexible and more robust networks that bring the promise of new value creation.

While today's power networks (with power flow control on the physical layer) have a centralized management framework for system operations, it will be vital to conduct strategic R&D that incorporates new ideas (autonomous distributed low-voltage distribution networks, for example) in order to enhance network flexibility. On the other hand, since power consumption activity at individual households is itself a matter of privacy—an issue shared with the IoT—addressing security related issues and how to protect people's privacy is also critical.

2.2.2 Promoting the integration of Bio-Medical Things (IoBMT)

(1) Overview

Owing to the emergence of next-generation DNA sequencers and other omics-related analyzers that followed the publication of an analysis on the entire human genome sequence around the beginning of the 21st century, we have recently seen a dramatic increase in the quantity of data produced from research in life sciences and medical science. This increase in data volume has prompted major changes in research methodologies. Whereas molecular biology and biochemical techniques have traditionally been the favored approach to studying the behavior of specific in vivo molecules, the analysis of enormous quantities of data (on genomes and the like) has become an important component of research in recent years. In addition to actively establishing platforms aimed at accelerating digitization in medical care, countries around the world are continuously preparing data collection platforms for the collection of large quantities of medical data (charts for hospital patients, etc.), which may be more aptly called "social measurements." Thus, we are seeing a worldwide trend to utilize these platforms for optimizing methods of allocating medical resources and providing medical care. In addition, we are beginning to see attempts to use routine data generated from technologies such as wearable devices for maintaining health and detecting early signs of diseases.

These developments suggest that one of the most important matters facing future research on life science and clinical medicine will be how to collect and analyze big data in life science and clinical medicine. However, unlike other countries that have quickly recognized the importance of this matter and changed course to adapt, Japan's response has been exceedingly slow.

To address this state of affairs, the CRDS has defined a new direction of R&D as the Integration of Bio-Medical Things (IoBMT) and is preparing a proposal for its implementation (scheduled for publication in 2018). IoBMT involves "the construction of an integrated data platform centered on the permanent and automatic collection and structuring of massive quantities of data related to life sciences and medical care, and the use of this platform to accelerate the structuring and integration of knowledge in data-driven life sciences, engineering, and medicine and the implementation of preemptive/precision medicine and suitable allocation of medical resources based on a social participation model."

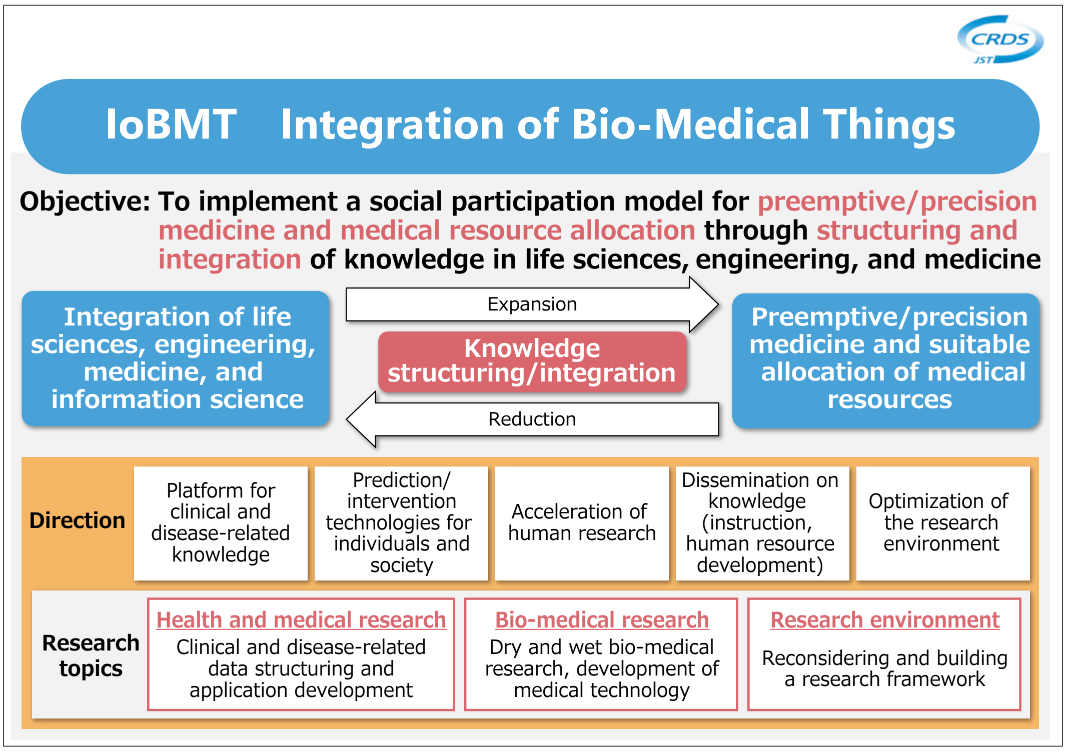


Fig. 2-2-2 Panoramic view of the IoBMT

(2) A transdisciplinary approach

The IoBMT is a concept that covers everything from basic life science research to the development of various applications related to health and medical care and decision support for medical administrations and includes numerous avenues for transdisciplinary research. Here, the types of data used in IoBMT can be broadly classified under life science and medical science data (genomic/experimental data, etc.) and health and medical care data (clinical data from hospitals, etc.), and each type of data comes with different issues that must be addressed.

While the former data type shares many data items with genomics and other omics, the research subjects and experiment conditions vary widely from researcher to researcher. Consequently, new value is not easily produced by integrating data from researchers around the world (or even domestically). Rather, getting researchers to work with a shared purpose by concurrently and strategically collecting specific data will likely be more valuable for the purposes of data utilization; for example, having researchers collect specific data items at the single-cell level for all of the cells in a human body (some 37 trillion) and storing these items in a database. While the attributes of the participants vary according to the target of data collection, transdisciplinary research among researchers in molecular biology and diseases and researchers proficient in data analysis for genomics and other omics have all common attributes.

For the latter data type, a lot of data from medical settings is collected as part of the administrative system. For example, prescriptions and other data already in a fixed format are generated every day at hospitals and clinics nationwide and stored in national and municipal databases. This data can be used in transdisciplinary research among researchers experienced in analyzing large quantities of data, and researchers capable of interpreting the analytical results to aid in the optimization of health care provision and decision support for medical administrations. However, so much of the data from medical settings is in an irregular format. The utilization of such data requires transdisciplinary research involving researchers proficient in natural language processing, medical ontology, and sensor technology, for example.

Making IoBMT a reality will not just require the establishment of research themes, but also the optimization of a framework for research organizations and institutes. Promoting more collaboration among, or the integration of, different research organizations and institutes will lead to great progress in transdisciplinary research.

(3) Issues and directions

While there may be a wide variety of research topics that should be pursued under IoBMT, the following two topics may be of particular importance.

- Structuring data in health and medical care and expanding applications: While the utilization of health and medical care data has been promoted recently in Japan and overseas, the results have been limited as actual analysis of the data has not been as easy as initially expected. The root of the problem is thought to lie in the quality of the data, yet there exists high quality medical data (case data, clinical guidelines, etc.) in Japan that remains unutilized. By analyzing big data while performing preprocesses on this medical data, we can produce new value (medical examination and diagnosis support systems, instructional systems, etc.) that is not possible using traditional medical data analyses. To this end, it is critical to develop required technologies, establish an analysis platform, and construct a durable data collection system.

- Reconsidering and building a research framework: Rather than being satisfied simply to conduct studies on the latest trending research topics, we must make the analysis of health and medical care data a source of vitality for medicine and medical care research in Japan. Therefore, we need to establish an institution for addressing this issue over the medium and long term, and we must also conduct extensive reviews of existing hospitals and research institutes.

2.3 Advanced design and manufacturing with Digital Twins and Cyber Physical Systems in future industries

(1) Overview

Digital twins are one form of cyber-physical systems that have been gaining attention in recent years as a core technology for driving the digitization of manufacturing. A digital twin is an advanced simulation technology that virtually replicates a physical product in cyberspace based on digital data and that predicts events that will occur in the future in this virtual, digital world (Fig. 2-3-1). This technology is expected to provide high added value throughout the entire value chain of a product or service. Digital twins will be useful in the development, design, manufacture, and maintenance (life prediction) of equipment and services related to transportation, energy, and the environment, as well as their improved productivity and quality, contributing to the realization of Society 5.0 and a low-carbon society. The development and application of digital twins has attracted much attention because the essence of the digital twin lies in the development and validation of complex event models (e.g., process models for mechanical damage) that intersect such technical fields as manufacturing, materials, structure and strength, machinery, combustion, heat transfer, fluids, vibrations, chemistry and electricity. However, we have been unable to create the advanced energy and environment related equipment and services we seek because the physical/chemical phenomena such as fractures that form the basis of modeling have not been fully clarified. By integrating various fundamental technologies based on the identification and understanding of these phenomena, we hope to develop and validate models after clarifying their basic principles, and develop efficient calculation techniques, and construct a knowledge platform from basic scientific research. The utilization of these achievements is expected to lead to the development of advanced equipment and services that will contribute to a low-carbon society.

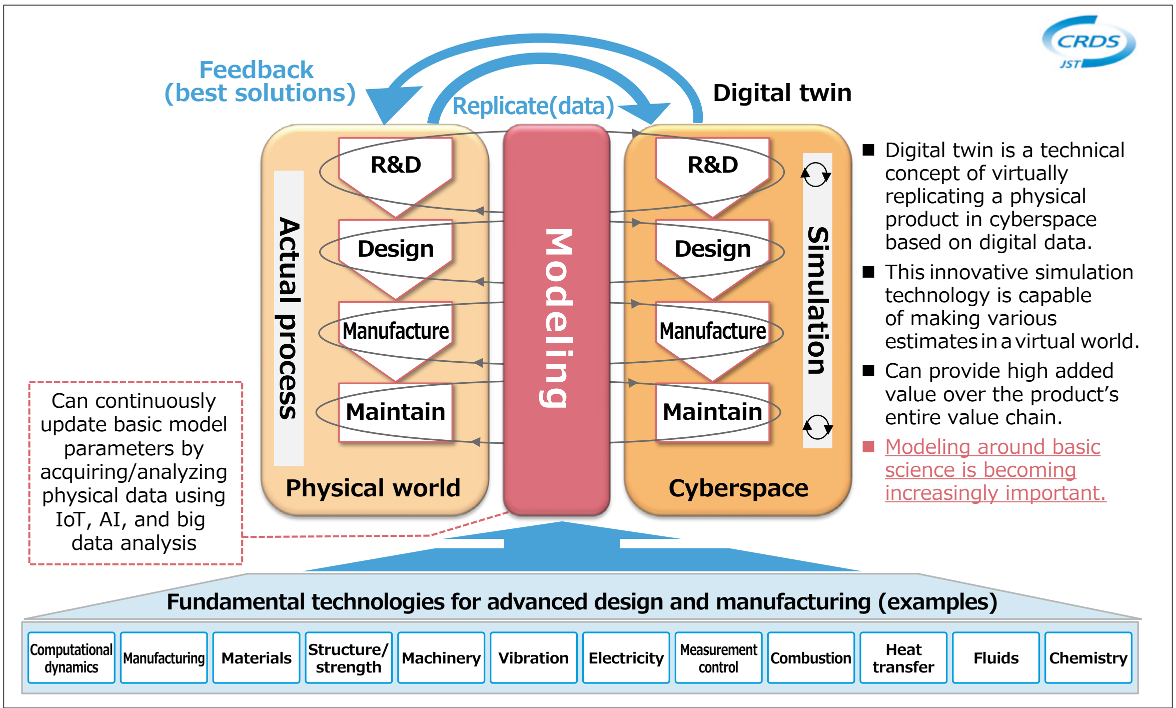


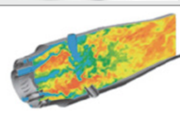
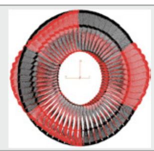
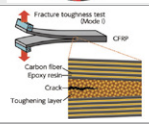
Fig. 2-3-1 Digital twins and fundamental technologies that support transdisciplinary modeling of complex events

With Japan's decreasing numbers of engineering experts, who are responsible for these fundamental technologies of manufacturing, there is concern that Japan has been declining relative to other countries regarding its research capabilities.

(2) A transdisciplinary approach

As described above, the key to digital twins is the elucidation and modeling of unexplained complex phenomena involving such varied fields as materials, structure and strength, machinery, combustion, fluids, and vibrations, and the differentiation of these models is a source of competitive strength. Table 2-3-1 shows examples of unexplained transdisciplinary complex phenomena, which form the basis of modeling. For example, in order to make progress in the elucidation and modeling of such unexplained complex phenomena as (I) mechanisms of damage and crack growth in mechanical elements, and (II) mechanisms of interaction between elementary combustion reactions caused by rapid transient phenomena and turbulent flows and heat transfer, a transdisciplinary approach will be required in (I) to integrate not just expertise in structure and strength and materials, but also expertise in other technical fields including manufacturing, machinery, vibrations, and fluids, and in (II) to integrate not just expertise in combustion, but also expertise in other technical fields including heat transfer, fluids, vibrations, chemistry, and electricity. Formulating next generation design and manufacturing technologies utilizing digital twins will require engineering experts that can combine their knowledge to go beyond fundamental technologies of manufacturing.

Table 2-3-1 Unexplained transdisciplinary complex phenomena forming the basis of modeling

Technical field	Unexplained physical and chemical phenomena (examples)	Reference drawing
Machinery (mechanical components/ tribology) and structural strength	• Processes of crack propagation in damage mechanisms of mechanical components, such as rolling bearings • Mechanisms of interaction such as lubricant film flows, structure movement, and surface deformation	
Combustion and fluids	• Mechanisms of interaction between turbulent flows and elementary reactions required for gas combustion control and aerodynamic control in response to rapid transient phenomena	
Fluids, structures, and vibrations	• Mechanisms of fluid-structure-sound interactions in rotating machinery and transportation equipment • Mechanism of self-excited vibration in complex fluid-related vibration phenomena	
Structural strength, materials, and fluids	• Processes of crack propagation in carbon fiber reinforced polymers (CRFP) immersed in fluid	

Source: JTEKT, Mitsubishi Heavy Industries , Faculty of Science and Technology at Ryukoku University, and JST

(3) Issues and directions

In order for Japan to retain its status as a nation of manufacturing by maintaining its strengths in creating highly reliably products and services unparalleled by other countries, it is essential that Japan continue to cultivate and maintain its core technologies in design and manufacturing. There is increasing concern that Japan's research foundation is weakening in engineering fields that support the manufacturing industry. A transdisciplinary approach involving the collaboration of industry, academia, and government is needed to solve the problems confronting industry and academia.

While efforts necessary for constructing digital twins for manufacturing are wide-ranging, it is hoped that the following three specific measures will be addressed in view of the importance of developing and validating complex event models.

(i) Developing and validating complex event models after clarifying their basic principles, developing efficient techniques for model calculations, and developing and standardizing methods of evaluating constructed models by integrating various fundamental technologies and going beyond disciplines

(ii) Constructing a knowledge base from basic scientific research that is instrumental in (i) (identifying and understanding physical/chemical phenomena, establishing the underlying constitutive equations, acquiring and accumulating evaluation data, etc.)

(iii) Developing human resources capable of understanding the basic principles of engineering, which supports the manufacturing industry, and human resources capable of manufacturing based on scientific rationale, utilizing (ii)

It is useful to select equipment or service areas related to transportation, energy, and the environment as target product categories or areas, owing to their highly challenging manufacturing technologies, long development periods, and high costs (Fig. 2-3-2). The use of a digital twin is expected to have a great effect in these areas and to play a role in future international market gains and Japan's contribution toward a low-carbon society. A digital twin is anticipated to be required output for the development, design, and manufacture or maintenance (life prediction) of environment/energy equipment and transportation equipment such as wind, gas, and steam turbines; automobiles; machine tools; and marine shipping.

Table 2-3-2 shows specific R&D issues aimed at achieving a unified implementation of measures (i) through (iii) described above. These R&D issues are thought to be bottlenecks common to products of different types. The objectives of addressing these issues are to elucidate the related physical and chemical mechanisms, establish constitutive model equations, develop and experimentally validate complex event models, and develop and standardize methods of evaluating models to create a dynamic foundation for establishing digital twin technologies. Naturally, after addressing these common issues, the next challenge will be the R&D required for developing these technologies to be used with the individual products mentioned above. The following are key elements in the issues common to many products.

