Analysis of synthetic approaches described in papers of the journal *Synthesiology*

— Towards establishing synthesiological methodology for bridging the gap between scientific research results and society —

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The methodology of synthesis has been studied by analyzing 70 papers published in the academic journal, *Synthesiology*, launched in 2008. As a result, it has been found that each technological field has its distinctive features, e.g. there are many break-through type syntheses in biotechnology and nanotechnology, and the strategic selection types are commonly observed in the metrology and measurement field. In addition, we have found a common synthetic method as a whole. A kind of methodology called "technological synthesis" has been found to be important in the *Full Research*, and continuous follow-up process called "synthesis for social introduction" is also found to be one of the features to introduce the research results to society. Both the former and the latter involve feedback processes, and moreover, in the latter case, a dynamic synthetic method that can be called a spiral-up process is observed, where many feedback processes are repeated successively through social trials.

Keywords : *Synthesiology*, synthetic study, *Full Research*, *Type 2 Basic Research*, technological synthesis, synthesis for social introduction

1 Introduction

The objective of the journal *Synthesiology*[Term 1] is to publish the research papers on the practice of how to integrate the individual elemental technologies and scientific findings and to synthesize the results of the R&D into a form usable in society. Specifically, the journal requires that the papers present the descriptions of the research objectives and social value, the clarification of the scenario to achieve the objectives, the selection and integration of the elemental technologies, and the result evaluation and its future prospects.[1] The knowledge of the research methods obtained through the accumulation of these research papers may lead to practical examples of *Full Research*,[Term 2 [2]] and if such research findings diffuse into society and contribute to innovations, *Synthesiology* can play a major role as a new type of academic journal. The elemental technologies alone do not contribute to creating innovations, but rationally linked with the knowledge of diverse disciplines, they need to be integrated and synthesized to construct a specific technology before introduction to society. We believe it is beneficial to society to clarify the synthesis methodology of the R&D.

Therefore, of the 70 papers published in *Synthesiology* Volume 1 No. 1 to Volume 3 No. 4, we looked at nine papers in the field of environment and energy, 10 in life sciences (biotechnology), seven in life sciences (human technology), 12 in information technology and electronics, 14 in nanotechnology, materials and manufacturing, 12 in metrology and measurement science, and 6 papers in geological survey and applied geoscience. We analyzed the methods of synthetic research scenarios in each research field, and attempted extracting the common methodology. Chapter 2 addresses the basic types of synthesis of the elemental technology, chapter 3 is the analysis of the synthesis method for each field, and chapter 4 presents the characteristics of the field based on the analyzed synthesis method. In chapter 5, we present the "technological synthesis" of which the necessity in the synthesis method has been clarified, and the characteristics of the "synthesis for social introduction."

By the method of analyzing the written papers, this paper attempts to synthesize the new "study" called synthesiology to connect the research results to society.

2 Basic types of synthesis of the elemental technology

Kobayashi, one of the authors, proposed the examples of the basic types of synthesis of the elemental technology: (1) aufheben type (method by which a new concept is created by

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the sublation of two opposing theses),[Term 3 [3]] (2) breakthrough type (method in which the important elemental technology is combined with peripheral technology and grown into integrated technology), and (3) strategic selection type (method in which the elemental technologies are strategically selected and synthesized).[4] These three types were extracted from the 12 research papers published early after the launch of *Synthesiology*.

One example of (1) aufheben type is the research by Nishii "A challenge to the low-cost production of highly functional optical elements"[5] that involves the combination of glass mold and imprint methods. In this research, a new technology was produced by the integration of the two methods that were considered impossible to coexist. Based on this example, in this paper, the aufheben type is used in a wide-ranging sense in this paper to describe the "complex synthesis method among multiple elements that were thought impossible to integrate." The concept specifically contains the integration and synthesis of the "structure," "function," "entity," and others.

The example of (2) breakthrough type is "Development of a small-size cogeneration system using thermoelectric power generation" by Funabashi and Urata.[6] This is an example where the discovery of layered cobalt oxides, an excellent thermoelectric material, became a breakthrough, and the integrated technology was formed by the addition of peripheral elemental technologies.

The example of (3) strategic selection type is the "A strategic approach for comparing different types of health risks" by Kishimoto.[7] In this research, the process of synthesis is the serial selection of several elemental technologies to achieve the research objective that is the risk assessment of chemical substances. Figure 1 shows the conceptual diagram of the basic types of synthesis method. These are extremely basic raw processes in the synthesis method. The processes where these are combined concurrently or in multiple steps, or where the improvements are made through the interaction of demand and actual environment can be observed. These raw processes were kept in mind when the following considerations were made. Table 1 shows the categorization of the types of synthesis by fields, and it includes the categorization of the combined types as well as single basic types. These types will be explained in detail below.

3 Analysis of the synthesis method for each technological field

(1) Environment and energy field

The researches categorized in the environment and energy field include the extremely wide-ranging topics from the assessment technology such as environment and risk assessments, behavior and control of environmental load substances, renewable energy, energy saving, and production efficiency. Diverse methodologies have been proposed in the *Synthesiology* papers. However, following characteristics can be seen: 1) there are clear social demands such as the reduction of environmental load substances, CO_2 emission control, and compliance to social and administrative regulations; 2) to repond to these, "compromising" type or multidimensional technological integration is conducted, such as the multistep linkage of elemental technologies that are supported by science; and 3) the existing technology is further advanced through the review of elemental technologies and re-synthesis from the engineering standpoint.

For example, for the social demand of "comparing the risks of different kinds of chemical substances," it is necessary to express the scale of risk by a common index. However, since the necessary elemental data used in conventional risk assessment are insufficient, the necessary elemental data are determined by breaking down the new social demands, and the method of making estimates from the existing data is considered. The calculation of risk becomes possible based on the common index by re-integrating the elements obtained.[7] Therefore, the method taken is to strategically select the elemental technologies that match the social demands and to integrate them, and this is the strategic selective type synthesis as explained in the previous chapter.

An example of the technological development to reduce the environmental load substance is the development of the catalyst production for clean diesel fuel by Yoshimura and Toba.[8] In the detoxification of the diesel exhaust, there is the social demand to dramatically decrease the sulfur content in the diesel fuel. To do so, it is necessary to develop a high performance hydrodesulfurizing catalyst. The authors identified the breakthrough point as the catalyst preparation method, and broke down the topic into several elements necessary for this technology and clarified the division of roles with the joint researchers (organization). By further breaking down the topic, key elemental technologies were

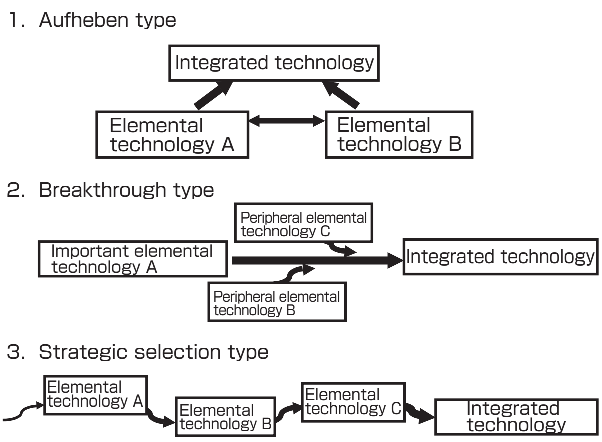

Fig. 1 Basic types of synthesis

Table 1. Categorization of synthesis by fields

	Aufheben	Breakthrough	Strategic selection	Spiral	Aufheben + Strategy	Breakthrough + Strategy	Breakthrough + Spiral	Strategic selection + Spiral	Breakthrough + Strategy + Spiral	
Environment/energy	2	1	3	0		3				9
Life science (biotechnology)		4	2	2		1	1			10
Life science (human life tech)	1		4			1		1		7
Information technology/ electronics	1	2	6				1	1	1	12
Nanotechnology/ materials/manufacturing	2	4	5		1	2				14
Metrology/ measurement science		1	11							12
Geological survey/ applied geoscience			3			1		2		6
	6	12	34	2	1	8	2	4	1	70

reviewed from the chemical and engineering aspects, laboratory level preparation method was completed as the important elemental technology, and commercialization was achieved through joint research with the catalyst producing company. Therefore, the elemental technologies broken down from the social demand had the multistep structure that was an aggregate of detailed elemental technologies. Since the lower level elemental technologies are solved by breakthrough type research and then are integrated, the overall scenario is the "strategic selection type + breakthrough type" synthesis (Fig. 2).

