Knowledge Science and Technology Creation

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Abstract---This paper introduces a research program on theory and practice of technology creation based on knowledge science. The goal of this program is to create a world-class center of excellence in the following areas: (1) Theoretical Research: With a final target of strategic research and the development of scientific technologies, we will study knowledge fusion and development in important scientific fields, and then establish a theory of scientific knowledge creation. (2) Practical Research: As we develop theories, we will apply them in scientific laboratories and improve them by feedback from practice. Repeating this task, we will improve the theory and promote the creation of useful scientific technologies. At the same time, we will train graduate students in this environment, and teach them to become knowledge coordinators or creators.

I. INTRODUCTION

This program will establish an interdisciplinary research field called the Study of Scientific Knowledge Creation. The new research field of Knowledge Science is the basis of this program, which models the process of knowledge creation and supports knowledge management. The School of Knowledge Science, established in 1998 at Japan Advanced Institute of Science and Technology (JAIST), is the first school established in the world to make knowledge a target of science. At this graduate school, knowledge management research is already producing results in areas such as knowledge conversion theory, knowledge systematizing methods, and methods for the development of creativity in the field of management science.

Knowledge science should help researchers produce creative theoretical results, not only in management science, but also in important natural sciences such as biotechnology, nano-technology, environmental technology, and information technology. For that purpose, it is necessary to design an environment, including time, place, people, context, etc. that supports the development and practice of knowledge creation theory: Socialization => Externalization => Combination => Internalization in technology research. This research program is a vehicle to integrate theory and practice, to combine knowledge in social science and knowledge in natural science, to produce new theories, and finally to create a new research field called the study of scientific knowledge creation.

This paper introduces the plan of this program followed by a systems methodology under development that could help the success of this program.

II. PURPOSE AND NECESSITY

Japan is poor in natural resources, and for this reason, its economy must rely on the creation of technology. The knowledge base that supports that technological creation may well be the most valuable infinite resource in our country. Thus, it is vital to begin to continuously and systematically develop the theory of technology creation, verifying the theory in scientific laboratories, and improving the theory by feedback from practice.

A. Goal of the program

The goal of this program is to create *a world-class center of excellence* in the following areas:

- *Theoretical Research*: With a final target of strategic research and the development of scientific technologies, we will study knowledge fusion and development in important scientific fields, and then establish *a theory of scientific knowledge creation*. With respect to education, we will select excellent graduate students from the School of Knowledge Science, train them in this environment, and teach them to become *knowledge coordinators* who can see the big picture and ably manage creative research activities.
- *Practical Research*: As we develop theories, we will apply them in scientific laboratories and improve them by feedback from practice. Repeating this task, we will improve the theory and promote the creation of useful scientific technologies. With respect to education, we will select excellent graduate students from JAIST's schools of Information and Materials Science, train them in this environment, and teach them to become *knowledge creators* with advanced research and development capabilities.

B. Unique features

Graduate courses designed to develop interdisciplinary fields have been established at many universities. However, simply establishing an interdisciplinary course or center is not enough. If the theory and practices that promote fusion of different fields are not followed, creative research results may not be produced. This research program is unique in the sense that it realizes a complete environment in which knowledge coordinators and creators can collaborate to produce theoretical and practical research on knowledge creation.

Moreover, the School of Knowledge Science has the expertise to train students as knowledge coordinators, since it is already doing research on systems to support knowledge creation and on the integration of social information. Likewise, the schools of Information and Materials Science have the expertise to train students as knowledge creators, because they are already doing advanced scientific and technological research. To create this environment, we will establish a new department called *Study of Scientific Knowledge Creation*, staffed by researchers selected from three schools, and dedicated to the powerful promotion of creative interdisciplinary research. In this sense, this program differs greatly from conventional organizations.