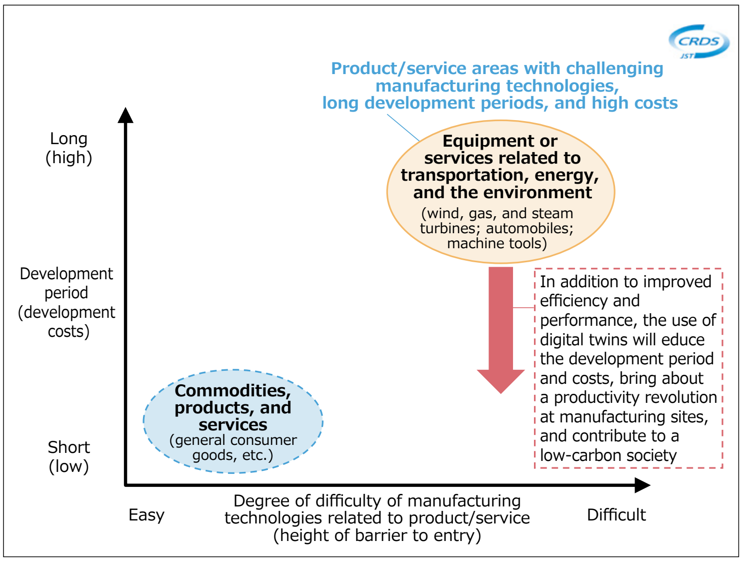


Fig. 2-3-2 Target product categories/areas in R&D issues on digital twins

Table 2-3-2 Specific R&D issues

R&D Issues	Target products for digital twins (examples)					
	Wind turbine	Gas turbine	Steam turbine	Automobile	Machine tool	Marine vessels
a Construct and validate process models for mechanical damage	○	○	○	○	○	○
b Construct and validate tribological models	○	○	○	○	○	○
c Construct and validate coupled models for fluids, structures, and vibrations	○	○	○	○	○	○
d Construct and validate coupled models for fluids, heat transfer, combustion, and chemistry		○	○	○	○	○
e Construct and validate a model integrating elements a–d (digital twin)	○	○	○	○	○	○

a Construct and validate process models for mechanical damage (elucidate damage mechanisms and crack propagation in mechanical elements including composite materials, etc.)

b Construct and validate tribological models (elucidate interaction mechanisms among lubricant film flow and surface deformation for sliding surfaces of rotating machinery, etc.)

c Construct and validate coupled models for fluids, structures, and vibrations (elucidate interaction mechanisms among fluids, structures, and acoustics in rotating machinery and transportation equipment, etc.)

d Construct and validate coupled models for fluids, heat transfer, combustion, and chemistry (elucidate interaction mechanisms among elementary combustion reactions and turbulence in rapid transient phenomena and heat transfer, etc.)

e Construct and validate a model integrating elements a–d (digital twin) (expand research to the target products mentioned above, develop and validate high-speed coupled analytical models for governing equations of complex events related to the motion, structural deformation, vibration, tribology, fluids, heat transfer, combustion, chemistry, and electromagnetism of mechanical elements, etc.)

Lastly, a system based on a network approach to promoting collaboration among industry, government, and academia (a consortium) must be appropriately constructed in order to effectively implement measures (i) through (iii) described above and to outshine the rest of the world in R&D on digital twin technology and the fundamental technologies for advanced design and manufacturing that support this technology. This will require comprehensive R&D covering everything from basic research to social implementation. At the same time, it will be crucial to work steadily at creating a collaborative platform for data sharing, and to develop human resources and exit strategies for international standardization and deregulation, for example.

2.4 Robotics as integration technology

(1) Overview

Robotics is a transdisciplinary field that will contribute to the formation of a new social system capable of ensuring safety, comfort, and quality of life through the realization of highly autonomous machines and close interaction between machines and humans. Robotics can be viewed as a compilation of engineering technologies. In the panoramic view shown in Fig. 2-4-1, robotics is organized into a three-tiered structure. The fundamental technologies tier is composed of materials, power, and sensors used to form robots as machines, as well as communication and information processing, and artificial intelligence (AI). In the functional component and integration technology tier, the fundamental technologies are reorganized into functional units, above which are established system configuration and integration technologies for constructing robots out of these functional units. In the uppermost tier called application areas, various robots that are active in society have been sorted into such categories as mobility/field, aerial, personal care and service, medical, and industrial/research. In addition, an area common to all categories of robots that has been designated “robotics and society” is the study of controversial issues related to the manifestation of robots as members of a social system, and their interaction with society to ensure our safety, comfort, and quality of life.

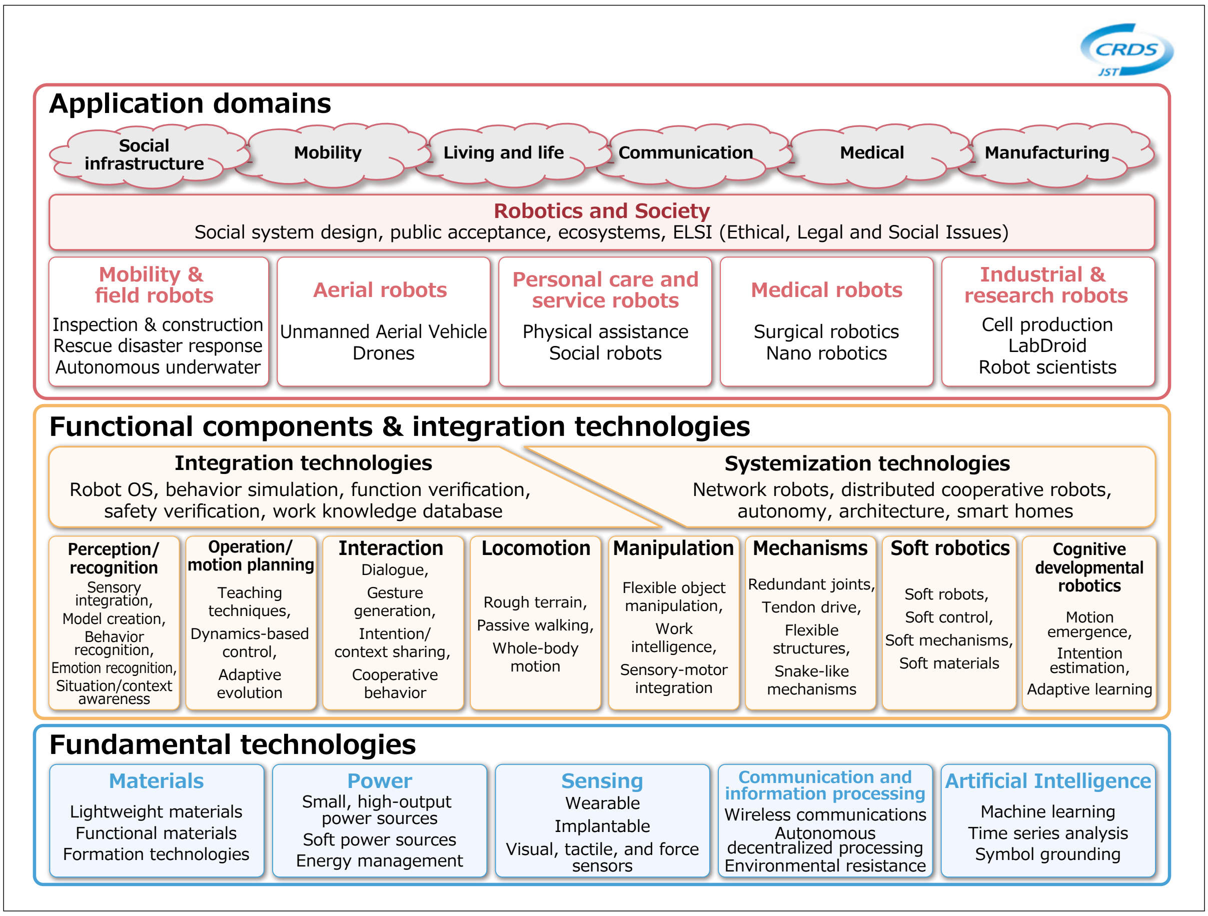


Fig. 2-4-1 Panoramic view of robotics

From the Panoramic View of the Systems and Information Science and Technology Field (2017) in the CRDS Panoramic View Reports

(2) A transdisciplinary approach

Robotics could be considered a technology of system configuration since robots are configured through the integration of such intellectual processes as recognition, judgment, planning, and action; the integration of such components as mechanisms, sensors, actuators, electronic circuits, computers, power supplies, wiring, exteriors, and software; and the further integration of such functions as locomotion, manipulation, dialogue, and user interfaces.

A strategic proposal published by CRDS entitled "Innovations of Basic Technology for Robots through Integration of Nanotechnology, Information Technology, and Mechanics" (2016) lays out the relationships of engineering fields that are closely related to three core elements of robots (see Fig. 2-4-2) and proposes the formation of new communities through collaboration across fields, as described below.

In order to promote the development of new underlying and fundamental technologies, collaboration among not just those researchers involved in robotics, but also researchers and technicians in information communication technology, nanotechnology and materials, and other dissimilar fields is essential. It will be crucial to establish common meeting grounds for researchers and technicians of robotics, ICT, nanotechnology and materials, and other fields within societies differentiated by specialty for the purpose of meeting and discussing underlying and basic technologies, as well as functional modules and systems.

Such efforts will be important in firmly establishing analytical sciences, as well as system integration and design sciences. To this end, we must find novelty and originality in the background and concepts of system integration and share a culture among academia and industry for properly assessing whether those ideas can contribute to the implementation of system integration.

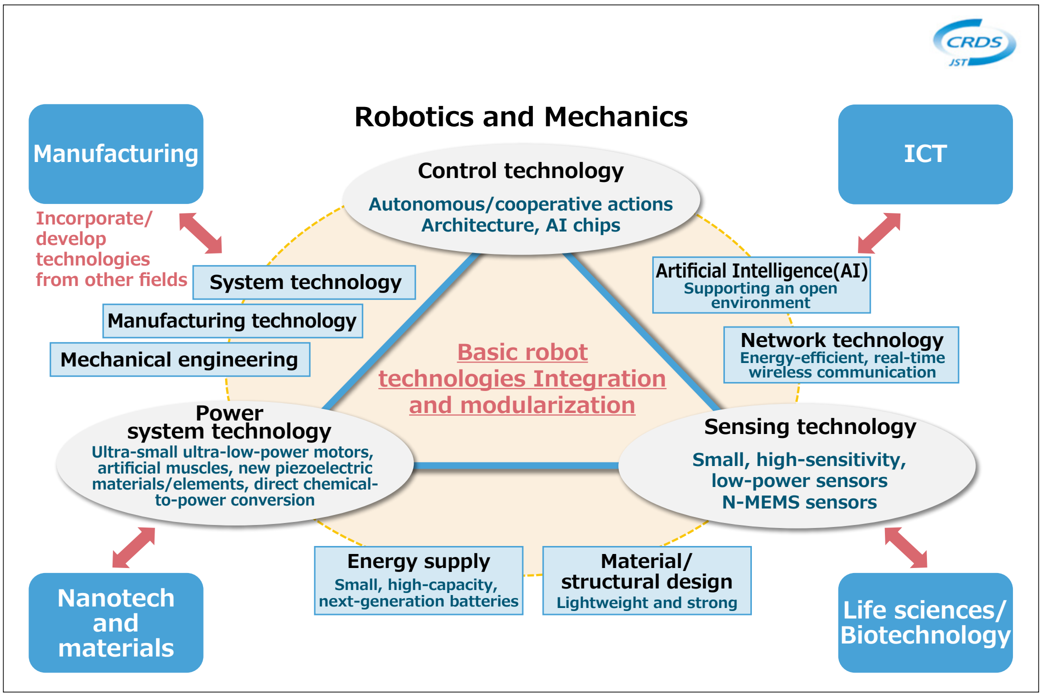


Fig. 2-4-2 Engineering fields closely related to the three core elements of robots
From the CRDS Strategic Proposal "Innovations of Basic Technology for Robots through Integration of Nanotechnology, Information Technology, and Mechanics"

(3) Issues and directions

The following transdisciplinary research topics address some issues to be resolved in robotics and the desired direction for robotics research.

(i) Community co-creation robotics

R&D must be conducted through the redesigning of social systems in which existing functions are not simply replaced with robotics, by promoting a plan for accelerating developments in system technology while refining the underlying technologies of robotics, a system design for maximizing benefit while mitigating the risks that accompany introduction of the system in society, and social implementation that includes constructing an ecosystem to implement a business cycle for accelerating permeation through society. For example, the 22nd term of the Science Council of Japan mentions "a recommendation regarding use of robots to resolve societal issues and policy measures for integrating advanced research needed to support these solutions: community co-creation robotics" indicating the need to promptly establish and implement community co-creation robotics, an open innovation framework that brings together end-users, researchers and suppliers, in order to bring about social reform and find solutions to societal problems through robot utilization.

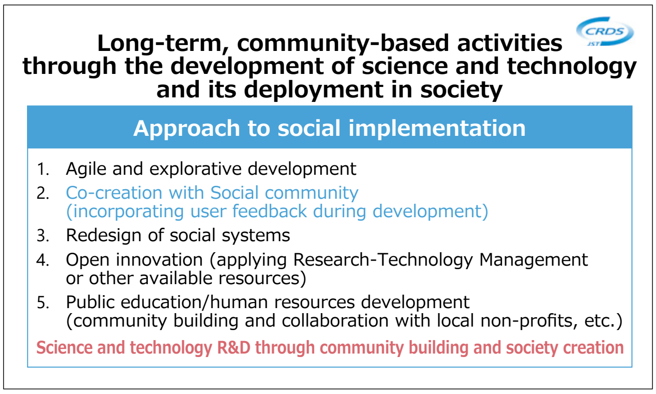


Fig. 2-4-3 Robotics as integration

(ii) New expertise and new technology creation

One of the new technologies of particular note is soft robotics. While robots have traditionally possessed highly rigid mechanisms and joints in order to perform operations with high precision, soft robotics is a new field that uses soft materials to create novel functions and models behavior after systems and processes found in living organisms. Robot "intelligence" is also attracting attention. Developments in AI technology, such as deep learning, have been trending globally in recent years, with many companies participating in addition to universities and research institutes. We have also seen advances in research on brain-machine interfaces aimed at building systems that operate through direct links between the human mind and machines. This technology is expected to enable humans to transmit intentions (commands) to robots and to receive responses without the use of voice commands or remote control operations. There have also been efforts to link subdural electrodes embedded in the brain with robot systems for medical applications.

(iii) Integrating funding and platform provision with R&D competitions

In addition to traditional funding for research themes, integrating R&D in a contest format with funding and platform provision, as with the disaster robotics challenge, provides essential opportunities for validating technologies developed in such research. Repeating a short cycle of preparation and implementation every 1–2 years will invigorate the research community and accelerate research progress. In addition, open source utilization is becoming a foundation for robotics research, and the software used in this research also becomes more refined and capable of withstanding use as numerous research groups utilize the same robot platforms to tackle the same issues.

2.5 Data-driven innovations in Materials and Life Sciences

(1) Overview

With the age of big data upon us, Internet-connected devices are expected to exceed 50 billion in 2020, with a trillion sensors blanketing the world. Consequently, the digital data generated by humans will increase exponentially and is expected to reach 44 ZB by 2020. Throughout the world, moves have been made to analyze this big data using artificial intelligence (AI) in an effort to benefit business, because in these times it is said that whoever controls data controls business. Owing to the continuous evolution of data analysis techniques such as deep learning, a core technology of AI, we are seeing a surge in new R&D employing big data and AI in academia. In the diversified and complicated society, there is heightened demand to accelerate R&D while reducing costs. At the same time, it is no longer easy to continue discovering and producing new knowledge and new materials solely through the intuition and experience of researchers. For this reason, novel research approaches, such as data-driven R&D, are drawing attention.

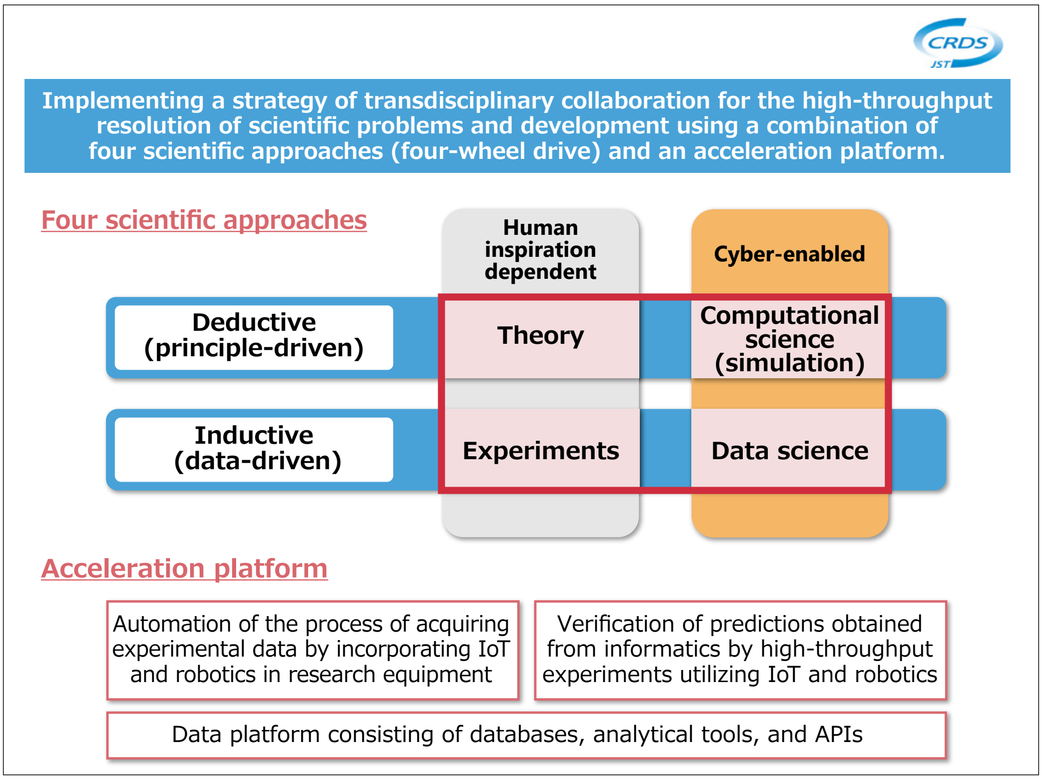


Fig. 2-5 Conceptual view of data-driven R&D

This section will address data-driven R&D in the field of life science and the field of materials science as examples and give a brief description of the present situation, challenges, and future direction of this R&D, including overseas trends.

a. Life science field

Owing to the advent of next-generation DNA sequencers (NGS) and improvements in their performance, genomic information can now be acquired more quickly and cheaply. This has had the effect of abruptly increasing the importance of bioinformatics, a general term for the discipline and technology to analyze biological data using information science techniques. Many studies in this area started primarily in the United States with the creation of the Precision Medicine Initiative in 2015 and the Cancer Moonshot Initiative in 2016, and have grown increasingly popular throughout the world under such terms as personalized/stratified medicine, genomic medicine, and precision medicine. It is hoped that analyzing enormous quantities of human genome information will clarify relationships among diseases and genetic factors. Another important area is AI-driven drug discovery, which is aimed at revealing previously unknown correlations among genes, diseases, drug targets molecules (proteins), and drugs (molecules). We are also seeing the beginnings of diagnostic imaging support that applies AI to medical imaging. From the perspective of basic research, various omics and omes studies are also required to derive relationships in large quantities of data produced from various instruments.

b. Materials science field

Led by the U.S. announcement of its Materials Genome Initiative (MGI) in 2011, materials informatics (a novel R&D technology combining data science with materials science) has become widely popular worldwide. The objective of materials informatics is to accelerate the discovery of new materials by using statistical methods to massive amounts of material-related knowledge and data acquired through experiments and calculations.