Another example of this type is the "Establishment of compact processes" by Suzuki *et al.*[9] To respond to the social demand of emission control of the environmental load substance from the chemical process, the technology using supercritical fluid of water or carbon dioxide instead of an organic solvent, which was a technology that was theoretically possible but not readily realized, was reviewed by breaking down into individual elemental technologies. It was found that unnecessary reactions occurred before reaching the optimal condition due to slow reaction, and the rapid heating and pressurizing methods were developed to attain the optimal condition rapidly as the elemental technology, and this process was synthesized along with other peripheral elemental technologies. The breakthrough was the process called detuning that involved purposefully withholding the ideal condition to create the optimal condition.

In the environment and energy field, since the goal is to fulfill the social demand by integrating the necessary elemental technologies, the synthesis is essential to meet the specific demand. In general, the strategic selection type scenario can be taken in the cases where the elemental technologies are identified by conducting strategic selection in the first stage and the results of R&D up to a point or their improvements to match the goal are used. This type of synthesis can be seen in three papers. On the other hand, in the case where there are major issues among the elemental technologies, which is shown in the low environmental load technology mentioned above, the breakthrough technology becomes essential, and the social demand can be met only if such breakthrough is realized. In these cases, the general scenario is the "strategic selection type + breakthrough type" synthesis, and there were three such cases.

There were also two aufheben types and one breakthrough type. The categorization is shown in Table 1.

(2) Life science field

The characteristic synthesis method in the life science (biotechnology) field is the cyclical development method. Suwa and Ono developed the comprehensive functional

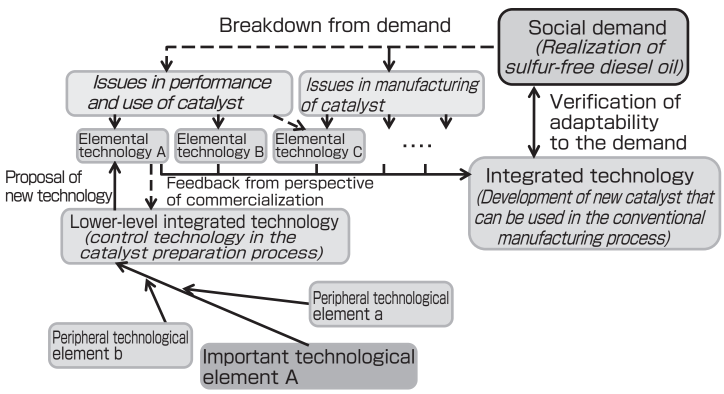

Fig. 2 Strategic selection + breakthrough type synthesis in the environment/energy field

analysis technology for drug design target genes through bioinformatics.[10] In the research that started in 2000, the elemental technologies such as gene identification and functional analysis tools were developed as *Type 1 Basic Research*, the pipeline for gene identification and functional analysis was constructed by combining the elemental technologies as *Type 2 Basic Research*, and the comprehensive database for cell membrane receptor GPCR was opened to the public as *Product Realization Research*. These became *Full Research* and the core technology was synthesized. Then, this core technology became *Type 1 Basic Research* for the next development, and resulted in the development of the new function program. Moreover, this technology contributed to the next development as *Type 1 Basic Research* for the application to organisms other than humans. The core technologies were subject to feedbacks from both the bioinformatics researchers and the experimental bioscience researchers. This helped the spread to society, and long-term maturation is taking place through the sequential development into larger *Full Research*.

Similar cyclical development can be seen in the *Full Research* for the bioluminescent protein by Ohmiya and Nakajima.[11] Ohmiya and Nakajima started from the scientific curiosity for bioluminescence, and discovered the bioluminescent proteins with different colors in fireflies. They decided to use this bioluminescent protein as the breakthrough technology for biofunctional tests. They altered the genetic structure so the protein will glow in the mammalian cells, and developed the technology to simultaneously detect the multiple gene expression in the cell. Since this technology can be used in the mammalian cells, the developed technology led to the product realization as the multigene expression kit to screen the effect of chemical substances on humans at cellular level, through joint research with companies. While this process may seem to be a relatively simple *Full Research* where the *Type 1 Basic Research* led directly to product realization, it is actually the fruit of efforts taken at each step including the demonstration of the correctness of the new concept through *Type 2 Basic Research*, product realization jointly with the companies, and social acceptance of the product. The researchers returned again to *Type 1 Basic Research* from here to handle multiple colors, and emphasized the importance of widening the concept further. Overall, the scenario is a cyclical development after the breakthrough type synthesis.

Although such cyclical development can be seen in other fields, the bio-industries seem to have characteristics unseen in other industries. Professor Gary P. Pisano of the Harvard Business School positions the bio-industry as a business that stands firmly in sciences, and offers the following analysis.[12] First, although bio-industry stands firmly in science, biology, its core discipline, is not as mature compared to physics and chemistry, and it is characterized by the extremely high uncertainty of the foundation technology. For example, it is like making a CPU without knowing the environment in which it will be used. The second characteristic of the bio-industry is the “integral type” nature. Personal computers are “modular types” where the issues can be broken down into modules and the optimization can be done for each module. On the other hand, the issues of automobiles cannot be broken down into modules, and it is an “integral type” that requires simultaneous optimization across the disciplines where the issues reside. The bio-industry is an “integral type.” Combining with the first characteristic, it is like building a car where one does not know whether it will run until it is made. In the bio-industry, since the uncertainty where one does not know whether a product is usable unless it is made is greater than other fields, it is necessary to commercialize even a small product in the market. This means that small *Full Research* is necessary to grow to large *Full Research*. The authors call such synthesis method “spiral type” (Fig. 3).

Such spiral type and the combination of breakthrough and spiral type syntheses were seen in three papers. In four papers that deal with biosensors, the breakthrough type synthesis through core technology is taken instead of the spiral type. In two researches, mass preparation of antifreeze protein by Nishimiya *et al*.[13] and practical application of regenerative medicine by Ohgushi,[14] the elemental technologies needed for realization are selected and integrated, and the researches are done by strategic selection scenarios. There is also the breakthrough type synthesis where the chromatography was advanced by a totally novel method of a single system pump using reservoirs, by Iemura and Natsume[15] (Table 1).

In human technology of the life science field, the objective of the R&D is to design a product that takes into account the characteristics of the person who uses the product. There, the basic point is to scientifically understand the human

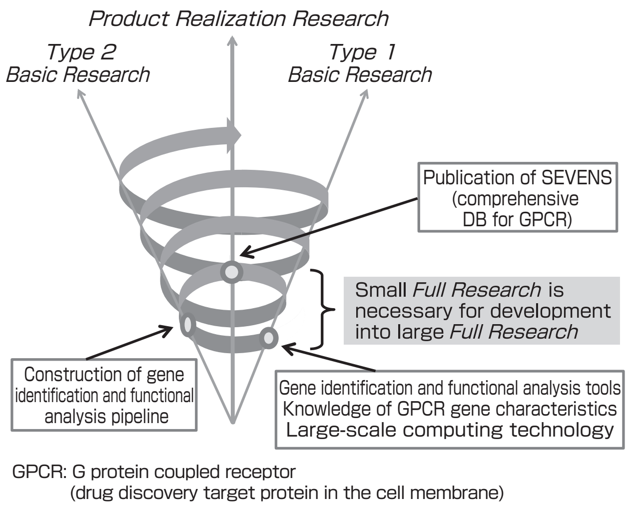

Fig. 3 Spiral type synthesis in the life science (biotechnology) field

functions. Although this is *Type 1 Basic Research*, the shift to *Type 2 Basic Research* becomes difficult if the human understanding is pursued excessively. It is necessary to clarify how the human function under study will be used and to synthesize the research scenario necessary for that purpose.

In the example of the R&D for well-fitting eyeglass frames by Mochimaru and Kouchi, the objective is to provide glass frames that fit each individual, and the technology was developed to help select the frame design that the customer prefers.[16] *Type 1 Basic Research* involves the development of shape design technology to formulate the glass frame that matches the head shape, and the elemental technologies necessary to apply this to the user purchasing the glasses are selected, and the technologies are integrated. The feature of this research is the development of the 3D shape model (homologous head model) that could be used for simple measurement, pattern categorization of the shape, and the perceptual evaluation. The overall goal was achieved efficiently. Therefore, the overall scenario is the synthesis by “strategic selection type + breakthrough type.” In fact, if the breakthrough technology does not occur, the efficiency of the synthesis becomes poor, and the research may stall. The development of the core technology as the breakthrough technology imparts great power to *Type 2 Basic Research*.

In the research on accessible design for the auditory signal that is compatible with the auditory function of the senior citizens by Kurakata and Sagawa,[17] it was important to determine the percentage of the elderly who can hear the auditory signal. Therefore, understanding the human auditory function precisely is not necessary, but the understanding of the distribution of the differences among people is important. This thinking was adapted to the understanding of the condition (auditory condition) at home where the alarm will actually be used. The sounds of the kitchen sink and television that may interfere with the auditory signal were measured, and by knowing the sound distribution, they were able to determine the sound volume that could be heard by the elderly. The property of the living environment must be understood to actually adapt the technology to the life scenes, and such study is necessary for the strategic selection type synthesis (Fig. 4).