C. Importance and possibilities

One of the problems of research and development in Japan is that scientific research has relied too heavily on the creativity of individual researchers. This program creates an environment in which we can carry out creative research into the theory and practice of knowledge creation and teach students to become knowledge coordinators and creators. *A knowledge coordinator will convert research activities into systematic creative research, and a knowledge creator will enhance the long-term future of our country based on original scientific research.*

To continuously create intellectual energy (talented people, information, support systems), we will establish a center where scientific technology development strategies can be developed in cooperation with outside research organizations, companies, and administrations. At the same time, we will establish a department of scientific knowledge creation, staffed by selected scientists from all schools at JAIST, and develop an education system that fully demonstrates the synergistic effect of combining the different fields. This system will continuously create scientific knowledge, offering an advanced model for setting important research priorities and promoting research and development, and thereby affecting management of research and development in other universities, research institutions, and enterprises. Thus, this program can contribute to strengthening the intellectual resources of Japan, so as to help it become the leading technology creation country in the future.

D. Expected results

The results of our research will be methodologies and techniques for knowledge creation; data, information and models for knowledge integration; systems to support creativity; and new technologies created as practical results. The most valuable result will be the theory of scientific knowledge creation, as developed by all project members in the "*ba*":

- *Integration of social information*: Methods for knowledge discovery, knowledge modeling, road mapping, representational models of knowledge, databases of scientific knowledge, and road maps.
- *Development of support systems for knowledge creation*: Knowledge systematization support, creativity support, awareness support, knowledge creation support, and visualization of complex phenomena.
- *Creation of scientific knowledge*: Applied technology of living functions, super-molecule biomaterial technology, applied technology of useful proteins, new materials with highly efficient characteristics, environmental protection technology, energy saving plastics, functional conductor technology, advanced sensitivity information technology, high reliability software, and ultra high-speed distributed networks.
- *Creation of an ideal environment for theoretical research and practice*: Theory of knowledge-creating systems, theory of environmental ("*ba*") design to promote scientific creativity, and theory of scientific knowledge creation.

The educational output will be the continuously replenished pool of talented people trained by the new department and the center. These people will be:

- *Knowledge coordinators*: People who can manage creative research activities based on the theory of knowledge creation.
- *Knowledge creators*: People with advanced research and development capabilities, who can take a broad view and identify future developments and trends.

E. Social implications

Since its creation in 1998, the School of Knowledge Science has been a leader in pursuing research about the mechanisms that create knowledge and value. One of the concrete research results is the knowledge management model for producing management resources and competitive power, which has been constructed by combining industrial organizational theory, technical management theory, management strategy theory, and management organizational theory. So far, these results have been restricted to management science. However, "knowledge science" has much to offer to natural science as well, especially in Japan, a country that aims to become the best technology creating country in the world.

The advances in science and technology that brought about the material abundance of the 20th century have led to the need to consider how new value is created by technology in relation to people, society, and the natural environment. An immediate need is to produce talented people, knowledge coordinators, who can help solve this problem based on the theories of "knowledge science", and knowledge creators, who are equipped to systematically carry out research and development in important practical technology areas based on theory. This research program does not merely aim at a fusion of different fields. Rather, the goal is to conduct theoretical research that promotes creation from fusion, and simultaneously train the knowledge coordinators and creators who can implement the theories, thereby contributing to Japan's intellectual property formation.

Scientifically, it leads to establishment of the study of scientific knowledge creation as a new research field. Socially, the technologies acquired as creative research results will contribute not only to material abundance, but also to human welfare and improvement of the global environment.

III. IMPLEMENTATION PLAN

The team of researchers in charge of this program consists of a theoretical group (ten researchers from the School of Knowledge Science and the Center for Knowledge Science), and a practical group (ten researchers from the School of Materials Science and the School of Information Science). The theoretical group will do research on methodologies, methods, and systems that support the creation of scientific knowledge, while the practical group will actually produce new technologies based on theoretical research. Finally, the two groups will cooperate to establish the theory of scientific knowledge creation.