(2) A transdisciplinary approach

Research in both the life science and materials science fields had been carried out under the leadership of theorists and experimentalists through the 20th century. In the researchers' work of hypotheses and verifications, developments were made in not only science and technology but also industry through serendipity owing to the experience and intuition of the researchers. During the digital age that began in the 21st century, advances in analysis, prediction, and design are likely due to computational science, data science, and IoT-driven automation.

The field of life science has grown into a big science (a shift in emphasis toward the interpretation of large quantities of data) owing to advances in NGS and imaging equipment. This signifies that the computer science aspect of the field has grown gradually, and the trend is expected to continue. The interplay between experiments and calculations continued in the field of materials science up until about 2010, but since 2012 the presence of computers has grown continually year after year, with the utilization of data sciences.

Furthermore, as the abilities of researchers have increased in countries and regions conventionally known as emerging nations owing to globalization, competition to reduce costs and increase speed has been intensifying. Developments in data-driven R&D are expected to reduce the required quantity of experiments and costs and greatly shorten development time. The current status of both fields will be described below.

a. Life science field

In the Human Genome Project led by the United States in the 1990s, about 3 billion U.S. dollars were invested up until 2003 when mapping of the human genome was completed. Until just a few years ago, sequencing of the human genome cost hundreds of thousands of yen and took approximately one week, but lately the same process can be accomplished in a few hours for tens of thousands of yen. It is likely that this trend of shorter times and lower costs will continue (it has been said that the age of 20-dollar genomes will arrive in 2020). These advances have brought us into an age of genomic medicine, an area integrating medical care with research.

Since the birth of deep learning technology in 2012, techniques in machine learning have improved every year, reviving research into the use of AI in drug discovery and diagnosis. These past few years major pharmaceutical companies have been investing on a large scale in AI drug discovery startups. In addition, while many countries continue to make advances in the use of image analysis for the pathological analysis of diseases, in April 2018 the U.S. Food and Drug Administration (FDA) approved the first AI-enabled device for detecting diabetic retinopathy as a medical instrument. The establishment of an environment to be shared by a large number of medical institutes is expected by around 2020. We have also seen continued developments in technologies that support refined pathological diagnoses, such as medical chart analyses, based on techniques including the semantic analysis of Japanese using AI. We anticipate that AI will also be applied to health care services (supporting the prediction and prevention of pre-symptomatic, lifestyle-related diseases) and the prediction of infectious diseases in the future. The Japan Agency for Medical Research and Development (AMED) is also engaged in genomic medicine and AI diagnostic imaging.

b. Materials science field

Global trends in R&D have been observed in inorganic materials such as battery materials, for example, organic materials used in organic electronics, and structural materials such as steel materials. Aspects observed in this research include (1) exploration of new materials, (2) understanding of correlations between microstructures and materials properties, (3) multiscale analysis from crystal structures to materials structures, and (4) measurement informatics.

In Japan, integrated R&D on (1)-(4) described above and including the creation of databases has been carried out in “materials integration,” one of the R&D topics in “Structural Materials for Innovation” of the Cross-ministerial Strategic Innovation Promotion Program (SIP) promoted by the Cabinet Office; the Materials Research by Information Integration Initiative (MI^{2}I), part of JST's program for constructing innovation hubs; “materials informatics” under the JST PRESTO program; “intelligent measurement analysis” under JST CREST and PRESTO; “revolutionary materials development” under JST CREST; and the “Ultra High-Throughput Design and Prototyping Technology for Ultra Advanced Materials Development Project” under NEDO and so on.

(3) Issues and directions

a. Human resource development (educational reform)

In order for Japan to lead the world in data-driven R&D, it will be imperative to establish a transdisciplinary approach for data sciences and natural sciences and to cultivate human resources capable of bridging these fields. For this purpose, it will be important to establish opportunities for researchers and technicians in dissimilar fields to conduct collaborative research, and to create an environment for studying both fields. It is essential to create an environment in which natural science researchers, who possess most of the experimental and computational data, and data science researchers, who are familiar with various techniques for data analysis, can work together toward the discovery of new knowledge and new materials while complementing each other's knowledge, experience, and skills so that these researchers can collaborate with a shared sense of purpose while going independently beyond disciplines.

b. Accumulation (sharing) of large-volume, high-quality data

Important issues in data-driven R&D common to both the life science field and the materials science field are how to maintain enormous quantities of data and guarantee the quality of the accumulated data. In other words, data of poor quality yields poor results, regardless of how excellent the data analysis techniques. Effective utilization of data science techniques for discovering new knowledge from various data will require the application of interpretation information known as annotation.

Cells and other elements of living organisms change constantly in response to the ambient environment, necessitating the standardization of sampling methods for each purpose. In structural materials, many structures and structural factors are related on every scale, such as the density and distribution of dislocations and other defects and the structures of grain boundaries and interfaces on the nanoscale; the size and shape of crystal grains and the distribution of stress and strain on the microscale; and defects and residual stress on the macroscale. However, this has given rise to an increasing number of issues, such as how and in what format this data should be compiled into a database and how the data should be annotated, since these factors can vary according to the process conditions in manufacturing and machining.

It is conceivable that we will create an environment in the future in which data for a desired purpose can be acquired on demand. To achieve this, the automation of R&D processes utilizing robots must be studied. A report published by the U.S. Department of Energy even alludes to studying the construction of a sample-centric research environment consisting mainly of conventional measuring instruments in which data can easily be acquired from a single sample using multimodal instrumentation. In other words, this approach considers drawing on IoT and robotics to utilize big data and AI.

c. Deriving cause-and-effect from correlations (candidate materials)

In the discovery of new materials using data science techniques, correlations and candidate materials are obtained, which often can yield several hundred or more units. In actuality, the causes and effects abstracted from correlations are validated through experiments. The limiting factor is expected to be the experimental processes, such as synthesis and validation using animal models. High-throughput experimental techniques should be established for abstracting cause-and-effect from correlations, such as a prediction technique for a synthesis process performed to create candidate materials and a technique for knocking out candidate genes from animal models.

2.6 Cutting-edge analytical instrumentation for deciphering biological phenomenon

(1) Overview

With the attribution of advances in next generation sequencing (NGS) and mass spectrometry (MS), life science research has recently opened a new door to the so-called "era of Big Data", where researchers investigate vast amount of omics data, such as genomes, transcriptomes, proteomes, and metabolomes, and a number of high resolution image data acquired from high precision imaging instruments i.e. cryo-electron microscopy (cryo-EM) and super-resolution microscopy. Conventional biological research has tended to have a reductionism aspect, focusing on individual factors; whilst macroscopic analyses of complex systems are increasingly becoming important in today's life science research.

We have identified the following three trends in the recent technological innovations in life science: (1) precision and high resolution technologies; technologies for the precise observation of life with high resolution in a spatial and temporal manner, (2) diverse and complex technologies; technologies which are applicable for various organisms, not only for model organisms, and can analyse a wide range of biological events from molecules to whole-body complex system, (3) systematic and integration technologies; technologies to integrate and analyse big data with the intent of projecting future prospects individually. The big data analysis of life science as described above is indeed an integrated multi-disciplinary and cross-disciplinary research requiring proficiency in data science and mathematical science, along with expertise in biology.

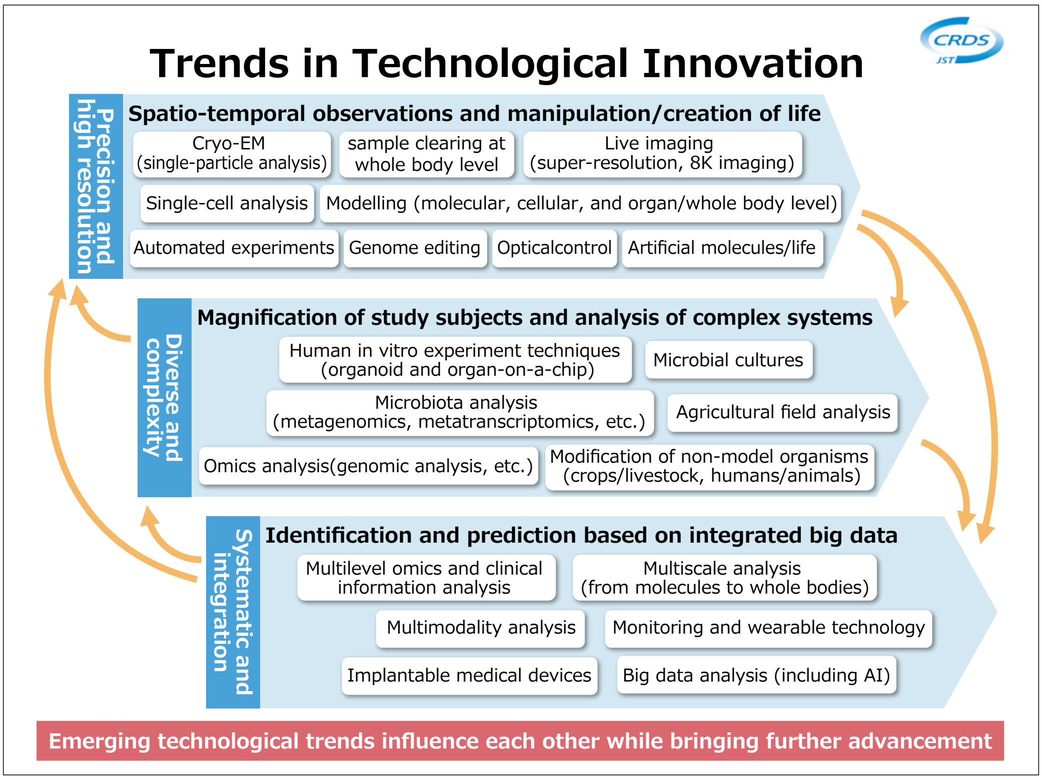


Fig. 2-6 Trends in Technological Innovation

As life science is becoming more and more inter/cross-disciplinary, technology development of measuring/analytical instruments is also becoming inter/cross-disciplinary. The history of the technological advancement of DNA sequencing is a good example to show how a series of new technologies, which are originated from various disciplines, are integrated into an analytical technology. The conventional electrophoresis-type DNA sequencing, which handles a chain of DNA molecule as a physicochemical polymer, is developed based on the integration of physicochemical and engineering technologies, rather than being based on biological knowledge. The development of the third generation DNA sequencing, which is capable of reading a long chain DNA sequence, was achieved through the integration of at least four disciplines: the technologies which enable the construction of nanopores with high-precision and high density; engineering techniques utilized to detect and analyse the infinitesimal electronic signals; expertise in molecular biology that enables the handling of proteins, and finally, the data-science/informatics that analyse the sequenced data. The technological advancement of cryo and super-high resolution microscopy can be categorised into the above mentioned (1) precision and high resolution -type advancement and is also a good example of the integration of multidisciplinary technologies. The development of cryo-EM has required the integration and coordination of the following three disciplines, namely: engineering (sensor technology), image analysis technology (single-particle analysis), and biology (the preparation of biomolecules). In addition to optics and image analysis, molecular biological techniques such as utilisation of fluorescent proteins have been integrated and coordinated into the development of super-high resolution microscopy, achieving extremely high resolution which is beyond the optical diffraction limit.

(2) A transdisciplinary approach

One good example of the recent trends in technological advancement, (1) the precision and high resolution technologies mentioned above, is the development of cryo-EM. Samples such as purified proteins were embedded in non-crystalline ice in a dispersed manner in the expectation that the samples would face various direction, and their three-dimensional structure were analysed by the cryo-EM, which employs the calculation method called single-particle reconstruction, resulting in the acquisition of three-dimensional structure of the sample with hitherto unknown super-high resolution. Such breakthroughs have been facilitated by three innovative technologies: namely, sensor technology, robotics, and software technology. First, the complementary metal-oxide semiconductor (CMOS) which can directly detect electrons works as a highly sensitive sensor in the camera system. As the scanning speed of the CMOS camera is remarkably faster than conventional charge coupled device (CCD) cameras, it allows the direct count of the number of incident electrons. Second, robotics offers automatic sample exchange. Third, the image analysis software, Relion, which is employed in the cryo-EM system provides the single-particle analysis, carrying Bayesian statistics element in the algorithm that takes into account the non-uniformity of the particle structure. The introduction of such software has greatly shortened the time required to acquire structural images with a near-atomic resolution. Biological knowledge is crucial for working with samples to be analysed under cryo-EM, since the biomolecules and particles have to be monodispersed in the non-crystalline ice. Furthermore, the technological advancement both in software and hardware has been necessary to handle huge amounts of data, for transferring, processing, and storing, as the images captured through cryo-EM reach as much as 11 gigabytes for one field view, exceeding 50 terabytes in one analytical data set. Structure determination at near-atomic resolution level can be achieved via cryo-EM analysis, where various expertise are coordinated, such as sensor technology, engineering (robotics), software technology for image analysis, computational technologies that enable the transferring of archived digital data, and biological knowledge for sample preparation and data implementation.

High throughput DNA sequencing technology seems to hold a prominent position in the trend of (2) diverse and complex technologies. While the first generation, electrophoresis-type DNA sequencing employed rather simple technology, the development of the second and third generation DNA sequencing has required multidisciplinary expertise. Second-generation sequencing utilized enzymatic reactions rather than electrophoresis and most of them employed optical methods to detect each nucleotide; expertise in molecular biology for the enzyme handling and know-hows in optics and electronics were essential to build up such DNA sequencing technology. As sample amplification by the enzyme was inevitably needed to read the DNA sequence in the second generation DNA sequencing, the wrongly amplified DNA were possibly contaminated in the sample, when the amount of DNA samples was inadequately small. To conquer this issue, a new technology facilitates the elimination of the DNA amplification step in the third generation DNA sequencing; the machine reads the single chain of the DNA molecule. One of the core technologies which have brought such breakthroughs in DNA sequencing is nanopore sequencing technology. In the nanopore DNA (RNA) sequencing system, a single DNA (or RNA) molecule is transferred through a nanopore consisting of proteins by electrophoresis. The magnitude of the electronic current density across the nanopore's surface characteristically changes depending on the nanopore's dimensions and the composition of DNA (or RNA) which occupies the nanopore. The nanopores constructed by proteins are arrayed on a sensor chip, and the measurement of the magnitude of the current values is controlled by an integrated circuit. As described above, unlike the first-generation electrophoresis-type sequencing, second- and third-generation sequencing have been developed based on the integrated technologies, where biotechnology, electronic engineering, and data science for comprehensive analysis on the measured data are coordinated.

Many of the conventional instruments have been developed based on physics, chemistry, and engineering technologies. In addition to the examples described above, recent technological innovations in life science related analytical instruments, however, tend to require expertise in biology.

(3) Issues and directions

・Coordination between information science and engineering

In order to understand the biological events and functions, it is essential to obtain high resolution imaging of various biological events ranging from molecular, tissue, to organ level, in a temporal and spatial manner. To facilitate such high-quality imaging, there is a need for the development of various technologies ranging from optical technologies including optical devices, lenses, and imaging elements, to engineering technologies such as scanning technology, which should be appropriately designed to fit the targeted biological events and desired samples. It is essential to have a good coordination with information science, such as data processing and analysis of wide-ranging big data, including vast amount of image data which could be in an order of nano- to centimeters and a variety of omics data which are usually huge in size.

- Standardization of measuring instruments and data

Even now, image data holds more information than desired by each researcher. Data sharing could increase the efficiency of research activity, as one piece of image data could be analysed from different aspects by different researchers. In addition, sharing and combining the data acquired via different techniques could offer more advanced interpretations. To make this possible, we must endeavour to standardize the format of image data, the instruments themselves, and the mechanisms that could support the transferring and sharing of the big imaging data.

- Career development for researchers and enhancing the collaboration among biology, physics, chemistry, information science, computational science, mathematical sciences, and analytical instruments and engineering

To develop the technologies for analytical instruments targeting life science research that should be widely utilized, it is important to orchestrate the balance between development of instruments, probes, and biological applications. Further, since collaboration with information science is essential for the effective handling of the big data, as described above, researchers from diverse fields such as biology, physics, chemistry, information science, computational science, mathematical sciences, and measuring and analytical instruments and engineering must work together to conduct R&D.

2.7 Bioproducts and Biosystems Engineering

(1) Overview

R&D of production systems including biological processes has recently attracted a wide range of attention. The final products of such bio-related production systems can be categorized into the following two main targets: (1) substances to be used as fuel, chemical materials, pharmaceuticals, and (2) organisms themselves, such as cells, plants, and animals. The products can be utilized in almost all the bio-related industries such as agriculture, forestry, fisheries, food and chemical manufacturing, and healthcare. As shown in this series of research fields, bioproduction systems have a strong interdisciplinary aspect, ranging from basic to applied studies like molecular biology, systems biology, crop sciences, fishery sciences, applied animal sciences, veterinary, and various field trials.