The setting of the research scenario is necessary to understand how the human properties can lead to the product design. In the example of the research on eyeglass frames, the scenario taken was to install a device that allows simple shape measurement and style recommendation at the stores, to enable the selection of a frame that matches the individual. On the other hand, as an example of accessible design, there is the scenario where the industrial standard is employed as the tool to be reflected in the product design. If the industrial standard is referred to, product design for the elderly can easily be realized. Also, in the research for providing moving images that do not cause visually induced motion sickness (VIMS) by Ujike,[18] initially the industrial standardization was attempted, but the researchers also constructed the image evaluation system that incorporated the VIMS property that was found in the *Type 1 Basic Research*. This system was to be used by the filmmakers to learn the effects the images might have on the viewers, and corrections were to be made if necessary. The author conducted the elemental researches necessary to construct the tool that could be used by the filmmakers, and this can be considered strategic

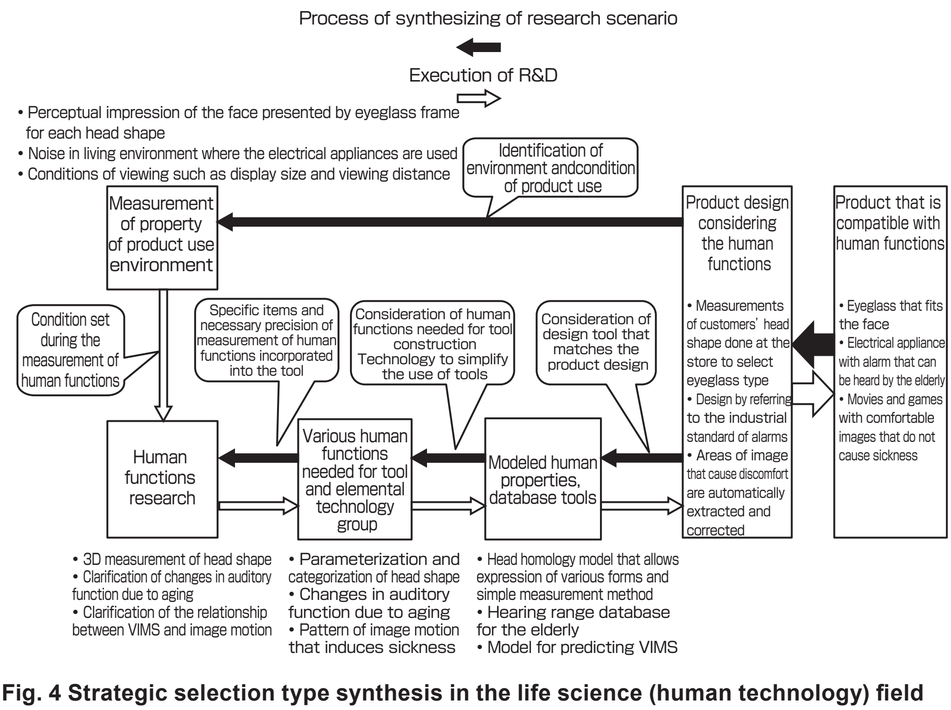

Fig. 4 Strategic selection type synthesis in the life science (human technology) field

selection synthesis. The development of the car navigation system by Ikeda *et al*. is similar.[19] In the field where a thing that is used by a person is synthesized, how the product will be used by the user (end user or the product designer) is estimated, and this is set as the goal. The basic method is to consider the elemental technologies necessary, and to synthesize the whole by strategically selecting the elemental technologies. There is also the aufheben type research by Kubo and Baba where the sensitivity based (kansei) lead user created a value different from the intent of the manufacturer of the IH cooking device,[20] and the strategic selection type and spiral type such as the Cyber Assist product where the users engaged in trials at exhibitions[21] (Table 1). The papers on the theory of service engineering are not included here.

(3) Information technology and electronics field

In the information technology and electronics field, the synthesis methods differ slightly for the device technology field such as electronics and photonics, and for the software field. In the synthesis methodology of the device field, the individual elemental technologies are clear and independent from other elemental technologies. There is a main elemental technology that becomes the breakthrough, and the integrated technology is synthesized as these technologies are combined.

A characteristic example is the research “Creating non-volatile electronics by spintronics technology” by Yuasa *et al*.[22] In this research, in addition to the extremely significant breakthrough where the giant tunnel magnetic resistance (TMR) effect was realized through the tunnel barrier of the magnesium oxide (MgO) crystals, there was a second breakthrough where the mass production technology was achieved by realizing the magnetic tunnel junction (MTJ) element with CoFeB/MgO/CoFeB structure that used an extremely special crystal growth formation. As is shown in Fig. 5, this can be considered a sequential breakthrough type where the scientific breakthrough and innovative manufacturing technology came one after the other. Such breakthrough type synthesis can be seen in the R&D for the cryptographic module by Satoh *et al*.[23] In the fabrication of highly functional optical elements by Nishii mentioned earlier,[5] the imprinting method that used to be difficult under high temperature was combined with the glass mold method that was used in the glass treatment, to realize a highly precise high-function optical element. This can be considered a typical aufheben type in which the two methods that used to be difficult to execute simultaneously are combined. The development of silicon carbonate (SiC) semiconductor power devices by Arai[24] is an interesting process of extracting the elemental technologies and issues that had to be realized, realizing these technologies individually, integrating them, and then realizing a practical technology. This is a strategic selection type synthesis.

In the papers of the software and systems field, the selection of elemental technologies and the interaction with the real society in the process of integration are the keys. In the construction of the system using middleware as in Tanaka’s Grid system,[25] the strategic selective selection and combination of the elemental technologies are shown, and the system construction is relatively clear as in the hardware system. Such strategic selection type synthesis is done in six R&Ds. In Motomura’s research,[26] the Bayesian net was used for modeling human behavior, and while it is a breakthrough type in the sense that sensing and interview technologies are added to the core technology, it is a synthesis of the combination of breakthrough and spiral type in the point that the user interaction is greatly significant as the “social circulation” (as indicated by Mochimaru,[26] Fig. 6).

In the R&D of intelligent wheelchair by Satoh and Sakaue,[27] the breakthrough technology is the omnidirectional stereo camera. Using this technology as the core, other technologies were selected strategically to synthesize the electric wheelchair, and the result of the trial by users was fed back to the development. The combination of the three syntheses is described in the paper (Table 1).

In the hardware field, the definition and selection of the elemental technologies and the synthesis method using them are relatively straightforward and clear, and the synthesis of middleware is similar. However, in the software and application fields where there are greater and more significant interactions between humans and environment, the defined and selected elemental technologies are not integrated in one direction, but they evolve and deepen through the interaction with the social environment.

(4) Nanotechnology, materials and manufacturing field

For the nanotechnology, materials, and manufacturing field, an example is the mass synthesis method of the organic nanotube by Asakawa *et al*.[28] This research involves the development of mass synthesis technology of organic nanotube and this was expected to be applied to wide-ranging fields by filling the tube with nanoparticles and proteins. This technology is a typical example of the seeds driven breakthrough type. However, mass production was made

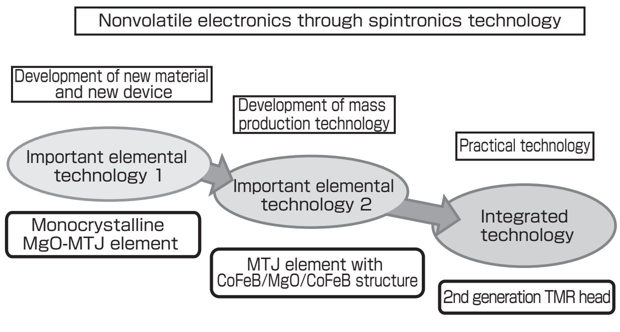

Fig. 5 Breakthrough type synthesis in the information technology/electronics field

possible by extremely fine molecular design and integrated technology, and the practical usages were pioneered through the joint efforts with companies (Fig. 7). Such breakthrough types are seen in four R&Ds including the study of non-combustible magnesium by Sakamoto and Ueno.[29]

On the other hand, in the technological development of large single-crystalline diamond wafers by Chayahara *et al*.,[30] the elemental technologies such as the microwave plasma CVD method, control of abnormally growing particles, and the size increase were strategically selected and integrated. To upsize the wafers, which was one of the elemental technologies, the breakthrough called "repeated lateral growth" was employed, but the overall synthesis is promoted by the strategic selection. Such strategic selection type synthesis is seen in five R&Ds such as of optical catalysts technology. Also, Kobayashi *et al*. developed a material with high hardness and high strength using the Fe-Al intermetallic compound by combining the technologies for casting and powder metallurgy.[31] This is an example of the aufheben type synthesis in which a new method was created by combining the new dry powder metallurgy synthesis and the conventional casting method. Aufheben is also done in the R&D of UV protection cosmetics by Takao and Sando.[32]

A characteristic example in the manufacturing field is the method where various products were developed using the aerosol deposition (AD) method by Akedo *et al*.[33] In this research, the AD method where the ceramics particles were solidified and densified at room temperature became a breakthrough, and through the strategic selective synthesis, the technology was applied to the manufacture of electrostatic chuck and MEMS scanner. The manufacturing method that employed the concept of "minimal manufacturing" with low cost, low environmental load, high function, and low resource consumption was synthesized. The R&D for PAN carbon fiber by Nakamura *et al*.[34] is also a combination of the breakthrough type and strategic selection type.