A. Theoretical research

The subgroup for knowledge systematization, in consultation with the members of the practical group, will devise a plan to collect scientific, technical, economic, and societal data that are required for creative research, as well as design a database system for scientific and technological knowledge. Based on previous research, this subgroup will develop methods for knowledge discovery, for modeling of knowledge representation, and for knowledge systematization. Moreover, this subgroup will improve the systems methodology for knowledge integration and creation, and also design an environment, or "*ba*," for developing the theory of knowledge creation, in cooperation with the next subgroup.

The subgroup for management of technology or knowledge, in cooperation with the members of the practical group, will create a plan to gather the technology prediction data considered necessary for creative research, and also design a database system for technology road maps. In addition, this subgroup will develop a technology management education program and propose a method of educating talented people within this program. Furthermore, based on past research on the methodology of technology management and the methodology of strategic research and development, this subgroup will produce a set of technology road maps in cooperation with the members of the practical group. They will improve the theory of organizational knowledge creation, and then design an environment, or "*ba*," for developing the theory of knowledge creation.

The subgroup for knowledge creation support will present the support systems that they have been developing to the members of the practical group, and, based on intensive discussions, improve the existing systems or develop new ones. More concretely, they will develop support systems for concept creation and awareness, an information system for knowledge creation from research to management of advanced technology, a system for the visualization of complex phenomena in physics, chemistry, or biology.

B. Practical research

The subgroups for biotechnology, for materials and the environment, and for information science will develop the database of scientific knowledge in cooperation with the subgroup for knowledge systematization, as well as the database of technology road maps in cooperation with the subgroup for technology or knowledge management. Based on the models and information provided by the knowledge systematization group, the technology development strategies provided by the technology or knowledge management group and the support systems provided by the knowledge creation support group, this subgroup would perform strategic research. Through these activities, all project members will contribute to establishing a theory of scientific knowledge creation.

The technologies planned for development in this program include applied life science technology, super-molecule biomaterials technology, applied technology of useful proteins, new materials with highly efficient characteristics, environmental protection technology, energy-saving plastics, functional conductor technology, advanced sensitivity information technology, highly reliable software, and ultra high-speed distributed networks.

C. Creative environment

We will construct a system for sharing data, information, and knowledge to support a creative research environment. The School of Knowledge Science already has brainstorming rooms, collaboration rooms, refreshment rooms, etc., where people from various fields can communicate. Using this infrastructure, the program will develop and improve the system of knowledge creation; based on this system, the program will form a "*ba*" that will establish a new research field of scientific knowledge creation.

D. Educational Implementation

The School of Knowledge Science has a unique education system that offers students an excellent learning environment to study knowledge creation or problem solving methodologies, methods, and support systems. This project will develop an education program beyond the frame of graduate schools, and establish an environment in which students can experience creative activities, uniting various value systems. We will produce "knowledge coordinators" who are familiar with both development and management of technology, and who can coordinate creation and circulation of knowledge. We also will produce "knowledge creators" who are creative advanced technology researchers with a unique education of the theory of knowledge creation, based on their advanced education in materials or information science.

We will prepare lectures on theoretical subjects such as Scientific Philosophy and History of Science, Economics and Management of Innovation, Methodology of Systems Science, Theory of Intellectual Property Strategy, etc., and on practical subjects such as Advanced Sciences, Biotechnology, Nano-technology, Environmental Science, Information Science, etc. Graduate students selected from all schools will begin to participate in the program immediately. In addition to a balanced selection of courses, each student must spend two months (master course) or six months (doctoral course) in different laboratories, doing practical or theoretical research. JAIST's Internet entrance examination, its satellite campuses in big cities, and its distance-learning program will enhance the pool of potential students.

IV. Systems Methodology

Definitions of knowledge range from the practical to the conceptual to the philosophical, and from narrow to broad in scope, which are summarized in [1]. For instance, knowledge is organized information applicable to problem solving [2]; knowledge is information that has been organized and analyzed to make it understandable and applicable to problem solving or decision making [3]; or, knowledge is reasoning about information and data to actively enable performance, problem-solving, decision-making, learning, and teaching [4]. These definitions require clear distinctions between data, information, and knowledge. Several authors try to distinguish them [5][6]. Several authors also define typologies of knowledge, for instance, Nonaka and Takeuchi [7] suggest that the conversion from tacit to explicit knowledge and vice versa is crucial in knowledge creation.