As traditional breeding and production management methods have very limited technologies, technology development in this field has been particularly cost- and time-consuming. Recent innovations in biotechnology, typified by genome editing technology, as well as highly advanced analytical technologies, the rapid development of information science and processing technology such as IoT and AI, however, have had a strong impact that has transformed bio-production systems research, while collecting the wide attention of industry, government, and academia. For example, AI technologies have been applied to design gene expressions, metabolic pathways, and feedback in combination with synthetic biology for the efficient cultivation of microorganisms to produce desired substances. In the field of precision agriculture, the application of drones, fieldservers, and other equipment connected by IoT has enabled more efficient data collection and AI technologies have been installed to analyze those data.

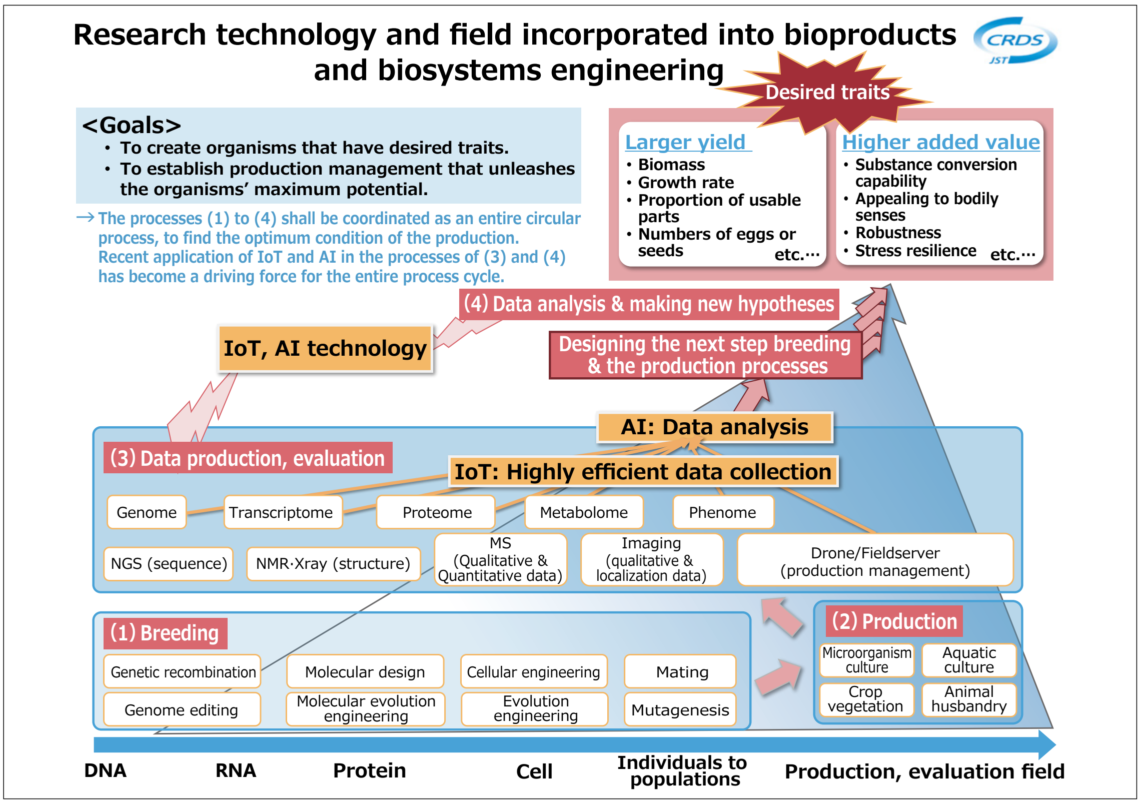


Fig. 2-7 Technology and research field incorporated into bioproducts and biosystems engineering

In addition to such technological advancements, the social context such as the recent introduction of sustainable development goals (SDGs) and the widely accepted concept of “bioeconomy” has also resulted in much attention being paid to the field of bioproduction. Living organisms are able to conduct material conversion by using renewable resources with lower energy consumption and less environmental load in comparison to chemical industrial processes; such attributes have led to their recognition as potentially significant contributors to the creation of SDGs and bioeconomy-related industries.

(2) A transdisciplinary approach

Life arises out of networks of complex molecular systems that are composed of various biomolecules such as DNA, RNA, proteins, carbohydrates, and lipids. It was a considerably complicated and tedious process to modify these molecular systems with following predictions and cultivate new varieties that show the desired characteristics. It was very important to find the right mutants and vast amounts of trial and error crossbreeding had to be conducted; in the end, usually such complicated modifications processes were largely governed by instinct, and a lot of experiences as well as some luck. Moreover, the process of the creation of new varieties was very time-consuming; to see whether the newly created varieties or the culture methods were actually effective or not, it was necessary to go through the whole production process. In the case of living organisms, which require longer growing time, such verification could take some years.

Meanwhile, biology has undergone a rapid development in the current era, a development that has completely changed its nature. During the 20th century, biological knowledge was accumulated through reductionist approaches, as typified by molecular biology. As an attempt to integrate the accumulated knowledge and to understand life as a system, the so-called field of “systems biology” appeared. Moreover, synthetic biology, the opposite of the reductionism approach, where various engineering principles are applied to design and assemble biological components has emerged. This movement has been greatly accelerated by recently developed genome editing technology. In addition, analytical technologies have advanced rapidly; for example, the next-generation sequencer (NGS), cryo-electron microscopy, various types of "omics" and imaging technology have established. These technologies enable the analysis of biomolecular systems with higher temporal and spatial resolution and the collection of vast amounts of comprehensive analytical data. Such data can be utilized to develop a new breeding system in which vast amounts of data are incorporated into some approaches of synthetic biology via information processing technology; this type of new breeding system is intensively applied particularly in the field of microorganisms bioproduction, where rapid research cycle is possible. The case of the bio-venture, Amyris, is a good example of this new breeding system: they have managed to establish a synthetic process to produce artemisinin by using microorganisms. Artemisinin is an anti-malaria drug originally produced by a plant. The driving force in this success was the automation and the systematic application of the Design-Build-Test-Learn process (the DBTL cycle), where “Build” means the high throughput establishment of the culture strains while taking advantage of genetic transformation, gene editing, and DNA synthesis, “Test” includes the evaluation steps of the culture strains via various omics analysis and enzymatic activity assessments, and the steps of “Learn and Design” are to uncover any imperfections during the “Test” process for the next phase breeding. Such new-style breeding methods in which large amounts of data analyses are being employed have been also widely applied in the field of agriculture, forestry and aquatic culture, where breeding and its evaluation usually takes a much longer time than in microorganism bioproduction. The establishment of genome-wide association study (GWAS) has enabled the discovery of genomic markers strongly associated with desired traits. On the other hand, genomic selection has enabled the discovery of living samples which should show the desired traits based solely on the genomic marker information and without the actual observation of the traits. In comparison to the conventional techniques, these newly established techniques have brought great savings in time, space, and labor.

In addition to the field of breeding and the establishment of new strains, data driven R&D has been actively employed in the area of the production process management; the advanced sensing technologies including the field sensors and drones which showed remarkable development in recent years are becoming incorporated into information processing technologies such as IoT and AI. This trend is particularly evident in the fields of agriculture, forestry, and the fishery industries, where the conventional monitoring technologies were too complex to apply. Now that the new IT-incorporated monitoring system has been developed, it is possible to apply pesticides to only severely affected areas detected by agricultural drones; moreover, it is now possible to identify the very early stages of red tide or disease by monitoring water quality with sensors attached to buoys. In addition, various other attempts have been undertaken: collected information such as environmental factors and management logs are analyzed together with variety of information with the aim of optimizing and automating field management processes such as fertilization, watering and harvesting, which require appropriate application in response to the changing field environment.

In order to facilitate data-driven inter-disciplinary research, it is absolutely necessary to provide appropriate access to the wide range of high precision analytical instruments, typically used in omics analysis, for example, mass spectrometry, NGS, and imaging equipment. These instruments, however, are all so expensive they are hardly affordable to purchase and maintain by a single laboratory. As the amount of data produced by these equipments is well beyond human processing capabilities, the consolidation of the data acquisition and processing is needed in terms of both hardware and software. As explained above, in the field of bioproduction research, the importance of transdisciplinary aspects has becoming strongly recognized, with showing the greater aspect of so-called “big science,” which requires abundant human resources and funding.

(3) Issues and directions

The environment surrounding the field of bioproduction has dramatically changed due to the innovations and integrations in biotechnology, analytical technologies, and information processing technology. Although such dramatic innovations have been incorporated into bioproduction research, efficiency in the research field is still inadequate. This is fundamentally due to the absence of consistent guiding principles for either breeding or production management processes. Even in the recognized successful example, the successful strains were obtained via the modifications or the improvements of the preexisting natural DNA or amino acid sequences. In other words, the rational design of new production systems and functional molecules based on entirely new sequences, and the prediction of their capabilities, still remains difficult. The speed of improvement in production processes has been largely enhanced, though the biological questions regarding the critical factors that brought the success tend to remain unanswered and treated as a black box. The most recent technological advances in this field mainly provide high throughput processes based on trial and error; however, trial and error itself is fundamentally a conventional method, and the technological advances have merely enabled it to be done many times, repeatedly and at very fast speeds. Such high throughput trial and error could provide useful clues for the improvement of the production process, if any successful goals are discovered; however, if no successful goals are discovered, the trial and error processes could lead the project nowhere and they are not even capable of showing whether a desired goal exists within the examined range.

In order to overcome this situation, a guiding principal which can govern the bioproduction system and its processes has to be established. Such a principal would contribute to a remarkable improvement in designing efficiency. For this purpose, it is essential that the accumulated knowledge regarding the wide range of life science is structured through the comprehensive understanding of the biomolecular system. Moreover, it is important that such basic understanding should be always linked to the bioproduction process. Recently inter- or cross- disciplinary research projects have started to gain popularity, though the research background of researchers in the field of bioproduction system is still largely limited even in the field of life science. As a series of cutting-edge outcomes can be found from various research projects, it will inevitably be essential to establish a research system that allows the integration of such cutting-edge outcomes, in order to promote bioproduction related research further.

The bioproduction system is fundamentally an interdisciplinary research area; various types of experiments and analytical instruments are required from the breeding stage to the evaluation processes. Such equipments are usually costly and its use requires highly skilled expertise. Moreover, the bioproduction system is also a type of data-driven science, as the analyses based on the accumulated high quality data often lead to next-step hypotheses. As it is a very costly and time-consuming process to establish such integrated research centers/institutions and to increase the number of trained informatics-related researches, there is an urgent need to facilitate the promotion of research development systems, from both the aspects of hardware and software. A rigid research management system that clearly aims to construct a generalized logical system by integrating each research outcome, rather than the simple collection of intriguing research results, has to be created. As described above, the bioproduction system is becoming a kind of big science, which requires big funding to conduct, thus the ideal research system could be as follows: industry and government should invest in research funding and industry and academia should devote themselves to establishing the fundamental basis of the research regarding breeding and the design of the high-precision algorithms for production processes.

As bio-production systems research includes the technologies related to the modification and creation of biological systems, it is mandatory to consider ELSI and dual use perspectives. However, the improvement of legal and regulatory frameworks typically lags far behind development of science and technology. It is important that regulations with superior general applicability and extensibility be put in place promptly while giving consideration to the impact that related science and technology have on society.

2.8 Nexus approach for water, energy, and food security

(1) Overview

Concerns about resource security that could be affected by various events such as extreme weather accompanying climate change, increasing world population, and over-population in large cities are globally increasing. Under such circumstances, discussions about tackling these social issuess about the sustainable supply and consumption of resources started around 2011. The keyword in these discussions is “water-energy-food nexus”.

Generally, the word “nexus” means “a connection between the parts of a system or a group of things” and is translated into Japanese as *renkan*. Research in this area focuses mainly on “synergy” concerning resources, “trade-off”, and “conflict”. In recent years, research has also been conducted on the “water-land-energy nexus”, “water-waste-soil nexus”, and other nexuses.

Researches and attempts to manage resources based on the nexus concepts is called as a “nexus approach” (Fig. 2-8). Numbers of researches related to the nexus approach are being carried out around the world, and basically those can be categorized into three types: (1) Nexus visualization and development of resolution measures; (2) Practical utilization of nexuses (problem-solving through cooperation with stakeholders; and (3) Development of general methods. The one of main research targets is the issue on the energy-water nexus. Public research institutions in Europe and universities in the US are actively conducting resarches of this field, and also found in the Middle East, South America, and Asia. In Japan, although the numbers of researches are limited compared with those in other active countries at this time, the importance of the nexus approach is gradually recognized.

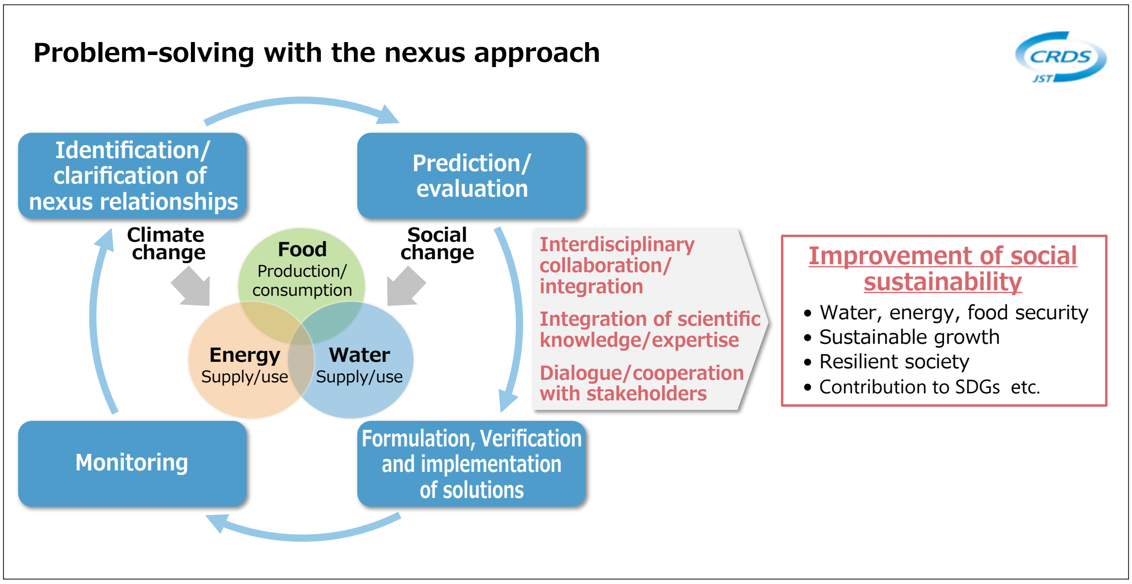


Fig. 2-8 Overview of the nexus approach for water, energy, and food issues
(Created by CRDS based on Tasaki and Endo (2017) and Hoff (2011).)

(2) A transdisciplinary approach

Under the nexus approach, multiple issues that conventionally have been addressed individually are regarded as one issue, and the connections among the individual issues are focused. For example, in the case of a sustainable city, the goal of the research is to construct a system for overall optimization by focusing on the connections between resources, such as securing the water necessary for supplying food and energy to the city and securing the energy necessary for supplying water to the city.

The research intrinsically requires an interdisciplinary approach. In dealing with a local issue, it is important to collaborate with various stakeholders including citizens, policy-makers and industrial sector. Good leaders, integration of scientific expertise, communication, and sharing goals for the research project among participants are also keys to success of the research. Making a systematic educational curriculum for this field would be also beneficial.

(3) Issues and directions

R&D issues

In many cases, nexus issues are strongly related to regional problems. The energy-water nexus is the one relatively popular theme of the nexus case studies. The research target is mainly on hydroelectric power generation, water for cultivating crops for biofuel, and technology for understanding and managing actual situations regarding energy necessary for operating pumps for wastewater processing or agricultural use. In some cases, researchers are conducting nexus projects as a part of support for developing countries. In terms of spatial scale, researches range from a local scale to a national/regional scale (even at a global scale).

Models for analyzing, visualizing, and predicting nexus relationships are being developed as necessary tools for the nexus approach (e.g., The Water, Energy, Nexus Tool 2.0). While currently there are no standardized model yet, R&D on such model is required due to the following significances: (1) for the communication with stakeholders such as local residents and policy-makers (social significance); and (2) for the integration of various information and scientific knowledge (scientific significance).

Issues that need to be considered moving forward include models' scope (types of resources, spatial spread such as cities or river basin communities, etc.); efforts to incorporate climatic and demographic uncertainty; collaboration between sub-models; excellent usability; and development of integration models. In addition to models, data is also extremely important. Collecting, processing and utilizing efficiently various types of data such as observational data, statistical data, data obtained through experiments, data newly generated through estimation are also quite essential research issues. Furthermore, it is required to consider legal and social-science perspectives to connect science and engineering knowledge and expertise gained from analysis of nexus issues to the resolution of local issues. For example, research is being carried out to list related regulations and examine their mutual relativity.

Future directions

In Japan, initiatives that explicitly mention a nexus approach are limited but relevant research may become more active in the near future, especially under the context of SDGs. Some types of research program could be considered: (1) a cross-ministrial program that support wide range of R&Ds in this field from basic science to technology tranfer; (2) a program for case studies aiming to collect and accumulate scientific knowledge/expertise and individual technologies; (3) a program for international projects jointly conducting in such as Central Asia, the Middle East, or Africa (e.g., desalination technology transfer); and (4) a program for encouraging participation of private-sector to this field (e.g., promoting companies' participation in projects, and/or promoting joint research with universities and/

or public research institutions).