In the study of the energy-saving process for ceramics manufacturing by Watari *et al*.,[35] focus is placed on the improvement of the binder technology upon carefully investigating the technologies that must be developed for energy saving, and excellent technology was established for evaluation and improvement. This is a combination of "strategic selection + breakthrough" types, in the sense that an improvement technology was established through the scientific approach upon strategic selection of the elemental technologies toward a clear objective. Moreover, in the study of rationalization of resource and energy use throughout the entire manufacturing process by Kita *et al*.,[36] the exergy (Gibbs free energy based on the environment) was analyzed in the entire process of aluminum manufacturing, and important guideline was obtained for the casting process that contributed to resource and energy conservation. This is a strategic selection type synthesis method in the sense that the analysis was conducted by continuously extracting the elements that must be evaluated toward a clear objective.

The characteristics of the synthesis method for the nanotechnology, materials and manufacturing field are not greatly different from the synthesis of the hardware technology such as electronic devices. For materials, the result of the research is seldom launched in the market as a full product but is often used as elemental technology later, and the synthesis method is relatively clear in the case where the demand is the fulfillment of a certain performance or specification. However, in cases where there are interactions with various demands, the feedbacks are likely to be reflected in the synthesis method itself. On the other hand, while there is no major difference in the synthesis method for manufacturing technology, one of its characteristics is that one innovative elemental technology may entirely change the synthesis method. The categorization of this field is also shown in Table 1.

(5) Metrology and measurement science field

As a characteristic of the standard and metrology field, particularly in metrology standard, the main assumption is that a highly reliable metrology standard (physical standard, chemical standard, or reference material) must be delivered to the hands of the end user. It is also assumed that such standards are recognized internationally. Therefore, the scenario is built and the R&D is conducted based on

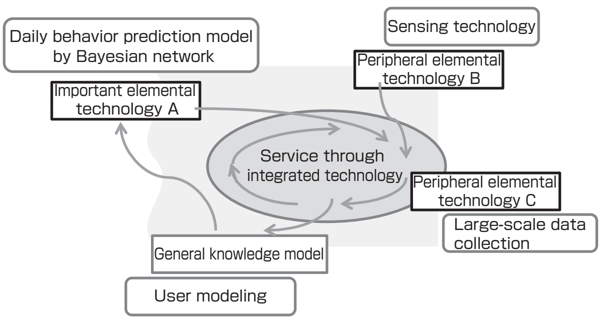

Fig. 6 Social circulation type synthesis (revised Fig. 6 in Reference [26])

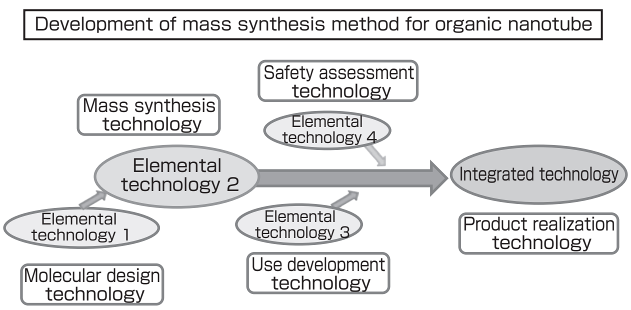

Fig. 7 Breakthrough type synthesis in the nanotechnology/materials/manufacturing field

the three requirements: 1) the establishment of national metrology standard traceable to the international standard (SI), 2) the maintenance of international consistency (through internationally recognized measurement method and international comparison), and 3) the construction of the traceability system that links AIST, the accredited calibration laboratories, and the end users. Requirement 1 corresponds to the "technological synthesis," requirement 3 to the "synthesis for introduction to society," and requirement 2 links the two. Two examples of the R&D for physical and chemical standards are shown below (Fig. 8).

An example of the physical standard is the research of the traceability system for the temperature standard to calibrate the thermocouple in the temperature range of 1000 °C ~ 1550 °C by Arai *et al*.[37] The temperature measurement in this range is particularly important in the industries where temperature management is crucial, including the materials industry such as iron and steel, as well as the parts manufacturing and semiconductor process industries where heat treatment is necessary. The thermocouple is a thermometer used most frequently in such industrial sites, but the reliability of measurement was not very high, and the establishment of the metrology standard and the organization of a traceability system had to be done quickly. The national metrology standards in this temperature range are the fixed points of temperature of pure metals. Specifically, they are the freezing point of silver (961.78 °C), freezing point of copper (1084.62 °C), and melting point of palladium (1553.5 °C). These temperature fixed points were determined by the Conférence Générale des Poids et Mesures (CGPM) comprised of the representatives of the member countries of the Convention du Mètre, based on the thermodynamic temperature scale [requirement 1]. For international recognition, international comparison (APMP-T-SI-4) was conducted with the metrology institutes of various countries, and AIST's calibration values and low uncertainty achieved the highest reliability among the participating institutes [requirement 2]. To construct the traceability system, a transfer standard that can deliver precise standard value between AIST and the calibration labs was necessary, and stability and sturdiness were required for such a transfer standard. Therefore, the highly reliable platinum-palladium thermocouple and the R-type thermocouple were developed to fulfill such conditions [requirement 3]. In this process, it was newly found that appropriate heat treatment contributed greatly to the stability of the thermocouple. Also, the application of the eutectic point as the fixed temperature point, an original technology developed by AIST, is spreading to the metrology institutes of the world, and in the near future, the provision of temperature scale with even higher reliability is expected.

The example of the chemical standard is the study of the development of the reference material to guarantee the reliability of analysis done by testing institutes for the hazardous materials (such as residual harmful substances and agrichemicals) in the food and environment that are directly linked to the safety of the Japanese citizens, by Ihara *et al*.[38] The quantitative NMR method was developed since there were over a thousand types of hazardous material in the food and environment that have been targeted for regulation by law, and there was a need to develop and analyze numerous reference materials quickly. This is an innovative method in which the calibrations of the multiple types of practical reference material are done by a minimum number of standards, rather than the conventional method where the reference materials were prepared for each chemical substance.

The NMR measurement method is normally used to detect unknown substances or to identify molecular structures,

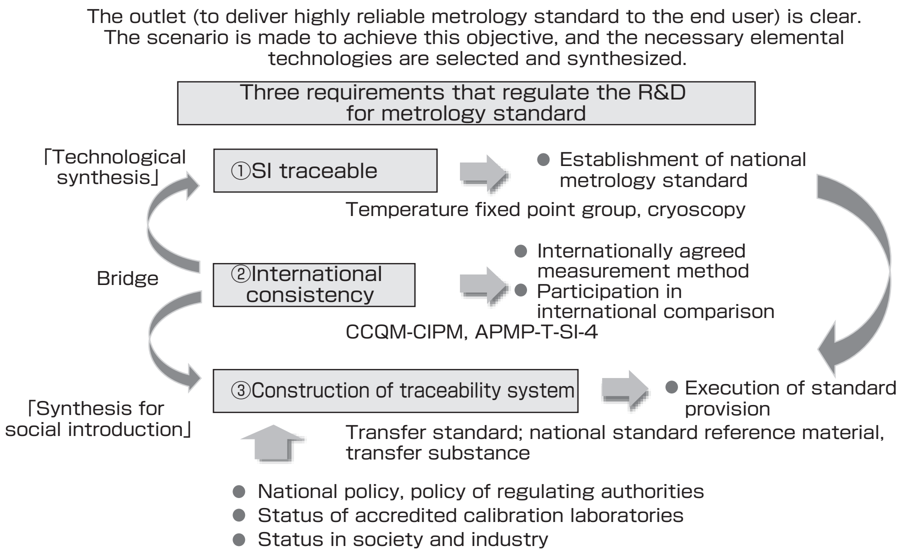

Fig. 8 Strategic selective synthesis in the metrology/measurement science field

while, in this case, the reverse thinking was used where the method was used for the quantitative analysis of known substances. Therefore, the important elemental technology was the search and selection of the measurement conditions totally different from the normal NMR (such as the adjustment of delay time of irradiation pulse or the optimization of audio filter). Also, the selection of the national reference material and the selection of the transfer material that allowed calibration of several substances were important points in constructing the efficient traceability system [requirement 3]. The SI traceability was guaranteed by using the cryoscopic method, a primary measurement method, as the check of adequacy [requirement 1]. Internationally, a proposal was made to employ this method as one of the standard measurement methods at the Comité Consultatif pour la Quantité de Matière (CCQM) of the Comité International des Poids et Mesures (CIPM), and worldwide agreement is being obtained [requirement 2]. As the supply system, through the collaborations (joint research, subcontract research, etc.) among AIST, national research centers, and private companies (manufacturers of reagent and clinical testing agents), the distribution of the reference material valued by this method was started from FY 2008. There are now over 100 kinds of substances tested. The overall structure of this research is summarized in Fig. 6 of the paper by Ihara *et al*.[38]