We here consider the deference between information and knowledge simply, but considers deeply the power or ability to convert from one to another, which is the ability to understand and learn things, or the ability to think and understand things instinctively or automatically. This consideration suggests that what we should do research by the name of knowledge science. This consideration also suggests the basic elements of knowledge science, which are people, information, and system. These are hints to develop a new systems methodology for knowledge creation [8].

A. Information and knowledge

Let us consider the definitions of information and knowledge, each of which has the following two meanings: Information is: (A) Knowledge transmitted by character, sign, and voice, etc. (B) Data arranged to be useful for decision-making. Knowledge is: (C) Recognition memorized personally or socially. (D) Judgment or a system of judgment that has objective validity. Apparently, there are no clear distinctions between information and knowledge. However, they are different and each of them is converted to the other. What is the energy to bring such transformation? Here, let us call it *intelligence*. Intelligence is: (E) Ability to understand and learn things. (F) Ability to think and understand things instinctively or automatically.

People convert data and knowledge into information for some purpose. They create new knowledge based on data and information. These conversion and creation require existing knowledge and some ability called intelligence. We can see that the approach from management science aims at developing the ability (E), while the approach from information science is related to the ability (F). Of course, both are important. However, their integration is difficult.

We should understand the limitation of our ability to objectify the real world, the limitation of our ability to understand indirect observation, and the limitation of our ability to analyze things objectively. The total system is inseparable, but we cannot perceive the inseparable whole. Therefore, we usually cut off weak links and nonlinear features, and consider individual linear subsystems that we can well imagine. Artificial intelligence inevitably inherits this weakness of human beings. Social scientists are never satisfied with such pieces of knowledge. That is why Nonaka theory requires direct experience in the knowledge management and creation process. From this background, two approaches have been developed separately. One is knowledge management by the persons concerned. The other is knowledge management by information and communication technology. However, there is clearly a limit in the approach to knowledge management from only one discipline. We think it is necessary to develop a systems methodology that uses both approaches systematically.

As we have just mentioned, in the context of contemporary knowledge management, there are mainly two approaches to develop intelligence of human beings: one is from management science and the other is from information science. To integrate these approaches and establish a new discipline is a quite natural idea, and then the School of Knowledge Science was established in Japan Advanced Institute of Science and Technology in 1998. Since knowledge will certainly become a key concept in every feld in the 21st century, the school has enlisted researchers from different fields to develop knowledge science that has a trans-disciplinary property in nature.

This is, however, not the first trial in our history, and most of them are not necessarily successful. Something is necessary for the success, which may be the idea of system. Systems science may have an important role for the success of establishing knowledge science. However, there are also two different schools in the field of systems science: hard and soft schools, which roughly correspond to the fields of information science and management science, respectively. Something is necessary more.

One of the difficulties, and also a challenge of knowledge science, is to deal with different kinds of knowledge. The most reliable knowledge source is the scientific investigation that produces public knowledge. This is objective, unique, universal, and repeatable. One the other hand, knowledge obtained in social science includes meanings given by people inevitably, which are wisdom-based knowledge, insight-based knowledge, and experienced-based knowledge. These kinds of knowledge are subjective, vague, ambiguous, and circumstantial. We would like to develop a systems methodology for integration, management and creation of these different types of knowledge. This is a challenge in knowledge science that creates justified true belief.

B. New methodology

We are developing a systems methodology that uses approaches in social and natural sciences complementarily. This systems methodology itself is a system consisting of five subsystems. The first one is scientific approach that uses physical laws, data analysis, etc. The second is information science, especially a large-scale computer simulation and the networking technology. The third is a method in social science, which is related to forming partnerships among social members. The fourth is knowledge science that integrates, transform, and create knowledge. Finally, systems science is used to manage these different approaches.