(4) Reference

– Endo, A. et al. "A review of the current state of research on the water, energy, and food nexus," *Journal of Hydrology: Regional Studies* 11 (2017), 20–30

2.9 Science and technology for sustainable use of critical resources and materials

(1) Overview

Since overuse and exhaustion of materials and resources negatively affect both the human society and the environment, the use of materials and resources in a circular way is a critical issue for society's sustainable development. With this viewpoint, efforts that utilize various means, such as grasping and analyzing the whole picture of each value chain by integration of scientific knowledge, development of various technologies, change of regulation, system construction, and cooperation with society, are required. The target systems can be divided into two categories: biogeochemical cycle and material flow.

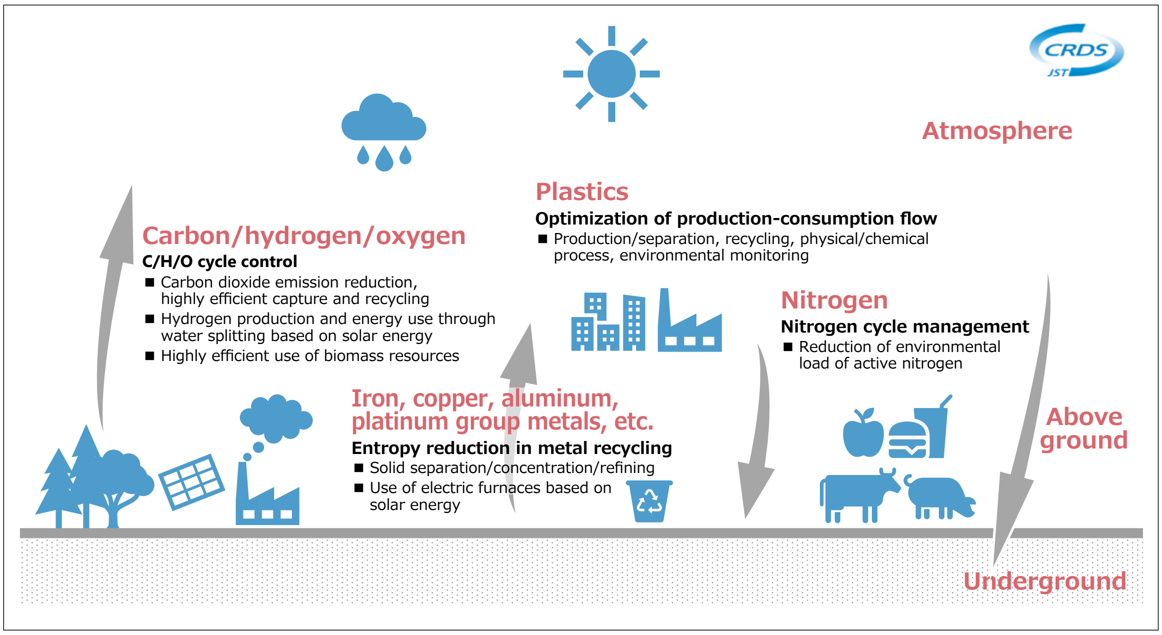


Fig. 2-9 Two types of materials and resources cycle

When considering the biogeochemical cycle, the main target elements are nitrogen and carbon. Nitrogen is an element in which the natural cycle process has been drastically changed by the establishment of the Haber-Bosch process. Through this process, 180 million tons of fertilizers are produced annually, and overuse of these fertilizers causes the diffusion of nitrogen compounds into soil, waterways, and the atmosphere. As for carbon, by consuming fossil fuels, huge amounts of CO_2 are released into the atmosphere, and it contributes to global warming. Carbon is also converted from water (H_2O) and CO_2 into organic matter (plants) via photosynthesis. This organic matter is utilized and consumed in a human society and then partially recycled. By integrating these individual processes, it can be found that carbon is cycled on the earth with various combinations of carbon, hydrogen and oxygen (C/H/O).

As for the material flow, the main target elements are iron, copper, aluminum, platinum group metals, other rare elements, and plastics (organic compounds). Among metals, iron, copper, and aluminum are often used in a pristine form without mixing, and large quantities are consumed. Rare elements such as platinum group metals are expensive and scarce, so these are collected and reused after their consumption. In the case of plastics, as they are non-biodegradable, they cannot be returned to the natural environment and are also difficult to separate and collect, resulting in a low recycling rate. Consequently, problems such as waste disposal and pollution of the ocean with microplastics are arising.

In view of the above, important topics are: C/H/O cycle control (CO_2 emission reductions/highly efficient capture and recycling, hydrogen production and energy use through water splitting based on solar energy, highly efficient use of biomass resources); nitrogen cycle management (reduction of environmental load of active nitrogen); entropy reduction in metal recycling (solid separation/concentration/refining, use of electric furnaces based on solar energy); and optimization of plastics production-consumption flow (production/separation/recycling technology aimed at the establishment of a recycling flow cycle, including physical and chemical methods).

(2) A transdisciplinary approach

Controlling nitrogen emissions from farmland to the environment is important to reduce the environmental load of active nitrogen. To this purpose, research and development on an efficient fertilization, water treatment and environmental monitoring and its evaluations should be integratively carried out. However, the scale of the biogeochemical cycle is basically broad, and it is often difficult to cover the entire cycle within a single funding program or a single ministrial initiative. Collaborative and cross-ministerial support is important. The US Global Change Research Program provides a good example for promoting a large-scale research program. This program has an overall plan and individual plans formulated by each ministry are principally based on the plan. If the R&D project is at the stage of verification and implementation of new schemes or technologies in the real world, collaborative research with various stakeholders such as local government bodies, experts (e.g., experts of agricultural practices), farmers, consumers, and others would be required. In some cases, international collaboration can be beneficial to tackle larger scale problems.

Regarding the C/H/O cycle, initiatives are needed to achieve a shift from the current flow of energy and materials that are mainly dependent on fossil fuels to more sustainable ones. To do this, it is necessary to enhance materials conversion technology that utilizes biomass and CO_2 as carbon sources (raw materials) with using electricity derived from renewable energy. For CO_2 recycling, plant photosynthesis (growth stimulation through genetic recombination, etc.), artificial photosynthesis (improvement of photocatalytic performance), and CO_2 separation/concentration (improvement of efficiency) are all important. A technology enabling direct use of CO_2 filtered from the atmosphere and industrial emissions—direct air capture (DAC)—is also gaining attention. Other keys to achieving CO_2 recycling include the production and utilization of hydrogen (improvement of efficiency of water-splitting, production of hydrogen from biomass and wastes, development of fuel cells that can be available in medium temperature ranges, high-efficiency hydrogen combustion, energy carrier technology for hydrogen storage/transportation); and efficient utilization of plant resources (biomass aggregation, high-efficiency gasification, production of chemical products using biorefinery technology, production of next-generation materials using cellulose nanofibers (CNF), etc.). To promote these initiatives, integration of agricultural science, engineering, physics, and environmental studies is important.

In the materials flow of rare elements, resource security is a critical issue, necessitating the development of efficient resource recycling systems such as "urban mining." Regarding iron, copper, aluminum, platinum group metals and other rare elements, the key issues are collection, and solid separation/refining, and concentration. In the case of plastics, separation/collection/refining/oilification/gasification technologies are important elemental technologies, and environmental monitoring is also important.

(3) Issues and directions

Since many unknown things and processes are remained, an adaptive management of the biogeochemical cycle (a feedback loop process in which interventions to the biogeochemical cycle by humans is occasionally adjusted based on the scientific knowledge) is necessary. Regarding to nitrogen in particular, severe environmental load is often occurred in East Asia, so reducing the load in this region is an important issue. For this purpose, R&D on economically affordable technologies for monitoring and regulating loads to the environment is required.

As for C/H/O cycle control, one of the main issues is how to control the emission of CO_2 derived from fossil resources into the atmosphere through human activities. Among various R&Ds, some initiatives or projects are recently focusing on the following themes: recycling technology utilizing solar energy (especially technology for producing hydrogen, which is necessary for reducing CO_2); energy carrier-related technology for hydrogen storage/transportation; high-efficiency biomass collection technology; high-efficiency biomass utilization technology; and high-efficiency rarified CO_2 collection technology.

In the materials flow of rare elements, Critical Materials Strategy has been promoted in Japan. This consists of five pillars: (1) "substitution" (substituting the function of rare elements by abundant harmless elements); (2) "reduction" (reducing the amount of use of rare elements and harmful elements to the utmost limit); (3) "regulation" (pursuing strategic development of innovation that transcend standards and regulations for the amounts of harmful materials that can be used by each country); (4) "new functions" (generating previously unknown functions from elements); and (5) "recycling" (promoting cyclic use and reproduction of rare element). While the first four of these have been actively addressed, the fifth pillar, "recycling", was relatively less active. It is, however, important to make more efforts to develop technologies and systems for constructing a more sustainable materials flow of each element. As for iron, copper, and aluminum, R&Ds including highly-efficient solid separation technology, steel-making technology with using hydrogen (COURSE50: CO_2 Ultimate Reduction in Steelmaking Process by Innovative Technology for Cool Earth 50), and concentration/refining technology for highly-efficient electric furnaces with solar energy are required. Regarding plastics, technologies for separation and processing different types of compound are needed.

2.10 Innovations in Separation Engineering: Separation science and technology for a sustainable society

(1) Overview

The natural world is composed of diverse mixtures comprising a variety of substances, where numerous chemical reactions occur simultaneously. The situation is similar in living organisms, where innumerable substances mingle and flow in the blood. In order to create a sustainable society, such mixtures must be processed to sort and extract useful matter while removing unwanted matter, but such processes require energy input. Separation for precisely sorting out useful substances using minimal energy is a basic process akin to synthesis and manufacturing and has an extremely important place in industry. Developing low-energy separation processes is an issue in wastewater treatment and seawater desalination, for example, and more effective separation technologies are needed for shale gas and shale oil as contaminated water produced when mining the shale has become an environmental concern. Other separation processes include the safe separation of radioactive materials, dehydration in biofuel refining, separation of airborne pollutants such as PM2.5, separation of CO_2 produced from power plants and factories, separation of high-purity hydrogen, and the dressing, smelting, and refining of mineral resources. However, due to the declining number of quality mines in the world, we have been forced to mine low-grade ore that contains arsenic and many other harmful substances and, therefore, need to develop low-energy methods of separating out the desired resources with low environmental impact. Humans industrially produce a wide variety of products from these resources, which after consumption then need to be separated again in order to be recycled. Thus, separation processes that consider this cycle are important issues. For living organisms, high-speed separation processes are needed for isolating specific cells or proteins and separating and purifying pharmaceutical ingredients to realize the early diagnosis and treatment of diseases and minimally invasive procedures. Technologies used in the separation of biological materials must be integrated with analyses and, moreover, it is important to be able to perform such separation and analysis on trace amounts with great precision either to reduce impact on the patient or simply because the component exists inherently in the body in small amounts. While the current requirements for separation are wide-ranging, it has become impossible to meet them using separation processes developed from conventional scientific systems such as chemical engineering and refining. The time has come to imagine a transdisciplinary approach to separation engineering from the perspective of today's scientific techniques and innovations and future demands in society and industry.

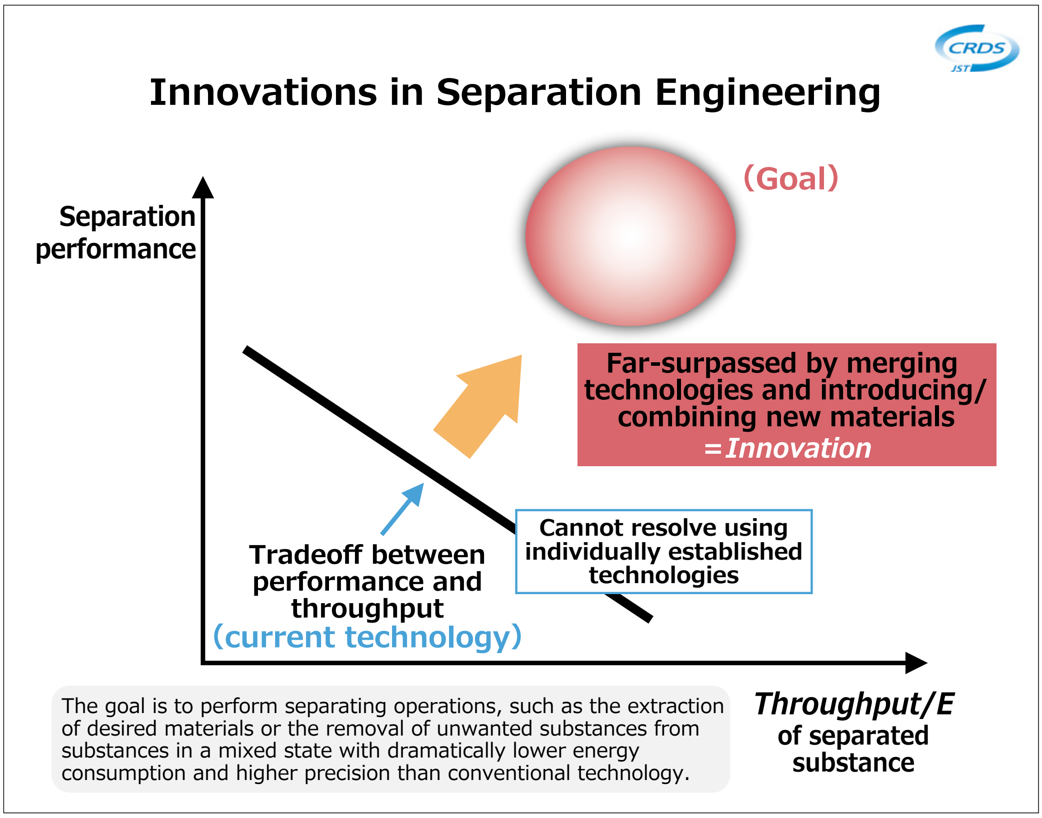


Fig. 2-10 Innovations in separation engineering

(2) A transdisciplinary approach

All separating operations stem from the chemical, physical, and electrical properties of substances. It is important to consider merging and integrating a broad range of fields in natural sciences, from basic research to system development and implementation, by conducting basic research to measure the states of various materials in each process that transforms substances in nature to usable materials in order to clarify their behavior and mechanisms of separation at the micro-level, and carrying out engineering research on separation control, optimization, and implementation at the macro-level. The basic principles of separation can roughly be divided into mechanical separation, equilibrium separation, and speed-difference separation, each of which is supported by an academic foundation. We must work toward realizing high-precision, energy-saving separation operations, which have traditionally been difficult to attain, by utilizing recent dramatic developments in nanotechnology, advanced measuring technologies, and simulation technologies to control at the atomic and molecular level these basic principles and the agents of separating operations that include substances, materials, devices, and processes. Although there is normally a tradeoff between separation performance and throughput per unit energy of the separated substance (see Fig. 2-10), our goal is to develop an innovative approach capable of realizing the required separation throughput while maintaining high performance. A solution to the current problem will not be found using individually developed technologies alone, but will require a more complex approach involving the integration of technologies, introduction of new materials and devices, and combination of reactions. To this end, our goal is to systematically organize separation engineering to provide a clear path connecting transdisciplinary efforts to innovation.

Today, more diverse and complex needs for separation emerge one after another. The challenges for such separation can be broadly separated into three principle requirements or directions: 1) gas-liquid separation, 2) separation of mineral resources and solid wastes, and 3) separation in biological, pharmaceutical, agricultural, and food systems. Formulating processes of separation will require mechanical engineering and fluid mechanics in addition to chemical engineering, metallurgy, and biotechnology. Common fundamental technologies that intersect these fields will be important and will particularly require contributions from academia that go beyond the existing system of disciplines, such as the elucidation and control of phase separation processes in mixed solutions and mechanisms in the nucleation of crystals, in-situ measurement technologies for gaining a better understanding of these phenomena, and the establishment of simulation models for understanding unmeasurable phenomena. The necessary scale and precision of separation differs among the above separation requirements, and the separation technology or combination of technologies and system to be applied differ according to the objective. Similarly, the required separation performance depends on the application. Thus, it is important to develop new separation technologies and processes and new separating materials with careful consideration for costs, in order to achieve these required performances. By systematically organizing separation engineering as a common fundamental technology, appropriate solutions can be formulated and provided reciprocally for a variety of separation requirements. One separation technology not suitable for a certain separation requirement could potentially be developed and applied to other separation requirements. In order to promote innovation in separation engineering through the integration of new knowledge, we must construct and develop a network of basic researchers, applied researchers, and engineers for allowing leading researchers and technicians to gain a new awareness of the status and challenges of their own research through the activities of academic societies. At the same time, the aim is to expand understanding and development of separation engineering in various academic fields. Currently, chemical engineering societies are the primary organizations dealing with separation engineering that targets gases and liquids. Considering separation technologies for metallurgical and biological applications will require widespread collaboration that transcends their borders.