As shown in the above two examples, the R&D scenario and the execution process are set up with the three requirements as the boundary condition, and these researches can be categorized as typical strategic selection types. Among the papers of metrology and measurement science field published in *Synthesiology*, the research of the x-ray generator driven by batteries for metrology technology by Suzuki[39] is a breakthrough type. There are 11 papers on metrology standard that fulfill the three requirements, and they can be categorized as strategic selection types (Table 1).

(6) Geological survey and applied geoscience field

The characteristic of the researches in geology field is the spiral development through the interaction in response to the various changing social demands, as the integrated strategy is synthesized from the perspective of advancing the understanding of the whole geological phenomenon (Fig. 9). It is not an overstatement to say that the depth of the understanding of nature well into the past determines the social response to the industrial location, resource and environment, and disaster prevention.

As an example of the long-term earthquake prediction (individual strategy A of Fig. 9), Sangawa established paleoseismology through the geological “breakthrough” of the discovery of liquefaction deposits at archeological sites.[40] Moreover, as the focused individual strategy of the research unit, in addition to geology and archeological, different fields such as geophysics and engineering were integrated, and this can be called the combination of the breakthrough and strategic selection types. Based on these results, the understanding of the history of active faults in Japan and the research of the physical model and strong ground motion model of the occurrences advanced. As seen in the study by Yoshioka,[41] these researches are strategically selected and combined and utilized in location selection and disaster prevention. Such methods are applied in the researches of past tsunami deposits by research units, and are contributing to the improvement in the accuracy of predicting long-term

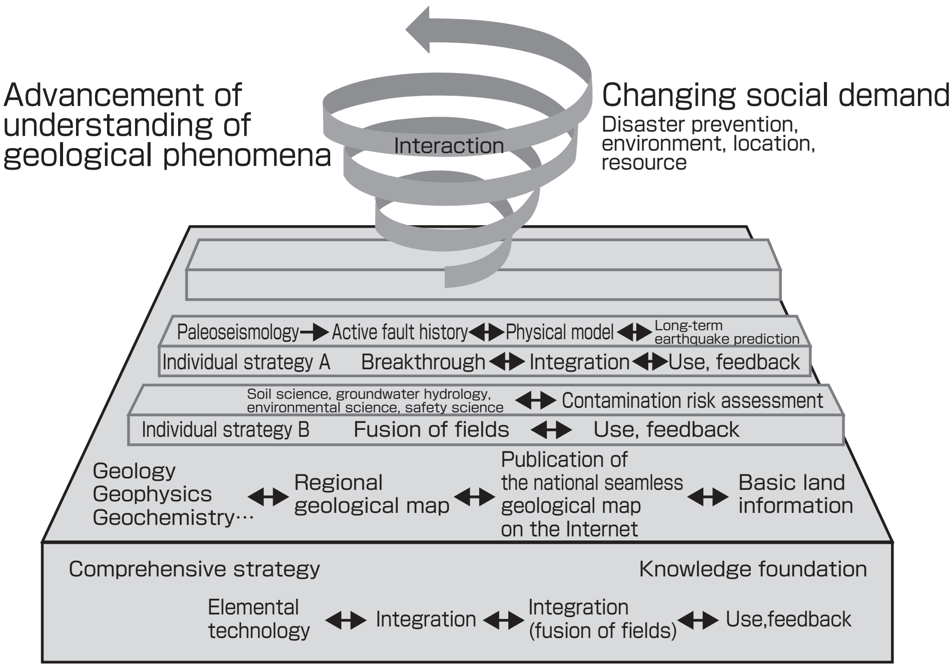

Fig. 9 Synthesis by individual and integrated strategy in the geological field

occurrences of earthquakes and their effects. In the risk assessment of the contamination of soil and ground water (individual strategy B in Fig. 9), as seen in the research by Komai *et al.*,[42] the fields of environmental science and safety science were integrated in addition to the elemental technologies of geology, the feedback was done through use in society according to the stages of advancement of the assessment method, and a refined assessment model was built.

These individual strategies may focus on a target in response to the specific demand of the changing society, and the research based on the integrated strategy for the basic land information and technology is essential as its core. The geological map that is the basic information of the land, as seen in the research by Saito,[43] is the knowledge base in response to the various usages including disaster prevention, environment, industrial location, and resources. By integrating the various elemental technologies (such as geology, geophysics, and geochemistry) based on the integrated strategy of the geology field, the understanding of the geological phenomena is deepened, and the results are provided to society as the public asset in the form of regional geological maps. Also, as seen in the research by Wakita *et al.*,[44] the geological information is joined using the elemental technologies such as information technology according to the demand of society, and the result is provided as the seamless geological map of Japan on the Internet where the updated,latest data can be used any time. With the improvements by feedback, this is the spiral type synthesis.

Many cases in the geological field take the strategic selection type synthesis (Table 1). The empirical model of the geology model is deepened through such research activities, and much deeper understanding of the geological phenomena can be reached by correlating with the deterministic model. Then, the improvement of prediction accuracy that can meet the social expectations may be realized. The research

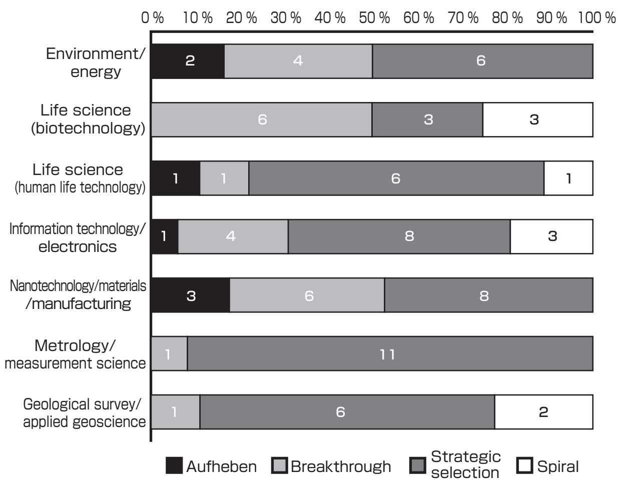

Fig. 10 Result of categorization into four types by fields (combinations types were counted into each type with overlap)

in the geological field advances as the understanding of the geological phenomenon as a complex system takes the spiral interaction in response to the various social demands.

4 Properties of the fields in the synthetic method

From the analysis of the synthetic research in the fields presented in the previous chapter, the characteristics of each field will be described in this chapter, and the common synthesis methodology will be presented in the following chapter. Table 1 shows the categorization of papers into the three types, aufheben, breakthrough, and strategic selection types, as well as the combinations of the three. Since there are not many combination types, to observe the characteristics of each field, it is assumed that combination types are composed of two or three types. The result of the overlapping count is shown in Fig. 10. Although this number is insufficient to present a quantitative discussion, differences by field can be seen. The breakthrough types dominate the fields of biotechnology, nanotechnology, materials and manufacturing, and environment and energy, particularly the R&D for low environmental load technology. These are fields where breakthroughs occur when there is good core technology. On the other hand, there are many strategic selection types in the human technology and the geology field. These are fields where the issues cannot be solved by one breakthrough technology. In all researches except one, strategic selection synthesis is done in the metrology and measurement science field, and it can be seen that multiple elements must be considered to construct the traceability system. On the other hand, spiral type can be seen in the fields of biotechnology, human technology, information technology and electronics, and geological survey and applied geoscience.