The developing system can be called a knowledge-creating system. The system integrates statistical data and individual persons' fragmentary knowledge, and then creates new knowledge nobody had before. Such knowledge must be tacit, otherwise someone including the system had it; this is a contradiction. Therefore, the system should have a process to convert tacit knowledge into explicit knowledge. This means that the members of the project or relevant people constitute a part of the system.

At the subsystem *Intervention*, we consider what kinds of knowledge are necessary to solve the faced problem, and request three subsystems to collect them. Here, knowledge is a problem. At the subsystem *Intelligence*, we collect necessary data and information, analyze them with a scientific attitude, and make a model for simulation or optimization. Here, knowledge is a model. At the subsystem *Imagination*, we simulate complex phenomena based on partial knowledge, using information technology. Here, knowledge is scenarios. At the subsystem *Involvement*, we hear opinions of people by organizing a meeting or questionnaire survey. Here, knowledge is opinions. At the subsystem *Integration*, we evaluate reliability and justifiability of outputs from three subsystems, and integrate them. Here, knowledge is solutions.

We evaluate the knowledge-creating system from the following viewpoint:

- Are the system, actors and contents well defined?
- Is its foresight power enough?
- Is the totality achieved?
- And, is it actually useful?

An example of complementary use of people and computer is as follows: Suppose now we have a problem of how to activate ecological industry. At *Intelligence*, we will make a model with computer based on ideas of people. At *Imagination*, we carry out computer simulation with assumptions given by people. At *Involvement*, we develop a network with the help of information technology initiated by people. Then, at *Integration*, we will build a strategic scenario-based system by consulting the relevant people.

This methodology is a system because it has the following properties:

- Hierarchical structure;
- Emergent characteristics;
- Function of communication;
- Function of control.

For example, if we consider sustainable development, the role of subsystem *Intelligent* is prediction based on scientific knowledge. To achieve this task, this subsystem asks the lower system to develop a mathematical model, and then the subsystem *Involvement* of this lower system will collect necessary data consulting the relevant people. Them, the next lower system will start collecting numerical data, qualitative data, and scenario data. The subsystem *Imagination* of this layer will ask to collect assumptions and ideas with their possibilities. In such a way, this knowledge-creating system has a hierarchical structure with functions of communication and control. Based on this knowledge with logical thinking and educated intuition, we can produce a systemic knowledge. We can consider that creation of such systemic knowledge or integrated knowledge is a kind of emergency.

The next question: how is the trans-disciplinary knowledge exchange achieved? The subsystem *Intelligence* is mainly based on natural sciences, mathematics, and engineering. The subsystem *Imagination* is mainly related to information science, economics, and statistics. The subsystem *Involvement* is mainly based on management science, social science, and cultural sciences. The other two subsystems *Intervention* and *Integration* are of course related to systems science and knowledge science. Different disciplines are used to determine boundary conditions or to check consistency of knowledge of subsystems. However, this is not performed automatically. This is an interactive system. This systems methodology is used for knowledge management or projects evaluation in the COE program.

V. PERSONAL LOAD MAPPING

The main target of academic labs should be “emerging technology” and “creative invention”, and academic labs should also play a role in the accumulation and expansion of scientific knowledge and inspiring researchers. We put forward a new methodology for knowledge management in academy by applying Interactive Planning (IP) [9]; IP is regarded as a basic methodology for solving creative problems, to develop personal academic research roadmap.

A. Road maps

“Roadmap” can mean different things to different people. What all those different roadmaps have in common, however, is their goal, to help their owners clarify the following three problems:

- Where are we now?
- Where do we want to go?
- How can we get there?

Road mapping techniques have been used in academic institutions as a strategic planning tool. Many academic institutions publish their research roadmaps; for example, the Berkeley Lab at the University of California makes and publishes a research roadmap for its High-Performance Data Centers. Road mapping is also very helpful for individual researchers. Little work has been done to consider roadmaps for individual researchers. The rest of this paper will describe a process of making personal research roadmaps by applying interactive planning method.