(3) Issues and directions

Thus far, researchers of separation technologies have tended to aim toward developing technologies with better performance under limited conditions, without fully grasping the required performance for separation, including an insufficient awareness of costs. Consequently, any good separation performance obtained was insufficient to compensate for the high costs in most cases. Henceforth we will first consider processes based on their economic feasibility, set requirements for separation performance and approximate the costs at which their use is viable, and only then select separation technologies and work to develop new technologies. Since the barrier for introducing new technologies to replace existing distillation techniques is high, new technologies must be developed not simply using new methods, but by combining those new methods with existing technologies in order to reduce costs and save energy and in some cases to greatly improve separation performance in the overall process system. However, in past R&D projects, there was a strong tendency for researchers to target specific substances to be separated and specific separation technologies. This approach requires further R&D to address new requirements that arise after formulating general guidelines for designing and developing separation materials, such as adsorbents, absorbents, and separation membranes. However, due to our inability to cover the elucidation and theoretical analysis of basic separation mechanisms and phenomena and our insufficient accumulation of basic scientific data, industry has been reluctant to incorporate these new technologies. Since the required separation technology and its processes and scale differ according to the target of separation and purpose of application, each R&D challenge requires a different approach when aiming at practical use. However, the minimum units of all targets of separation range from the atomic and molecular scale to the micrometer scale and their basic scientific principles and utilized technologies share many aspects. Therefore, R&D on common fundamental technologies that intersect gases, liquids, solids, and biomaterials and specific new technologies as well as common principles and tools will be important to spark new innovation in separation engineering, which would not be possible through applied research and development alone.

Next, the three separation requirements will be described. For gas-liquid separation technologies, the idea of developing a technology to replace all distillation in the petrochemical industry is inappropriate. For example, membrane technology has shown promise for use in water treatment associated with oil drilling, i.e., in the development of oil and gas fields, due to the demand for lower energy use. Japan is known to have some of the world's best underlying technologies for membranes, for example, but membranes alone are not sufficient to achieve energy savings. Only by designing technologies for a process system using membranes will energy savings be realized. As an example, adopting a joint R&D format with oil- and gas-producing nations is likely necessary at the technical demonstration stage of a process system. It is particularly important that demonstrations take place in locations that account for the actual operating environment. When demonstrating the process system, an engineering perspective is indispensable for anticipating specific troubles in operations, such as breakthrough in the membrane, and for producing designs that incorporate diagnosis and prediction technologies to infer such troubles in advance, as well as a post-breakthrough repair technology. Thus, the construction of an industry-academia system of collaboration is needed at an early stage. Participation is also necessary at the national level in the regulation of intellectual property rights for developed technologies. To this end, we must study a project funding system implemented by institutions proficient in joint international strategy. A process system aimed at efficient mass-production must be developed for commercial applications. This will require the establishment of technologies for measuring basic properties, databases for accumulating basic properties and theoretical analyses, and fundamental technologies for simulation. Although the verification of long-term operation reliability of the process system is necessary for implementation, multiple researchers of advanced technology producing their own testing facilities individually for similar subject matter is a waste of time and money. For example, the necessary arrangement may be one that establishes a demonstration test center capable of running test operations approaching the demonstration level in a public research institute. The center must sufficiently meet the nation's safety laws and regulations and allow researchers to conduct practical research. Such an arrangement could accelerate research and development.

One promising technology in the separation of mineral resources and solid wastes is the refining of rare-earth metals and the like, but this will necessitate the establishment of a recycling system in society. Recycling today does not have a social system or structure capable of optimizing intermediate processes, physical sorting, and chemical sorting and, hence, the cost structure for recycling is disadvantageous in most situations. We must rethink the way products are designed to account for separation in recycling in order to realize a social system that can yield the benefits of recycling. Establishing an in-situ observation technology for electrolytic refining as a common basic science and technology will be necessary for understanding the behavior of substances in reaction processes and solutions at the atomic and molecular level. Perhaps ideas in smelting research that were previously abandoned should be readdressed using our present-day technological strengths. Impediments in scientific approaches to sorting solids that produce nonuniformity and complexities in the target material are universal issues facing the world. Sorting technology can be an important tool for gaining a competitive edge in a wide range of fields but, unlike various products that directly impact social life, is an approach for overcoming technological issues in order to achieve a goal. Therefore, simultaneous development of a social system is necessary for gaining a competitive edge through innovations in separation engineering.

Separation in biological, pharmaceutical, agricultural, and food systems is performed at a different scale from the previous two areas. That is, high-precision separation is required at the molecular and cellular level in extremely small samples of picoliters (10^{-12} L) or femtoliters (10^{-15} L) or less. Owing to the small target scale, there is a high probability that completion of the underlying technology will lead directly to practical implementation in society. When the target of separation is intercellular organelles, which like exosomes were discovered in recent years, analytical techniques will need to be developed simultaneously with the separation technology. If the substance to be separated has high demand in medical care, a simple yet delicate technique must be perfected along with the simultaneous development of various peripheral technologies.

2.11 Next-generation Biomaterials Engineering: Controlling interaction between materials and biological environment

(1) Overview

"Next-generation biomaterials engineering" is a field of science in which materials are designed, created, and evaluated based on the mechanisms of organism-material interactions that take place when a component substance of an organism—biological tissue, cells, body fluids, etc.—come in contact with materials. The advancement of this field is expected to lead to the creation of new materials that make enable active control of organism-material interactions in adaptation to a diversity of biological environments.

With the arrival of the super-aged society, diversification of medical and health needs, and advancement of medical technology/devices, it is becoming increasingly necessary for materials used in medicine and healthcare to provide various functions for controlling biological phenomena. For example, materials that encourage tissue regeneration by leading cells to injured areas; materials that exchange substances and information with organisms in real time to make diagnoses and provide treatment; and materials that promote the formation of three-dimensional cell structures outside the body, constructing tissue/organs that can be used in transplant or model tissue that can be used for drug development/medical research. In this way, there are demands for the creation of materials that provide certain functions in response to biological environments. However, what are known as biomaterials, meaning materials that are utilized through contact with biological tissue, cells, body fluids, and other component substances of organisms must be readily compatible with the organism—that is to say, it is essential that they have "biocompatibility" —but much remains unclear about the mechanisms controlling how biocompatibility is expressed within the diverse and complex biological environments, and there are aspects of biomaterials R&D that are forced to rely on experiential trial and error.

In order to overcome such situations, it is necessary to move away from the concept of searching for materials that are suitable for biological environments on which previous R&D has been based, by establishing materials design policies based on mechanisms controlling interactions between organisms and materials. The aim of next-generation biomaterials engineering is to meet as-yet unsolved medical and healthcare needs by creating new materials that enable active control of interactions with organisms, thereby contributing to the realization of a healthy longevity society (Fig. 2-11-1).

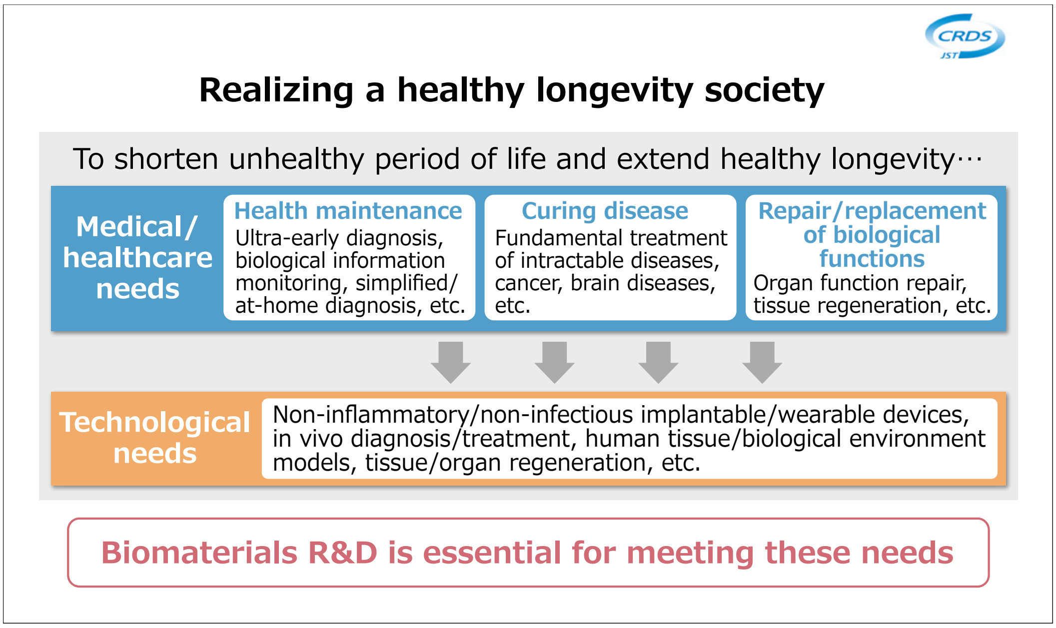


Fig. 2-11-1 Meeting health/medical needs through next-generation biomaterials engineering

(2) A transdisciplinary approach

Explaining next-generation biomaterials engineering in simple terms, it is a scientific field that "clarifies mechanisms controlling phenomena occurring between organisms and materials through quantitative evaluation and analysis, and based on the knowledge obtained from these results, design and create materials that enable the control of organism-material interactions." In order to promote next-generation biomaterials engineering, collaboration and integration is required among science and engineering researchers who will be responsible for establishing various material systems and measurements, and for quantitative analysis of organism-material interfaces; biological sciences researchers undertaking research utilizing biomolecules, cells, and small animals; and medical researchers seeking new medical/healthcare technology and treatment methods. Major R&D themes in the field of next-generation biomaterials engineering are shown below.

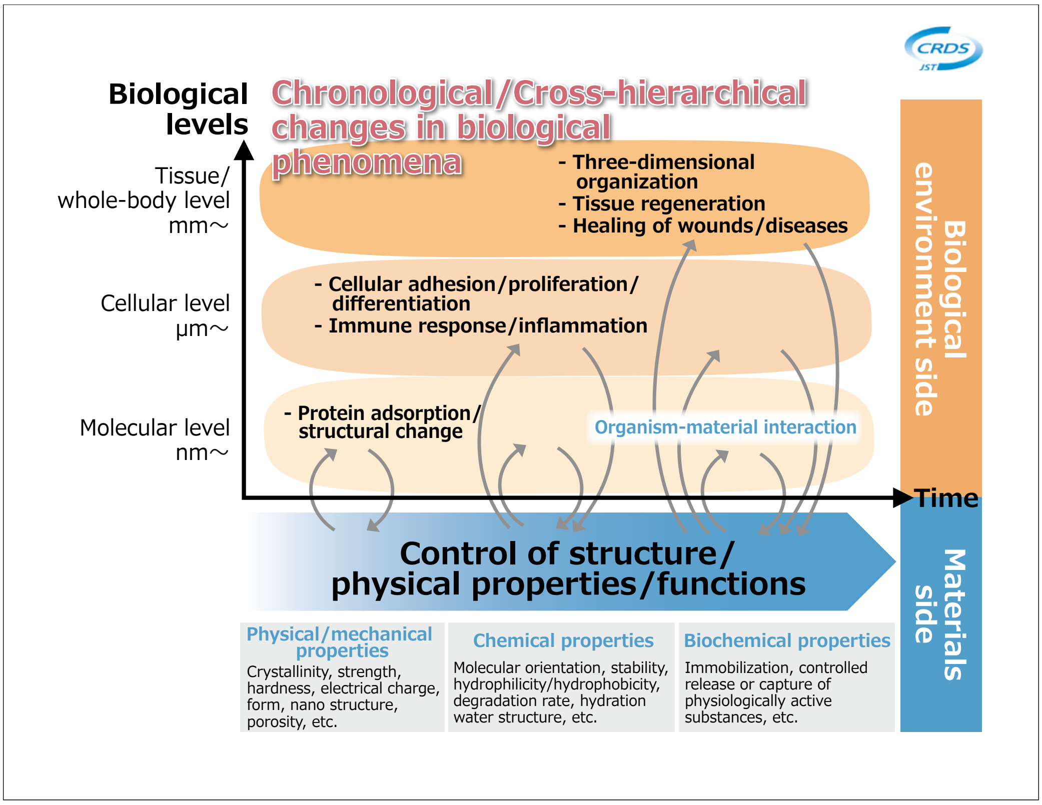


Fig. 2-11-2 Cross-hierarchical biological phenomena/changes and interactions with materials

(i) Understanding phenomena that arises through organism-material interactions

Organism-material interactions begin at the instant when the material makes contact with the biological environment creating an interface. Such phenomena progress chronologically and cross-hierarchically, beginning with phenomena that occur in less than a microsecond (such as hydration, ion adsorption, and biological molecule adsorption) and continuing through phenomena that occur in minutes to hours (such as cell adsorption/propagation), followed by phenomena that occur on a tissue, organ, or whole-body level. Although the biological phenomenon that should be noted differ depending on the purpose and usage environment of a material, it is important to quantitatively clarify background chronological and cross-hierarchical changes as well as understand and clarify the mechanisms for these changes. It is important to understand the complex biological phenomena from medical and biological sciences perspectives while at the same time understanding the structure/properties/functions demonstrated by materials in a diverse and complex biological environment and the chronological changes that occur in those materials. It is essential that perspectives and knowledge from different research fields be concentrated and efforts made to investigate organism-material interactions.

(ii) Development of new technologies and devices necessary for enabling quantitative evaluations and measurements in diverse biological environments

In order to understand complex biological environments that change spatiotemporally and interactions that occur between organisms and materials, it is imperative that technology be developed that enables the chronological and quantitative measurement and analysis of diverse phenomena that are caused by such interactions. Technologies that need to be developed include: technologies enabling the application of existing measurement/analysis technologies to complex organism/material interfaces; in vivo measurement technologies for physical/chemical properties such as local hardness or pressure, body fluid flow, temperature, and pH; three-dimensional dynamic imaging technology enabling minimally invasive/non-invasive in vivo observations; and information science methods for analyzing enormous quantities of data obtained from various types of measurements and omics. In addition to medical/biological sciences researchers and science/engineering researchers, collaboration with information science specialists is essential

(iii) Designing and creating new biomaterials

Based on understanding of chronological, hierarchical biological phenomena caused by organism-material interactions, materials with structures/properties/functions enabling them to actively control organism-material interactions are designed and created. Using the advanced materials design/synthesis/production technologies that have been accumulated in Japan thus far, as well as nano technology and processing technology, materials with the desired characteristics are realized. To enable the materials' characteristics to be controlled at will, materials with different characteristics—metal materials, inorganic materials, synthetic polymers, biological molecules, etc.—should be broadly perceived as research subjects, and integrating these various materials as necessary is an effective strategy in materials design. Collaboration and integration among researchers in various materials fields and processing technology specialists is essential.

(iv) Establishing evaluation bases necessary for the practical application of newly created materials

In order to develop newly created biomaterials into practical medical/healthcare technologies, it is imperative that evaluations tailored to the usage conditions and purposes when the materials are actually used be carried out, thoroughly ensuring safety and effectiveness, and optimizing the materials as products. It is important to build evaluation bases by resolving various issues regarding biomaterials evaluation— creating models of actual biological environments in which the materials are to be used, and setting evaluation methods/indicators, etc. Collaboration among materials engineering researchers, medical researchers who are highly familiar with clinical practices and regulatory science specialists is required.

Furthermore, in promoting these R&D themes, it is essential that research subjects do not deviate from actual medical/healthcare needs. Accordingly, from the theme-setting stage it is necessary for researchers in different fields—centered on materials researchers and medical researchers—to establish thorough communication and share scientific definitions used in biological environments where materials are used, as well as the materials to be created and the functions these materials are to have (Fig. 2-11-3).

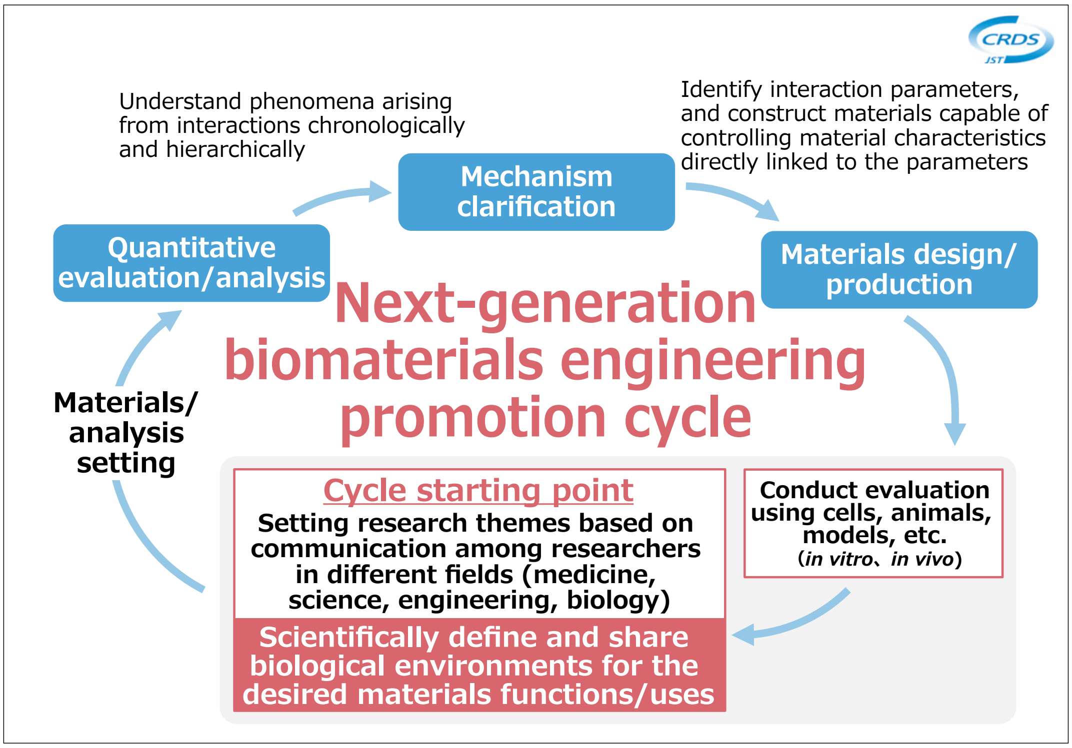


Fig. 2-11-3 Next-generation biomaterials engineering promotion cycle based on integration/collaboration among different research fields

(3) Issues and directions

To realize the practical application of new medical/healthcare technologies, it is essential that they pass the assessment processes to ensure their safety and effectiveness, and that they gain approval. However, enormous time, effort, and money is required to obtain approval for new biomaterials. With regard to materials that are used in vivo especially, it is extremely difficult to obtain approval from the Pharmaceuticals and Medical Devices Agency (PMDA), leading to the derailment of many R&D projects during the development process. Consequently, under the current circumstances, development of medical devices is frequently premised on the use of approved biomaterials with assured safety. However, there are cases in which the functions or properties necessary for realizing a medical/healthcare technology cannot be achieved using only already-approved existing materials. Expectations are held for the birth of new technologies capable of meeting as-yet unsolved medical/healthcare needs, and in order to meet these needs, R&D on new materials focusing on functional expression is required.