In the fields of materials, electronic and photonic devices, manufacturing technology, and in the fields of chemical and physical metrology and measurement science, there are many researches where the elemental technologies are clearly defined and the synthesis methods are relatively clear. However, in the fields of geology, biotechnology, and human

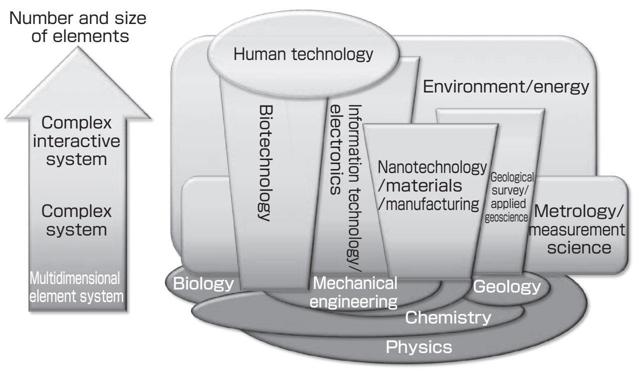

Fig. 11 Properties of the field in synthesis method

technology, the elemental technologies are complex, and the interaction with humans, society, and environment is gaining weight in the synthesis method. Figure 11 is a diagram of tentative thoughts that presents the number and size of the elemental technologies and the relationships among the fields.

The major academic disciplines that form the basis of the technological fields are shown in the basis at the lower part of the diagram. The elements can be defined clearly in the fields of physics and chemistry, and they are thought to form the basis. When the elements are finely analyzed in physics, one reaches quark and lepton, and they synthesize substances as they climb to the higher levels of nucleus, atom, and molecule mediated by interaction. The characteristic of chemistry is that the complex interaction among the electrons creates various reactions and various substances. In mechanical engineering, a main branch of engineering, the main interaction is mechanical or electromagnetic interaction, but the elements are macroscopic and the number of elements is limited. In geology and biology, the number and the complexity of the elements increase dramatically and the descriptions become increasingly diverse.

The fields that are established on these academic disciplines include: the multidimensional elemental systems such as nanotechnology, materials, and electronics that have relatively few elements; complex systems such as geology and environment and energy where, the interaction among the elements can be clearly defined in terms of physics and chemistry although the number of elements increases dramatically; and the complex interactive system such as information technology, biology, and human technology where the interactions among the elements themselves are diverse.

As the number and size of elements increase, the synthetic method becomes diverse, and this is related to the way the scenario is set up and its characteristic. In the multidimensional element system where there are few elements, the scenario can be relatively easy to understand because the elements and the synthesis method are clear. Since the technological synthesis method is clear, the logical development of the scenario can be done readily. It can also be said it is relatively easy to spell out the milestone and roadmap of the technological development. In contrast, in the complex and complex interactive systems, the number of elements increases, the interactions become diverse, and the range of synthesis spreads. The ways in which the scenarios are written are not uniform, but are characterized by the fact that the development changes through the interaction with the real society and users.

The technological fields presented here are the fields for which the R&Ds were promoted by the former Ministry of Commerce and Industry, former Ministry of Posts and Telecommunications, and former Agency of Industrial Science and Technology, Ministry of International Trade and Industry, in response to the demand of industrial promotion since the Meiji era. Although they include a wide range of fields, they do not include all the technological fields. Therefore, it must be noted that the characteristics of the fields presented in this chapter are limited.

5 Synthesis method in *Synthesiology*

(1) Technological synthesis method

Upon analyzing the 70 papers, we extracted the common characteristic of the synthesis method. The synthesis methodology seen in *Synthesiology* involves the series of processes from strategy building and scenario setting → element selection and combination → technological synthesis → trial in society. In addition to such linear process, “feedback” is a characteristic process in some cases.

As an example of individual elemental selection and

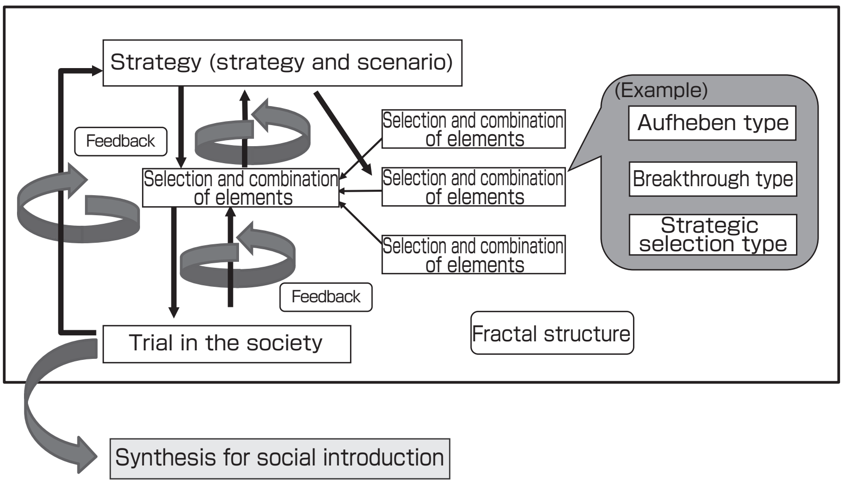

Fig. 12 Technological synthesis in *Synthesiology*

combination, the main description can be given by the aforementioned categories such as the aufheben, breakthrough, and strategic selection types. However, as shown in Table 1, the realistic thinking is that these three types are combined serially or parallelly, rather than existing independently. The synthesis normally takes place over several steps, and in some ways, a fractal structure can be seen in the technological synthesis. An example of multistep synthesis is seen in the environment and energy field as described in chapter 3 section (1). Here, the strategic selection method broken down from the social demand and the breakthrough method of important elemental technologies are combined (Fig. 12).

On the other hand, this synthesis method is conducted based on a strategy. When the elemental selection and combination are done, it is fed back to the strategy and the scenario, it is then fed back again to the elemental selection and combination. There are cases where the combinations are changed or improved, or there are cases where the strategy evolves along with the advancement of the synthesis method as the objective becomes clear. The example of the latter is "Development of real-time all-in-focus microscopes" by Ohba.[45] Here is the process where the elemental technologies were integrated and synthesized to the higher element, the objective that was ambiguous became clear, the technologies were finally integrated as the three-dimensional real-time all-in-focus microscope, and the product was commercialized. Initially, the research started with somewhat vague hypothesis formation of "realization of high-performance optical microscope." After meeting with several companies and completing the prototype, the hypothesis was advanced, the processes of clarifying the strategy and scenario for its realization were repeated, and the product was finally commercialized. It should be noted that the verification and advancement of the hypothesis occurred through encounters with several companies.

As the synthesis progresses, the synthesized artifact comes into contact with society as a product, and the "trial in society" is conducted. It is extremely rare that the introduction to society starts smoothly. Here is the next feedback loop. When the "trial in society" is conducted, the responses from various stakeholders are offered as feedbacks, and new strategies are proposed. There may be feedback on the selection and combination of the elements rather than the strategy itself. The example of bioinformatics by Suwa and Ono presented in the life science field in chapter 3 section (2) shows the spiral structure where the effective feedback was given by the researchers who used the research result, and this led to the building of strategy and scenario, thereby turning the loop several times. In the example of geology shown in chapter 3 section (6), the understanding of geological phenomena and model building advanced as the social demand gradually changed, and the feedback to the strategy and synthesis method occurred consecutively.

On the other hand, when the feedback to the synthesis result is given through social contacts and on site trials, the dynamic movement of synthesis being conscious of time is necessary. A representative example is the analysis by Chuma on the recent decreased international competitiveness of the Japanese semiconductor industry.[46] The system-on-chip (SoC) is a design method of aggregating the necessary functions as a system on the semiconductor chip. As the clock speed increases dramatically, there are three central issues of the system design: response delay speed among the individual element, transfer speed, and the communication structure that links each job. This means that it is necessary to understand the relationships of the elemental technologies in an extremely dynamic manner. According to Chuma, the decrease in the international competitiveness of the products was because the development system of the Japanese companies could not keep up with this dynamic motion in the world. From the investigation of various case studies in this paper, it was found that in any synthesis method, the relationships among the individual elemental technologies were closely correlated and synthesized, and this correlation was temporally contiguous, and the dynamic movements such as concurrence and interchangeability were not apparent. In the future, as the competition of R&D becomes more severe, the dynamic movement and quick feedback of the linkage among the elements, as well as acceleration of R&D will become necessary.

(2) Synthesis method for introduction to society

As the final major issue, there is the "synthesis for introduction to society." As described in the research by Ishii,[47] Fujii,[48] and Osawa *et al.*,[49] in cases where the point of introduction to society is the obtainment of traceability as in the metrology standard, it is necessary to build a social system consisting of calibration laboratories, and it is necessary to seek a measurement technology that corresponds to the traceability system. Also, in cases where the demand is clear in society, for example, a specific performance index such as the memory capacity, the technology that can meet that demand will be introduced relatively quickly. As seen in the research by Yuasa *et al.*,[22] the production technology is important as the issue for introduction to society. However, in many cases, the social activity affects the introduction independently from the technological development. For example, giving of values such as subjective sensitivity to a product and impactful concept may promote the introduction to society. Also, rather than pushing the introduction to society in a short time, it may be also necessary to promote autonomous synthesis like sowing the seed of necessary elements. Also, it is important to respond to the feedback from society, rather than the one-way provision of technology.