B. New methodology

This new methodology has six phases with some cycles among those phases. The following is the brief description of those phases.

Phase 1: *Forming groups.* The new methodology suggests that the road mapping is a team activity. A group should contain two kinds of members in addition to the regular members. The first is experienced researchers, for example, professors, associate professors and so on. The second is knowledge coordinators. Knowledge coordinators are those people who can manage creative research activities based on the theory of knowledge creation. Knowledge coordinators can be master students, doctoral students or any other people who have the ability to be knowledge coordinators.

Phase 2: *Explanation from knowledge coordinators*. For applying the methodology smoothly, the knowledge coordinator should first explain the role of every member, the usage of personal research roadmaps, the process of making personal research roadmap, and the schedule of the group's road mapping activity

Phase 3: *Description of present situation*. In this phase, the experienced researchers give a description of the present situation in this field. In fact, it is very difficult to present all this information at one time, so this phase commonly includes several workshops.

Phase 4: *Every member's current status and idealized design*. In this phase, every member needs first to describe the experience (the skills and knowledge) he/she already has. The list should be shared with the entire group, so that other members will be able to effectively contribute good opinions and ideas in later discussions.

Phase 5: *Research schedule and study schedule*. In this phase each member puts forward a research schedule and study schedule that can fulfill the research goal and presents it to all group members; members can present more than one option. After getting opinions and ideas from the group members, members can refine and modify their own research schedule and study schedule. As in Phase 4, the knowledge coordinator(s) of the group must arrange several workshops until each member's research schedule and study schedule have been accepted by all (or most of) the members.

Phase 6: *Implementation and control*. The roadmap should be continuously refined in practice, which accords with the continuity principle of IP. The knowledge coordinator(s) should arrange regular seminars and workshops to monitor and control the implementation of the personal research roadmaps.

Similar to Ackoff's notion that the process of planning is more important than the actual plan produced, here the author would like to say that the process of road mapping is more important than the roadmaps produced. Road mapping is a never-ending process.

C. Support system

We are developing a road mapping support system. The system is web-based and can be accessed from anywhere through an Internet connection by a user with an authorized user account and a password. This enables group members to work together to keep the process moving without having to physically meet each other. This also can promote the participation of some important stakeholders. In scientific labs, the directors or experienced researchers, who can be thought as important stakeholders, may be very busy, with no time to participate in all of the discussions that play such an important role in the road mapping process. With this system, they can input their ideas through Internet, and those ideas will be stored in the system and available to those who can benefit from them.

The system heuristically asks users to input the information and ideas that can be used to make personal academic roadmaps. That information and those ideas can be edited at any time. Researchers are frequently asked to submit their research plans or proposals, but as the available information or knowledge changes, a researcher may find that new ideas change his/her thinking about the research. The online system can record and manage researchers' ideas and their "thinking history". A picture is worth at least one thousand words. Therefore, the system not only automatically produces the formatted roadmaps, but it also will generate figures to enhance understanding.

The system provides a platform for group members to share ideas. A user can view other members' research roadmaps, comments on them, and see other members' comments on his/her own roadmaps. It also will provide tools for Internet-based brainstorming and consensus building. As many users, in different labs/groups, make their personal academic research roadmaps within the system, a roadmap archive will be formed in a bottom-up way. This archive will provide intelligence for data mining that will tell users who is doing similar work, who may be a potential research partner, and so on. Users will also be able to find some research trends from the archive.

VI. CONCLUDING REMARKS

One of the important research topics in knowledge science is to develop systems methodologies for trans-disciplinary knowledge exchange with information and communication technologies. By the name of knowledge science, we are developing methodologies and methods related to information environment with which we can convert subjective, implicit or individual ideas into justifiable or hopefully reliable ones. This is not necessarily implies the utilization of information technology only. The methods and ideas in knowledge science should be those that guarantee justifiable trans-disciplinary knowledge exchange. The role of systems science is crucial for development of knowledge science.

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