2.12 Structural reforms of research systems/laboratories; nationwide research infrastructure/platform for promoting transdisciplinary research

(1) Overview

In all scientific fields, research targets become increasingly complex as the stage of scientific development advances. For example, nano-technology has enabled complex structures and functions of materials to be controlled at the atomic and molecular levels, and thanks to genomic analysis, genome editing, and stem cell technologies, research is now being carried out that is even approaching the redefinition of life. In conducting such research, in all scientific fields advances are achieved through the possession of advanced and expensive experiment equipment as well as the implementation of an enormous number of experiments, and the possession of computing capabilities enabling vast quantities of data to be obtained through these experiments. It is gradually becoming obvious that these are generating decisive disparities in global research competition.

In major countries, the construction of frameworks for establishing, opening and sharing research hubs for user facilities—including advanced experiment equipment and computers, (in the present times) research data and data processing software, and standardization of experimental methods (sample standards and measurement standards)—has been progressing rapidly. Furthermore, research hubs shared in this way in regions around the world are demonstrating a tremendous presence as places of mutual resonance for pioneering industry-academia-government collaboration and transdisciplinary research, becoming wellsprings for research momentum and competitiveness as R&D platformers. In addition, recent advancements in robot technology have led to the introduction of so-called robotic experiment equipment that automatizes the huge number of times an experiment needs to be repeated in the course of research. We are now coming to an age in which research styles will change dramatically. It is more than justified to say that, in order to respond to these trends, it is essential to implement educational reforms that break down vertical structures in each discipline and develop mathematical/data science education and basic skills as liberal arts. Below we discuss research system and laboratory reforms for maximizing R&D investment efficiency from the perspective of creating R&D infrastructure/resource platforms.

(2) A transdisciplinary approach

In the fields of nanotechnology and materials science, the petrochemical and semiconductor industries played a leading role up until the 20th century, and research was conducted under the leadership of experimentalists and theorists. Serendipity arising from researchers' experience and intuition in fact provided the motivation for implementing tremendous advancements in science and technology as well as related industries. In the ICT era of the 21st century onwards, advances have been made in enhancing the functionality of computing devices using computational science and data science; conducting analysis and measurement using the automatization of computation and data processing; and designing materials functions. Today, with the introduction of computational science and data science methods in research becoming a relentless trend in the pursuit of development, individual researchers now refer to themselves as theorists, experimentalists, computational scientists, or data scientists. However, what is now required is a research style that mobilizes researchers in all of these roles, rather than just one role. Of course, it is only natural for individual researchers to have areas in which they are strong or weak, or in which they do or do not have specialist knowledge; they must not, however, use their weaknesses or lack of specialization to avoid challenges in new research fields. Researchers must not divert their eyes from issues that can be addressed through team efforts leading to solutions when individual efforts to resolve them have failed. From a research environment perspective, access to research environments that maximize research efficiency is decisively important. For example, advanced research infrastructures cannot be considered separately from the issue of enhancing specialist human resources to enable full and proficient utilization of such infrastructures. These infrastructures include access to cutting-edge measurement and analysis equipment, beginning with atomic resolution aberration-corrected electron microscopes and synchrotron radiation facilities; access to materials synthesis and nano/microfabrication devices that enable materials control on a nanometer scale, access to experts with the highly specialized skills for proficiently utilizing these cutting-edge devices and to their knowledge and know-how; access to super computers used for carrying out molecular dynamics calculations and first principle calculations for simulation of groups of molecules/atoms numbering in the tens of thousands; and use of software and other data science tools for realizing target functions and structures from big data databases related to materials and devices. It is therefore strategically important that these infrastructures be organized and accumulated centrally at several specified locations and utilized as platforms as quickly as possible. The important point here is to develop these locations as places of mutual resonance for researchers with a range of specialties and issues to pioneer transdisciplinary research in collaboration with industry and academia, and as fertile soil for researchers to acquire new research skills and improve their existing skills.

In the field of life science, with the sudden rise to prominence of molecular biology, research focusing on specific genes and molecules has long been underway, leading to the discovery of many new building blocks for life. Also, the introduction of the Next Generation Sequencer (NGS) and mass spectrograph in the mid-2000s onwards and the advancement of various technologies utilizing these devices is gradually making it possible to conduct research on the temporospatial dynamics of life. Furthermore, due to the rapid advancements in these devices, an emphasis has been placed on data analysis, and big science aspects requiring expensive equipment, abundant human resources, and funding are gaining strength (transformation of “life science” into “big science”). In other words, these trends suggest that in the future computer science will become increasingly pervasive, while at the same time, R&D will move towards knowledge-intensive research styles.

The Broad Institute launched in the United States in 2004, is famous for inventing the CRISPR/Cas9 genome editing technology that was introduced in 2013. The Institute states that: “The traditional academic model of individual laboratories working within their specific disciplines was not designed to meet the emerging challenges of biomedicine. To gain a comprehensive view of the human genome and biological systems, they instead had to work in a highly integrated fashion.” Based on this awareness, MIT and Harvard University jointly designed and established a research laboratory based on the following concepts.

- Working in agile teams that combined biology, chemistry, mathematics, computation, and engineering with medical science and clinical research

- Working at a scale usually seen in industry, with access to world-class infrastructure
- Fostering an atmosphere of creativity, risk-taking, and open sharing of data and research

For example, in the fields of precision medicine, personalized medicine, and genomic medicine—which are currently becoming global healthcare trends—are fields in which correlations and causal relationships among genomic information, omics information, human disease information, and environmental information are being clarified and playing a useful role in diagnosis and treatment. In such medical treatment and basic research apart from transdisciplinary research as well, the key technologies for research that can be said to be global trends—including nerve connectome, microbiome, complete cell atlas, complete molecule atlas/trans-omics, and nucleome（gene expression mechanism—all comprise the integrated use of three technologies: sequencing-based omics technology, imaging technology, and data analysis technology. These are typical themes that clearly require scale and knowledge intensification. In other words, the accumulation and sharing of immense amounts of data as well as the construction and extraction of knowledge (data) from this accumulated/shared data is required. In order for such research to be carried out in university laboratories that have conventionally focused on research in specialized fields, the fundamental nature of research systems and laboratories must undergo structural change, and those who address this issue quickly will undoubtedly become the R&D platformers of the next generation.

（3）Issues and directions

Sustainability of research infrastructure platforms (PF) and centers and diversification of management resources

When public institutions such as universities and national research institutes are in charge of PF management, it is important that open and equal opportunities for using facilities as R&D centers are provided stably to industry, academia, and government. Considered from the departure point of maximizing “overall” investment efficiency for industry-academia-government R&D, funding resources can be broadly divided into three categories: operating expenses for the relevant public institution; usage fees paid by users, related joint research fees, and other contributions; and construction and operating expenses for PF implemented by the national government for the purpose of improving infrastructure for such research infrastructure. With regard to funding resources from usage fees, in the case of academia, a portion of commissioned research fees from businesses and competitive research funds from the national government is allotted. This may not necessarily be the correct answer to the question of what the optimum ratio of the three types of funding resources should be. However, in consideration of operating flexibility and sustainability, it is vital to avoid as far as possible over-dependence on a certain funding source from the perspective of enabling the provision of a stable environment for research infrastructure usage by preventing the unevenness of one type of funding resource from exerting an excessive impact on operations. In contrast, when private corporations are in charge of PF operations, the PF operations are carried out as an enterprise, and so increasing growth and profits is a prerequisite. Here “profits” refers to the amount obtained by subtracting operating costs from income obtained from PF users, etc., and so for profit-seeking PF, the focus is placed on users who pay higher usage fees and those who make investments. Accordingly, usage is limited to those with the ability to pay a certain amount for using research facilities, or reflects the intentions of investors. This model therefore is only viable in cases where profits counterbalance the costs of procuring and maintaining the devices, technology, and information provided by the research institution.

When public institutions such as universities and national research institutes are in charge of PF management, one issue in particular that may emerge is cutting-edge equipment that needs to be renewed every few years. Technology in superseded by new next-generation technology once every two to three years in the case of life sciences-related devices, and every five to seven years in the case of nano-technology/materials-related devices, and it is extremely difficult to sufficiently cover the cost of upgrading equipment within the main research scope with these three types of funding resources. However, even though not all research uses cutting-edge technology, being unable to keep up with generational shifts in technology means falling short of the cutting-edge of global research. The current situation is that this funding for equipment procurement and upgrading is largely reliant on chance, such as funds received for research projects selected for competitive research grants of a certain scale or higher, or national government budget allocations implemented for a special purpose. It is imperative that operating budgets be formulated so as to include the cost of planning and carrying out equipment procurement and upgrading in the medium term as PF operating costs. To do this, it is thought that, in the case of Japan it is important to construct virtual networks of large-scale hub research PF and medium-scale PF specializing in technological fields and functions, providing nationwide coverage of research infrastructure based on consideration of degree of technology accumulation, geographical conditions, and relevant scale. In other words, in attempting to strategically manage research infrastructure so as to maximize research investment efficiency, success depends on constantly securing expenditure equivalent to a certain percentage of both research funding for implementing research themes/projects and the total amount of these funding resources, thereby maximizing the total amount obtained through the above-mentioned three types of funding resources.

Highly specialized engineers and research support human resources

In addition to researchers, universities and national research institutions (laboratories, research centers, research departments) also require various other humans resources, which can be broadly divided into three categories: human resources with specialized technical capabilities with regard to research equipment and technology fields; administrators responsible for accounting and financial matters; and human resources responsible for intermediating and matching intellectual property and technology transfers. In times such as the present, in which measurement devices develop and equipment is upgraded at a rapid pace, it is not sufficient to simply purchase equipment. It is imperative that this equipment is installed as a team with expert human resources with the ability to provide high-technology enabling the equipment to fully function in accordance with their specifications; to repair and remodel equipment; and in certain cases, to formulate development proposals. With regard to human resources responsible for funds and contract management and intermediating intellectual proportion and technology exchanges, it is becoming important for research institutions to have human resources capable of coordinating a wide range of activities, from fundraising for diversified funding resources to strategic management accounting, communicating as a bridge between industry and academia, and providing support for the combination, meeting, and commercialization of technology and human resources. In countries with many restrictions on R&D

resources, securing sufficient human resources for all universities and national research institutions is unrealistic, and so it is important that structures that guarantee a certain amount of fluidity and constancy are secured in the above-mentioned PF/base units.

How do researchers divide their time?

For those conducting research, one of the most important issues is research autonomy. This means researchers determining their research themes for themselves as they endeavor to observe the world with their own eyes and depart from the intrinsic intellectual curiosity they hold within their own area of specialization. They decide on how to approach their theme, and publish their findings in the form of academic papers, publicly disclosing and sharing with the world human knowledge that has been made clear for the first time. In carrying out research as a job, how researchers divide their time between different aspects of their research activities—how much time they allocate to each task—is directly connected to the productivity of the research. There are two main issues here. Firstly, because research themes are becoming more and more complex and the implementation of large numbers of experiments and data processing is becoming necessary in an increasing number of cases, automation of these tasks through access to the above-mentioned research infrastructure PF and incorporation of robot technology is an issue. Of course, self-producing devices necessary for conducting experiments, conducting experiments and making calculations manually, and thought experiments and the construction of thought experiments are all essential to the processes of discovery and invention. However, problematic spaces in research themes—especially integrated and transdisciplinary research themes—require even more complex space construction, and in order to address this, infrastructure tools for shortening the time required and access to and collaboration with a diversity of specialist human resources is decisively important.

The second issue is the relationship between how researchers divide their time and their career paths. It is especially important to concentrate on research during doctoral and post-doctoral studies to develop a fundamental skeletal structure as a researcher. In order to do this, it is imperative to choose research themes that are “essential themes”. Today, however, with the increase in fixed-term positions limited to the duration of a research project, young researchers in particular have an urgent need to produce effective results in a short period of time in order to secure their next research post. In some cases, number of published papers and impact factors may be used as blind indicators. However, in many traditional research fields in developed countries, researchers are aging. The pros and cons of being dependent on the research themes of large research laboratories as well as avoiding the risk posed by taking on the challenge of opaque integrated and transdisciplinary research themes in fields for which evaluation methods have not been decided, or for which it is uncertain whether or not results will be recognized, create difficulties in relation to researchers’ career formation.

Invisible factors hindering transdisciplinary research

The expansion of transdisciplinary research is generally said to be “a process developed over 15 to 20 years or longer”. However, for example, under Japan’s public funding system many research grants are for (program/project) research periods of between 3 and 5 years and so are inadequate for transdisciplinary research. Furthermore, because each of these funding programs operates independently and there is a lack of mutual connectivity, researchers pursuing transdisciplinary research need to reapply to different programs each time they apply for funding in order to continue their research until full integration is achieved. Moreover, programs themselves are frequently overhauled, making continuity even more difficult to maintain.

In addition, there are currently no human resources who are capable of evaluating transdisciplinary research and no established evaluation methods. In traditional disciplines, it is common practice to request renowned researchers with a proven performance record to conduct evaluations, but needless to say, this approach is not suitable for evaluating transdisciplinary research. Consequently, sufficient evaluation has not yet been carried out, and as described above, in some cases this has made researchers hesitant to take on the challenge of exploring new research themes and been particularly discouraging and detrimental to young researchers' motivation. For post-doctoral students, and young researchers, and technicians who are employed for the fixed period of the duration of the research project, whether or not research themes in integrated/transdisciplinary fields for which evaluation has not yet been established will produce fruitful results is a matter of life and death that weighs heavily on them.

However, it has been pointed out that the ability of young researchers to search for and propose new research themes is declining, and that they are not being provided with research environments or educational opportunities that foster this ability in Japan. There are also some who say that setting themes for transdisciplinary research—which takes time to yield results—is difficult in light of the tendency in recent years to seek short-term results. Meanwhile, with regard to programs with integration-related themes, it has sometimes been pointed out that damage is being caused by some research projects bringing together participants merely for form's sake without actually establishing true collaborative ties, and this is a point for discussion. In order to address these issues, it is important that the following mechanisms be implemented along with incentives for participating organizations and human resources.

- Formation of domestic/international networks of knowledge and researchers centered on research infrastructure/PF measures and funding systems
- Construction of open R&D centers to form the core of network formation, and reform of funding management systems and employment systems (limitations on contract terms, evaluation, cross-appointments, etc.) that hinder the sustainable development of research centers
- Reform of development and implementation of laws related to university and national research institution governance mechanisms in Japan
- Introduction of mechanisms for researchers in different fields to mutually benchmark their work, inspiring new ideas.
- Formation of joint industry-academia-government-society platforms for sharing ideas/status of social issues and R&D; setting R&D direction; accelerating innovation; addressing Ethical, Legal, and Social Issues (ELSI); and training human resources.
- Creation of organization, mechanisms, and environments that facilitate researchers (especially young researchers) to take on the challenge of integrated and transdisciplinary research themes.
- Appointment of researchers to undertake research on integrated and transdisciplinary research themes; organizational change and appointment of human resources undertaken proactively by

universities and research institutions, and reform of evaluation standards and systems necessary for achieving this
- Provision of support for base construction expenses incurred by universities and research institutions endeavoring to realize change through these initiatives
- Organizational operations that watch over researchers and enable them to take on new challenges
- Creation of an invitation to opportunities for young researchers to experience new research trends and different research fields
- Establishment of integrated/transdisciplinary science and technology educational programs centered on "problem-solving"
- Nurture and support of academic societies that proactively address and are involved in social issues, social expectations, and integrated/transdisciplinary science and technology, and that proactively investigate integrated/transdisciplinary science and technology, and formation of a foundation for research publication and evaluation

Without addressing each of the above structural issues, it will not be possible either to raise the amount of research results generated, or to further develop and expand integrated and transdisciplinary research themes. An R&D infrastructure resource platform that promotes the reform and integration of research systems and laboratories is axiomatic in maximizing R&D investment efficiency.

3 Systems and Programs in Japan

Chapter 3 presents examples of Japanese systems. After giving an overview of changes in how "integrated fields" are perceived in Japan under the Science and Technology Basic Plan, we present four examples of basic programs that promote transdisciplinary research: the Creation of Innovation Centers for Advanced Interdisciplinary Research Areas Program, the World Premier International Research Center Initiative (WPI) (overseen by the Ministry of Education, Culture, Sports, Science and Technology (MEXT)), the Center of Innovation (COI) program, and the Program on Open Innovation Platform with Enterprises, Research Institute and Academia (OPERA) (overseen by the JST). We discuss the characteristics of each program and the research bases adopted under them.