Table 2. Example of scenario for social introduction

In case where the demand is clarified by industry	• Construction of traceability system for metrology standard • Development of production technology that matches the new technology
In case where the demand is not clarified by industry	Display elemental technology and provide samples • Show impact of new technology by demonstrating the function using the sample • Extract technological and research topics to be solved through feedback obtained from sample trial
	Provision of the product for wide trial opportunity • Rent out prototypes to target users, and extract problems and necessary functions from open prototype • Show impact of realized function by creating the product
	Promote technological introduction to the stakeholder • Take time to obtain understanding of the value of new technology • Promote understanding by seeking problems jointly with the people on site
Establishment and expansion of the industry	• Add use value of the product through perceptive leading user • Collaboration with different businesses, competition by collaboration and standardization with competing companies, construction of joint relationship

As a method to get the evaluation of whether something has become a usable technology, sample provision and trials at exhibitions are done. For example, as in the research by Asakawa *et al.*,[28] the value of the technology can only be understood by having the people use the organic nanotube. Also, as seen in the research of electric wheelchair by Satoh and Sakaue,[27] in the case where the developer and the users are separate, the demands that the developer could not foresee must be incorporated. In the researches by Nakashima and Hashida[21] and Eto *et al.*,[50] the long-term trial in the field is effective in the extraction of technical issues such as reliability in software development. Such feedback through trial use can be a step that determines the additional technical development necessary to realize a product. When the major technical issues are solved and something that can be used as a product is created, still various factors are involved for such a product to diffuse into society. One factor that may be a trigger for diffusion is the technological impact that is highly visible, showing what can be accomplished. As seen in the researches by Ishikawa[51] and Ohba,[45] the standard for length that is portable and the real-time all-in-focus microscope are such examples.

The people who visit exhibitions or request sample provision are those who are seeking new technology, and have an active attitude of incorporating the technology. On the other hand, there may be cases where a major change is not really wanted on site, and people may not necessarily be enthusiastic in solving the problem even if they understand that there is an issue. As seen in the research by Kinoshita and Takai[52] in the technological transfer for system verification, it may be necessary for the provider of the technology to actively enter the field and to work on the solution with the people on site. Also, there may be people who understand the superior technology but are hesitant to introduce the new technology due to the issues in manufacture technology. In such cases, rather than promoting the introduction rapidly, it may be better to obtain gradual understanding of the value of the technology and wait for the people to autonomously initiate the introduction, as stated by Takao and Sando who developed the ultraviolet protective cosmetics using the ceramics powder technology.[32]

In the case where the scale of diffusion is large as in the consumer product, the perceptual impact to the consumer is necessary as well as the performance impact. As described in the study of induction cooking device by Kubo and Baba,[20] people called the sensitivity based (Kansei) lead users who can provide new ways of using the product to the consumer through the mass media may enhance the value of the product.

In the case where the product is composed of an integrated system including the infrastructure, the collaboration within the industry is effective to realize both the performance improvement and cost reduction. As shown in the study by Ikeda *et al.*,[19] the competitive and the collaborative developments by the companies and the common area that would be standardized were strategically laid out in the process of realizing the car navigation system. This pushed the introduction to society.

There are several steps in the synthesis, including the phase of elemental technology development where the technology is incorporated into the product, the phase of assembling from elemental technology to product, the phase of establishment as an industry after product realization is completed to some degree, and the phase where the product is diffused to the consumer. The effort differs in the case where the technological demand is clear and the case where the demand is unclear in industry. In the latter case, much difficulty is expected, and the impact of the product may be presented, active approaches to stakeholders may be done, as well as provision of samples, but there is also the strategy of "wait until the time is right" (Table 2).

6 Conclusion

The synthesis methods were analyzed and characteristics were extracted from the papers of *Synthesiology*. The characteristics of the *Synthesiology* papers are: the researcher clarifies the social objective, sets the issues that must be overcome to achieve the objective, and clarifies the scenario for how to solve the issue; the research is conducted along the scenario; and the process of execution is written as a paper of synthesiology. The contents of 70 papers were analyzed based on Kobayashi's three basic types, but we sometimes asked the authors to confirm their understanding. Whether the paper was strategic selection, breakthrough, or aufheben types depended on the difficulty of the realization of the core technology, but the decision of whether a paper was a breakthrough or aufheben type relied on our subjective view. In some papers, the overall strategy was emphasized, and in other papers, the breakthrough of the elemental technology was emphasized. Since most of the papers were written by the researchers themselves, we judged that the papers expressed the important points of synthesis from the viewpoint of the researcher.

In *Type 2 Basic Research* conducted to utilize the research result in society, there is the "technological synthesis," and there are several basic types of synthesis. As the characteristics for different fields, although there were differences in diversity due to the number and size of elements, and the difference in the ways of reaching the goal, it became clear that a feedback process by comparing the combination of elemental technologies based on the strategy and the trial in society was necessary. It was recognized that the dynamic synthesis approach called the spiral-up where the feedback process is repeated several times through the interaction with the actual demand in society was extremely important.

In addtion, to introduce the research result into society, it was found necessary to continuously promote something called the "synthesis for introduction to society." While there are several steps in the synthesis phase, different approaches are necessary when the expansion of the industry is attempted, depending on whether the social demand is clear or not. Although the number of case studies is still insufficient, when considering the "technological innovation to society," we must accumulate the examples of such syntheses and analyze their dynamism.

7 Acknowledgement

We express our deep gratitude to the authors of the papers in writing this article. How much we were able to understand the individual research in the limited time is an issue, but we have made our best efforts in trying to understand the scenarios and the methodologies of the researches. However, I think there are cases where we failed to understand the authors' intentions, and we will be glad to have them pointed out. We would also like to express our gratitude for the valuable advices we received from many people, including the comments in the workshops and other opportunities.

Terminology

Term 1: *Synthesiology*: an academic journal launched in 2008 for the purpose of accumulating "what ought to be done" to utilize the research results in society as knowledge. The journal publishes papers that describe the specific scenario and research procedures including the research goal and social value, and the process of integration of the elemental technologies. It shows the readers what approaches can be taken to practice research that may be useful in society, and provides a place for discussion.[1]

Term 2: *Full Research*, *Type 1 Basic Research*, and *Product Realization Research*: "*Full Research*" is a research based on *Type 2 Basic Research* where the process from *Type 1 Basic Research* to *Product Realization Research* is conducted continuously and concurrently, by establishing a system where wide-ranging researchers can participate in specific issues that arise from the scenario in which the research theme is written all the way to the vision of future society.
Type 1 Basic Research is the research for building the universal laws and principles by analyzing the unknown phenomena by observation, theoretical calculation, and *Type 2 Basic Research* is research where various known and new knowledge of multiple disciplines are combined and integrated in order to achieve the specific goal that has social value. It also includes the research that attempts to derive a general methodology. *Product Realization Research* is the research for the practical utilization of the new technology in society by using the result and knowledge obtained from *Type 1 Basic Research, Type 2 Basic Research*, and actual experiences.

Term 3: Aufheben: "aufheben"(in German) is a concept in Hegelian dialectics, where the thesis and the contradicting antithesis are integrated to achieve the synthesis at higher level. In English it is called "sublation."[3][4]

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Discussions with Reviewers

1 Overall evaluation

Comment (Kanji Ueda, AIST)

This paper attempts to establish synthesiology as a science of synthesis through actual practice, and I think it is very interesting and highly significant.

2 Title of the paper and objective

Question and Comment (Kanji Ueda)

The objectives of this paper can be understood as an analysis of the synthesis method from the papers published in *Synthesiology* (main title), and to arrive at synthesiology to link the research result to society (subtitle). Does this mean the positioning of this paper is an attempt to synthesize (or create) a new "study" called synthesiology by the analysis (as a method) of the existing papers, or in one phrase "synthesis by analysis"? If so, I think you should state this clearly.

Answer (Naoto Kobayashi)

Thank you very much for your clear suggestion. As you indicated, the objective of this paper is to "aim for the new study of synthesis" as stated in the subtitle, and that means that the "analysis of the synthesis method" is conducted, as stated in the main title. The meaning is certainly "synthesis by analysis." I added this point to the end of chapter 1.

3 Definition and use of the terms "integration" and "synthesis"

Comment (Akira Ono, AIST)

In *Synthesiology*, "integration" and "synthesis" are central concepts. Since these two terms are used frequently in this paper, I shall comment on their definition and use.