3.1 Examples of Japanese Systems and Programs

3.1.1 Background information: "Integrated Fields" under the Science and Technology Basic Plan

Under the 2nd Science and Technology Basic Plan (2001-2005), which designates priority research areas in fields such as life sciences, with regard to "Integrated Fields" it is noted that "in promoting R&D, peripheral fields or fields that may appear irrelevant should not be excluded, as new S&T fields are frequently borne of combinations of different fields, with the rapid advancement of S&T and its further specialization." Under the 3rd Science and Technology Basic Plan (2006-2010), such fields are referred to as "Emerging and Interdisciplinary Fields", and furthermore, "creating bases for advanced interdisciplinary research" is identified as a measure for generating innovation with the awareness that "innovation is frequently created from new interdisciplinary research areas, and such areas are effectively created by active involvement in the search for business solutions based on socioeconomic needs". The 4th Science and Technology Basic Plan (2011-2015)—which discusses task-achieving R&D—also maintains these policies. The 5th Science and Technology Basic Plan (2016-2020)—which discusses open innovation—states that, "Ultimately, it is people that give rise to innovation. The exchanges of people between organizations and sectors enable the flow of various kinds of knowledge, resulting in cross-stimulation and cross-fertilization, and merging into the creation of new value. We can observe that overseas, the movement of personnel between universities and companies, between companies of different scale and different sectors, and the concurrent deployment of people in multiple organizations, contributes to the rapid achievement of innovation." The Plan thus emphasizes not only integration of research fields but also the increasing mobility of human resources and integration borne from such mobility.

3.1.2 Creation of Innovation Centers for Advanced Interdisciplinary Research Areas Program

(1) Program Summary

In order to consistently maintain a competitive advantage within the global community, foundational science and technology strength and the continuous generation of innovation based on this strength are essential. Furthermore, in order to appropriately resolve diversifying social needs, rather than taking a conventional approach, it is imperative that synergy effects from the fusion of different fields be utilized to the maximum to generate new knowledge. The objective of this program is to form research bases that carry out R&D aimed at avoiding "the Valley of Death" through consistent entry-to-exit industry-academia collaboration with a view to future commercial viability, while endeavoring to nurture researchers and technicians to lead the next generation in cutting-edge integrated fields. Through the proactive commitment of universities and companies in the program (matching fund style), these research bases will powerfully promote R&D to generate innovation with major social and economic effects, such as the creation of new industries with an outlook 10 to 15 years into the future. (From the Creation of Innovation Centers for Advanced Interdisciplinary Research Areas Program website; abridged.)

(2) Term and budget scale

Three years prior to rescreening: approx. 300 million yen/year
After full implementation: 500–700 million yen/year

Centers adopted in FY2006

Innovative Techno-Hub for Integrated Medical Bio-Imaging	Kyoto University
Center of Excellence for Nano Quantum Information Electronics	The University of Tokyo
The Matching Program for Innovations in Future Drug Discovery and Medical Care	Hokkaido University
Formation of Centers for the Creation of Innovative Mergers of Leading Edge Technologies	Tokyo Women's Medical University
Intelligent Artificial Agents and Information Systems inspired by the Dynamics of Biological Systems	Osaka University
Center for the Creation of Nanobio-targeted Therapy through Interdisciplinary Research	Okayama University
Creation of IRT to Support Human and Aging Society	The University of Tokyo
Innovative Research Center for Preventive Medical Engineering through Biomedical Analysis and Diagnostics*	Nagoya University
Interdisciplinary Research on Integration of Semiconductor and Biotechnology	Hiroshima University

Centers adopted in FY2007

Photonics Advanced Research Center	Osaka University
Translational Systems Biology and Medicine Initiative	The University of Tokyo
R&D Center of Excellence for Integrated Microsystems	Tohoku University
Innovation Center for Medical Redox Navigation	Kyushu University
Center for Innovation in Immunoregulative Technology and Therapeutics	Kyoto University
Creating a Co-mobility Society	Keio University
Center of Excellence for Sophisticated Fiber Science Using Nanotechnology	Shinshu University
Photo-Medical-Valley	Japan Atomic Energy Agency
Creation of Strategic Innovation in Marine Biotechnology*	Tokyo University of Marine Science and Technology

* Provisional translation by CRDS/JST

Centers adopted in FY2008

Establishment of Research Center for Clinical Proteomics of Post-translational Modifications	Yokohama City University
Vertically Integrated Center for Technologies of Optical Routing toward Ideal Energy Savings (VICTORIES)	National Institute of Advanced Industrial Science and Technology
Innovative BioProduction Kobe (iBioK)	Kobe University

3.1.3 World Premier International Research Center Initiative (WPI)

(1) Program Summary

With competition to acquire outstanding brainpower intensifying in recent years, in order to lead the world in scientific and technological strength it is necessary to create open research bases that are positioned within the "circle" of the global flow of outstanding human resources, and draw human resources from throughout the world. The World Premier International Research Center Initiative (WPI) is a program launched in FY2007 by MEXT in awareness of this issue. The objective of this program is to form "visible research centers" boasting outstanding research environments and high research standards, draw frontline researchers from around the world and autonomously implement system reforms through intensive government assistance for concepts aiming to create world-class research bases centered on top-level researchers. Under this program, research bases are required to fulfill the four conditions of: "advancing leading-edge research", "creating interdisciplinary domains", "establishing international research environments", and "reforming research organizations". In order to realize these goals, the World Premier International Research Center Initiative (WPI) Program Committee—comprising past and present university presidents, Nobel Prize winners, representatives of industry, and renowned experts from overseas—screens adopted research bases at the time of adoption as well as on annual follow-ups (evaluating progress).

(2) Term and budget scale

Term：10 years

Grant amount (for one base/year): Up to 700 million yen/year x 10 years maximum (bases adopted in FY2017)
Up to 700 million yen/year x 10 years maximum (bases adopted in FY2012)

Centers adopted in FY2017

Center name	Outline	Host institution	Center Director
International Research Center for Neurointelligence (IRCN)	Tackling the ultimate question – "How does human intelligence arise?"	The University of Tokyo	Takao Hensch
Nano Life Science Institute (NanoLSI)	Understanding nanoscale mechanisms of life phenomena by exploring "uncharted nano-realms"	Kanazawa University	Takeshi Fukuma

Centers adopted in FY2012

International Institute for Integrative Sleep Medicine (IIIS)	World-class institute for sleep medicine, aiming to solve the mechanism of sleep/wakefulness by conducting basic to clinical research	University of Tsukuba	Masashi Yanagisawa
Earth-Life Science Institute(ELSI)	Globally-Advanced Interdisciplinary Research Hub for Exploring the Origins of Earth and Life	Tokyo Institute of Technology	Kei Hirose
Institute of Transformative Bio-Molecules (ITbM)	Changing the world with molecules: Synthetic Chemistry and Plant/Animal Biology	Nagoya University	Kenichiro Itami

Centers adopted in FY2010

International Institute for Carbon-Neutral Energy Research(I2CNER)	The Grand Highway for a Carbon-Neutral Energy Fueled World	Kyushu University	Petros Sofronis

Centers adopted in FY2007

Advanced Institute for Materials Research (AIMR)	Establish a World-Leading Research Organization in Materials Science	Tohoku University	Motoko Kotani
Kavli Institute for the Physics and Mathematics of the Universe (Kavli IPMU)	Cross-Disciplinary Research Center for Addressing the Origin and Evolution of the Universe	The University of Tokyo	Hitoshi Murayama
Institute for Integrated Cell-Material Sciences (iCeMS)	Creating a new field of integrated cell-material science in the mesoscopic domain	Kyoto University	Susumu Kitagawa
Immunology Frontier Research Center(IFReC)	Observation of immune reaction - Unveiling dynamic networks of immunity -	Osaka University	Shizuo Akira
International Center for Materials Nanoarchitectonics (MANA)	Materials Nanoarchitectonics - New paradigm of materials development -	National Institute for Materials Science	Takatoshi Sasaki

3.1.4 Center of Innovation (COI) program

(1) Program Summary

This program provides funding for a maximum of up to nine years for challenging and high-risk R&D aimed at realizing the visions of an ideal society in 10 years' time. Under the Center of Innovation Science and Technology based Radical Innovation and Entrepreneurship Program (COI STREAM), which was launched by MEXT in FY2013, the anticipated needs of society 10 years hence were examined, and the images of an ideal society and the lifestyles to which these needs lead ("visions") were set.

Under this Center of Innovation (COI) program, based on these visions the JST provides intensive support for R&D through industry-academia collaboration aimed at commercial viability from the basic research stage to enhance innovation platforms to continuously generate cutting-edge innovation, in addition to identifying innovative R&D themes with a view to 10 years in the future, and eliminating walls to existing fields and organizations. The Program also supports the realizing of cutting-edge innovation through industry-academia collaboration, which cannot be achieved by universities or companies alone. Intensive support is provided for basic themes in interdisciplinary/connected fields that present high risks but also show high promise for commercialization. Throughout the entire R&D period, the activities of COI Sites are managed thorough resources from industry and supported by JST.

(2) Term and budget scale

Term: F2013–FY2021: maximum of 9 years (planned)

Grant amount (for one base/year): approx. 1 billion yen

(3) Adopted sites

Vision 1 Secure sustainability as a country advanced in its aging population and declining birth rate

Site name	Core institution	Project Leader	Research Leader
Innovative Food & Healthcare MASTER	Hokkaido University	Masanori Yoshino Hitachi, Ltd.	Akiko Tamakoshi, Hokkaido University
Center of Healthy Aging Innovation	Hirosaki University	Toshihiko Kudo MCS Corporation	Shigeyuki Nakaji, Hirosaki University
The Center of Innovation for Creation of Platform on Big Life Data from Unconscious Sensing to Support Human and Social Well-Being	Tohoku University	Iwao Waga NEC Solution Innovators, Ltd	Tomokazu Matsue, Tohoku University
Self-Managing Healthy Society	The University of Tokyo	Tomihisa Ikeura The University of Tokyo	Ung-il Chung/ Yuichi Tei, The University of Tokyo
Center of Open Innovation network for Smart Life Care	Kawasaki Institute of Industry Promotion	Hiromichi Kimura Kawasaki Institute of Industry Promotion	Kazunori Kataoka, Kawasaki Institute of Industry Promotion
Bright Future for All Ages with Healthy Innovation by Daily Exercise	Ritsumeikan University	Takahide Tanaka OMRON HEALTHCARE Co., Ltd.	Tadao Isaka, Ritsumeikan University
The Last 5X innovation R&D Center for a Smart, Happy, and Resilient Society	Kyoto University	Tsuyoshi Nomura Panasonic Corporation	Hidetoshi Kotera, Kyoto University

Vision 2: Create a living environment with a high quality of life as a prosperous and reputable country

Creating Innovation for "Synesensory" through Inspirational Arts and Science & Technology	Tokyo University of the Arts	Koshi Yamamoto JVC KENWOOD Corporation	Takashi Kiriyama, Tokyo University of the Arts
Research Center for the Earth Inclusive Sensing Empathizing with Silent Voices	Tokyo Institute of Technology	Toshiyuki Hiroi Sony Corporation	Hitoshi Wakabayashi, Tokyo Institute of Technology
COI Site to develop a "Super Nippon-jin" by activating human power	Osaka University	Takeshi Uenoyama Panasonic Corporation	Kazuhiko Matsumoto, Osaka University
Center of KANSEI Innovation Nurturing Mental Welfare	Hiroshima University	Takahide Nouzawa Mazda Motor Corporation	Shigeto Yamawaki, Hiroshima University

Vision 3: Establish a sustainable society with vitality

Frontier Center for Organic System Innovations	Yamagata University	Toru Miyake Dai Nippon Printing Co., Ltd.	Yoshihiro Ohba, Yamagata University
Innovative Center for Coherent Photon Technology(ICCPT)	The University of Tokyo	Junji Yumoto The University of Tokyo	Shinji Tsuneyuki, The University of Tokyo
Center of Kansei-oriented Digital Fabrication	Keio University	Kenji Matsubara Longfellow Inc.	Jun Murai, Keio University
Construction of next-generation infrastructure using innovative materials	Kanazawa Institute of Technology	Shouichi Ikebata Daiwa House Industry Company, Limited	Jun Murai, Keio University
Global Aqua Innovation Center for Improving Living Standards and Water-sustainability	Kanazawa Institute of Technology	Shouichi Ikebata Daiwa House Industry Company, Limited	Kiyoshi Uzawa, Kanazawa Institute of Technology
Mobility Innovation Center	Nagoya University	Takayuki Morikawa Nagoya University	Takayuki Morikawa, Nagoya University
Center for Co-Evolutional Social Systems	Kyushu University	Shinya Ishihara Nippon Telegraph and Telephone West Corporation	Masato Wakayama, Kyushu University

3.1.5 Program on Open Innovation Platform with Enterprises, Research Institute and Academia (OPERA)

(1) Program Summary

The objective of this program is to expand industry-academia partnerships in basic research and human resources training, and accelerate open innovation through the formulation of "technology and system reform scenarios." These scenarios will mobilize universities' intellectual property through cooperation with industry and the nurturing of new key industries, and accordingly through R&D research in non-competitive fields that incorporates both academic challenge and industrial innovation. In addition to endeavoring to generate innovative technologies that will form the core of new key industry development, the program aims to create platforms with sustainable research environments, research systems, and human resources training systems with the capability to nurture new key industries. By integratedly promoting industry-academia joint research in non-competitive fields, training doctoral students and other human resources, and industry-academia collaboration system reforms through university-private enterprise consortium-type collaboration, the program aims to be a full-fledged driving force behind open innovation, realizing full-blown industry-academia collaboration through "organization" vs "organization".

The program is a matching fund-type R&D program utilizing private funding provided by corporate enterprises, which participate in projects from the stage of basic research planning by the relevant university.This contributes to cutting R&D costs and personnel expenses for doctorial students, etc., and promotes full-scale industry-academia joint research. Universities and private companies form "alliance consortiums" to head research platforms and promote R&D. In order to nurture human resources to take the lead in generating innovation through cutting-edge technology, participation in projects by a wide range of human resources, including students and young researchers, is recommended. Moreover, with regard to human resources training for doctoral students, expectations are held for the construction of human resources training systems with a view to collaboration with the WISE Program (Doctoral Program for World-leading Innovative & Smart Education) overseen by MEXT.

(2) Term and budget scale (Changes depending on the fiscal year of recruitment/adoption)

Approx. 100–170 million yen/fiscal year over 5 fiscal years

Areas adopted in FY2016

Research area	Consortium	Project Leader
World-Leading Open Innovation Platform of Fusion Technologies Bridged IT and Transportation System Areas	Industry-Academic Co-creation Consortium for IT and Transportation System	Tetsuo Endoh, Tohoku University
Creating Ultimate Organic Function Materials, Building Platform Technology for Integrating Them Into Social Systems, and Development Towards Soft Matter Robotics*	Soft Matter Robotics Consortium	Yoshihiro Ohba, Yamagata University
Creation of Platform Technology for Building a New Social System Based on Human Machine Harmonization Systems and Their Values*	Human machine harmonization system consortium (HMHS Consortium)	Kazuya Takeda, Nagoya University
Innovative Creation Technology of Useful Cells and Organisms by Genome Editing Technology*	Consortium for Industry-University Cooperation in Genome Editing Technology	Takashi Yamamoto, Hiroshima University

Areas adopted in FY2017

Creation of Advanced Quantum Application Technology for a Safe, Secure and Smart Long-living Society*	Quantum Innovation for Safe and Smart Society	Takashi Nakano, Osaka University
The Creation of a Development Platform for Implantable/Wearable Medical Devices by a Novel Physiological Data Integration System*	Consortium for Creating Implantable/ Wearable Medical Devices	Naoto Saito, Shinshu University
Creation of Technology for Continuous Social Activities in Large-Scale Urban Buildings in Normal Times and the Time of Disaster *	Consortium for Socio-Functional Continuity Technology (SOFTech)	Satoshi Yamada, Tokyo Institute of Technology

* Provisional translation by CRDS/JST

■ Contributors of Beyond Disciplines ■

Toshiki Nagano (**Supervising, editing and writing**)
Toshikazu Fukushima (Information science and technology for decision-making in a complex society)
Satoru Bannai, Koji Oyama, Masahiro Tsuji (R&Ds for solving social issues by data science)
Tatsuya Ohira (Advanced design and manufacturing with Digital Twins and Cyber Physical Systems in future industries)
Tsuyoshi Motegi, Toshio Baba (Robotics as integration technology)
Satoshi Miyashita, Hiromoto Shimazu (Data-driven innovations in Materials and Life Sciences)
Kunio Hori (Cutting-edge analytical instrumentation for deciphering biological phenomenon)
Hideaki Yamamoto, Asuka Kuwabara (Bioproducts and Biosystems Engineering)
Ryoji Nakamura (Nexus approach for water, energy, and food security)
Yasushi Sekine, Ryoji Nakamura (Science and technology for sustainable use of critical resources and materials)
Toshiki Nagano, Kazuo Matsuda (Innovations in Separation Engineering)
Aya Araoka (Next-generation Biomaterials Engineering)
Hiromoto Shimazu, Toshiki Nagano (Structural reforms of research systems/laboratories; nationwide research infrastructure/platform for promoting transdisciplinary research)
Takashi Nakagawa, Hiroaki Harada (Systems and Programs in Japan)
Mina Komatsuzaki, Junko Negami, Masataka Horiuchi (Organization)
Tomohiro Nakayama (Planning/conception)

CRDS-FY2018-RR-02

Beyond Disciplines

— JST/CRDS focuses on 12 transdisciplinary research themes (2018) —

March, 2019
ISBN 978-4-88890-633-3

Center for Research and Development Strategy, Japan Science and Technology Agency

7, Gobancho Chiyoda-ku, Tokyo 102-0076 JAPAN
Phone +81-3-5214-7481
E mail crds@jst.go.jp
https://www.jst.go.jp/crds/

ISBN 978-4-88890-633-3