In "integration," the main interest is in the process and the fact of gathering separate elements and combining them into one. What is created as a result of such combination is subordinate. Hence, the direct object of the verb "to integrate" is the element.

On the other hand, in "synthesis," the focus is on the thing that was made as a result, and the main interest is in what elements compose the thing and how its structure is. The interest in the process of combining the elements seems to be subordinate. The object of the verb "to synthesize" is the thing that is made.

If you agree with the above definitions of the terms, please review the use of the terms "integration" and "synthesis" in this paper.

Answer (Naoto Kobayashi)

Thank you very much for indicating this interesting point. As you say, the center of "integration" is the "process" of combining the elements, while "synthesis" can be considered the act of "precisely adjusting" the interaction among the elements concurrently with "integration" "toward some objective." The use of the terms were reviewed from this perspective, and when we refer to "synthesis and integration" in the paper, we reversed the order and said "integration and synthesis."

4 Relationship among the elements and fractal structure

Comment (Akira Ono)

Figure 1 shows the three basic types of synthesis. The diagrams that show the relationship between the elemental technologies and the integrated technologies represent the mutual logical relationship, and they don't necessarily represent the anterior-posterior relationship on the time axis (i.e. time flows along the direction of the arrow). On the other hand, the "spiral" in Fig. 3, "circulation" in Fig. 6, and "feedback" in Figs. 9 and 12 seem to be concepts that represent the anterior-posterior relationship on the time axes.

Also, as shown in Fig. 2, the technological system generally has a multilayer structure, and the integrated technology in the lower level may be repositioned as an elemental technology as it moves to the upper level. In the "fractal structure" in Fig. 12, the relationships between the elemental and integrated technologies seem to be similar to each other regardless of the scale of the phenomena, and have the same logical structures. Also in Fig. 3, it seems that small *Full Research* develops spirally and becomes larger *Full Research* in the upper level. Do the authors agree with this view?

Answer (Naoto Kobayashi)

I think it is as you indicated. The relationship diagram in Fig. 1 does show the anterior-posterior relationship on the time axis. For example, in the case of the breakthrough type, after a certain important elemental technology is created, it may become an integrated technology through addition of the peripheral technologies. However, the peripheral technology may already be in existence, and it does not show a structure with clear temporal flow as in the "feedback." The fractal structure is as you indicated where the integrated technology in the lower level might be positioned again as an elemental technology in the upper level. A similar structure can be seen in the case of *Full Research*.

5 Content of aufheben type

Comment (Kanji Ueda)

In chapter 2, it is stated that the aufheben type is when there are two theses that are in pro-con relationship, a new concept is created through sublation. However, in the similar issues of science and technology, rather than the sublation of strictly opposing antinomy as stated in Hegelian philosophy, I think there are many cases where the opposition entails conflict, trade off, or overall optimization problem among multiple (not necessarily two) elements. I think it will be easier for the readers to understand if you explain the basic types in terms, not only of concept, but of "structure," "element," "requirement," "function," or "entity." Please quote any references in which the authors discussed the basic types.

Answer (Naoto Kobayashi)

As you indicated, the aufheben type described here includes the issues of conflict, trade off, and overall optimization of multiple elements, rather than the sublation of strictly opposing antinomy. We did wonder whether the word aufheben should be used, but we came to a decision when we were considering the example where the combination of two technologies that have very different characteristics and may not coexist together led to an advanced integrated technology. One example is Reference [5] "A challenge to the low-cost production of highly functional optical elements" by Nishii. In this research, the integration of "structures" was done through the glass mold method and the imprinting method. Developing this way of thinking, we have employed the wide-ranging meaning of the "complex synthesis method among multiple elements for which integration and synthesis were considered difficult." Also, I added the description in chapter 2, that it includes the "structure," "element," "requirement," "function," or "entity," rather than being a mere concept.

The description of the basic types was not published in an earlier paper, but it was first presented by one of the authors (Kobayashi) in the discussion with Professor Lester in Reference [4].

6 Utilization of the basic categorization in actual research

Question and Comment (Akira Ono)

I wish that the synthesis methods (categorization into the three types) presented in this paper is useful when executing actual researches. In that point, whether the three-type categorization of this paper is reasonable will be demonstrated by seeing whether they can be used effectively in actual research execution. How do you think the various schemes shown in Figs. 1 to 9 can be used practically in the planning, proposal, organization, management, and evaluation of research projects?

Particularly, referring to the *Synthesiology* paper "Formation of research strategy and synthetic research evaluation based on the strategy - Toward research program evaluation as a creative activity" [N. Kobayashi, O. Nakamura and K. Ooi, *Synthesiology English edition*, 4 (1) 19-34 (2011)] that was written by Kobayashi, one of the authors, what is the possibility of applying the present synthesis methods to the research evaluation?

Answer (Naoto Kobayashi)

Thank you very much for your valuable indication. Certainly, whether the three categories of synthesis presented here and their combinations are reasonable must be verified by seeing whether they can be used effectively in the actual research execution. On the other hand, I think it is possible to use them in the planning, proposal, organizing, management, and evaluation of the research project.

For example, recently, there is a demand for planning and design of research projects with the goal of innovation creation right from the beginning. The points are: 1) to clarify the "logical development structure" where the upper level elemental technologies are synthesized and these will synthesize the even higher level elemental and integrated technologies, by clarifying the elemental technologies that must be developed in research, as well as the characteristics of the elemental technologies and their relationships; and 2) to incorporate beforehand the method of the "feedback process" where the synthesized integrated technology is subjected to actual application including trial in society, and the result is fed back quickly to the next synthesis. In this case, it is possible to utilize the various schemes shown in Figs. 1 to 9, and overall, the developmental structure shown in Fig. 12 can be applied. In cases of research proposals or research organization, we can consider the "elemental concept" and "elemental group" instead of the elemental technology.

In research evaluation, the application to the series of processes for evaluating the research project can be considered. In this case, the elemental group (for example, technological elemental group or managerial elemental group) that produced the research result is extracted, and the "elemental evaluation" is done by evaluating their specific properties. Next, the relationships of such elemental groups and the temporal development relationships are analyzed to conduct the "integration evaluation" where the process that produced a certain bunch of research result is evaluated. Then, the "evaluation from the viewpoint of outcome (feedback)" can be done by projecting the outcome obtained from the research results into the future, by feeding back from the actual application. In the process of analysis in this paper, we did not consider whether this synthesis method can be applied to planning and evaluation, but we have realized that there is potential through the indication from the reviewer.

7 Characteristic of the synthesis method for each technological field

Question and Comment (Kanji Ueda)

In chapter 3, you analyze each technological field and extract some interesting characteristics, but I ask two questions. First, the six research fields at AIST are characterized by the social (or political) demand, unlike the definitions of the general academic field, and perhaps you should explain the definition of the fields or their origin, so external readers can understand and to develop this further as a general discussion.

Second, don't the original characteristics of such fields characterize the synthesis method? That is, for example, aren't you falling into a self-contradictory explanation where the fields with strong strategic characteristic have the strategic selection synthesis method?

Answer (Naoto Kobayashi)

For the first point, it is as you indicated, and we added the definitions of the fields at the end of chapter 4.

For the second point, as you indicated, it was found that the strategic selection type synthesis was used frequently in the metrology and measurement science field because the strategic goals are clear. However, this method was discovered when reviewing the papers of other fields (environment and energy field), but it was also seen frequently in the metrology and measurement science field. Also, please understand that there are many technological breakthroughs in the strategic selection type synthesis.

8 Example of the hypothesis formation in the scenario

Comment (Kanji Ueda)

One of the essences of synthesiology is the hypothesis formation in the scenario where the possible candidates of a solution or the process of reaching an effective solution are presented, since there is no unique solution. I think you should discuss what kind of hypothesis formations were done in the papers analyzed.

Answer (Naoto Kobayashi)

The example where the product realization and commercialization were accomplished by repeating the cycle of hypothesis formation, realization, clarifying the scenario, and then advancing the scenario through the next hypothesis formation, is shown in Reference [45] "Development of real-time all-in-focus microscopes" by Ohba. There, product realization was attempted based on the prospective elemental technologies that were developed earlier. Initially, the hypothesis formation was rather ambiguous "realization of high-performance optical microscope." However, after meeting with several companies, feasibility study was conducted, the product was completed, the hypothesis was advanced, the scenario toward realization was clarified, and this process was repeated. In that process, the strategy became clear and the product was finally realized. The author mentions that it was greatly significant that there were several encounters with the companies before reaching an effective solution. I thought this was an excellent example of synthesiology based on hypothesis formation, and I addressed this point of the paper in chapter 5.