Title	Knowledge process analysis : Framework and experience
Author(s)	Sugiyama, Kozo; Meyer, Bertolt
Citation	Journal of Systems Science and Systems Engineering, 17(1): 86-108
Issue Date	2008-03
Type	Journal Article
Text version	author
URL	http://hdl.handle.net/10119/8831
Rights	This is the author-created version of Springer, Kozo Sugiyama and Bertolt Meyer, Journal of Systems Science and Systems Engineering, 17(1), 2008, 86-108. The original publication is available at www.springerlink.com, http://dx.doi.org/10.1007/s11518-008-5069-7
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Published as a paper for J. Systems Science and Systems Engineering (vol.17, no.1, 86-109, 2008)

KNOWLEDGE PROCESS ANALYSIS: FRAMEWORK AND EXPERIENCE

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Abstract

We present a step-by-step approach for constructing a framework for knowledge process analysis (KPA). We intend to apply this framework to the analysis of own research projects in an exploratory way and elaborate it through the accumulation of case studies. This study is based on a methodology consisting of knowledge process modeling, primitives synthesis, and reflective verification. We describe details of the methodology and present the results of case studies: a novel methodology, a practical work guide, and a tool for KPA; insights for improving future research projects and education; and the integration of existing knowledge creation theories.

Keywords: knowledge process analysis, knowledge process modeling, primitives synthesis, reflective verification

1. Introduction

Knowledge process analysis (KPA) is concerned with studying the process of *knowledge work*, referring to a certain unit of creative activity such as a scientific research project at a university, an R&D project at a company, a product design process etc. Knowledge work involves logic and reasoning, tacit forms of knowledge (Polanyi, 1983) and creativity (Simonton, 2004) and encompasses a wide spectrum of knowledge types and processes. KPA is an important research subject in the field of *knowledge science* (Sugiyama and Nagata et al. 2002).

In this paper, we try to form a framework for KPA including the modeling of knowledge space and process, and develop a practical work guide for an in-depth KPA in a systematic way. For this purpose, we extract fundamental concepts (or primitives) from the literature on knowledge creation/management theories and combine them into knowledge space and process models and a work guide. We intend to apply them to the analysis of concrete own research projects *reflectively* in an explorative way (Coghlan and Brannick 2005, Redmond 2004) and elaborate them through the accumulation of case studies. Thus, this study is based on a methodology consisting of *knowledge process modeling*, *primitives synthesis* and *reflective verification*.

The aim of this framework is to identify critical incidents (Flanagan 1954) that arose during the course of the project with regard to knowledge creation and use, and to identify supporting and hindering conditions during the course of the project, both with regard to the internal and external environment and structure of the project. Ultimately, the analysis of such processes can lead to a knowledge creation model specific to the project. Such models can then serve as a foundation for further successful projects in similar settings.

2. Knowledge Process Model

There are no universal concepts on knowledge, knowledge processes, and knowledge science (or knowledge scientific studies). We base our understanding of knowledge processes on the concepts from literature presented below. We prepare several basic concepts such as a knowledge space called a *knowledge pyramid*, a knowledge process in a knowledge space, and a compound hierarchical process called a *meta-pyramid* that characterizes the knowledge-scientific studies well.

2.1 Knowledge Space Model

2.1.1 Zins' Knowlwdge Model

Zins (2006) discussed *knowledge types* and *knowledge order*. He employed two categories to distinguish knowledge types: subjective and objective; and data, information, and knowledge, which results in 6 concepts of knowledge types. According to Zins, knowledge types and knowledge order are summarized as follows:

Subjective knowledge exists in the individual's internal world as a thought, while objective (or universal) knowledge exists in the individual's external world as an object or a thing. Objective knowledge is a product of the externalization of subjective knowledge and the realization of objective knowledge necessities. Subjective or objective knowledge become real and meaningful only to the individual who is aware of it by his or her own subjective mind. Objective knowledge can be characterized as recorded, documented, or physically expressed subjective knowledge.

Data, information, and knowledge are related to each other. Generally, the three concepts are conceived as a part of a sequential order: data, information, and knowledge. Data is the input for the analyst, investigator, or problem solver: no matter what form and of what origin. Data is the raw material for information. Information is the raw material for knowledge. In the subjective domain, data are empirical perceptions, information is empirical knowledge, and knowledge is a thought in the individual's mind, which is characterized by the individual's justifiable belief that is true. In the objective domain, data, information, and knowledge are sets of symbols, which represent empirical perceptions, empirical knowledge, and the meaning of thoughts that the individual justifiably ascertains to be true, respectively.

These are represented in a diagrammatical form in Figure 1(a), where vertical and horizontal axes refer to knowledge order and codifiability, respectively. In the figure, *meta-knowledge* is added on the top of the triangles by the authors.

2.1.2 Meyer's 2D Knowledge Categorization

Meyer and Sugiyama (2007) discussed the categorization of knowledge types from different viewpoints: non-explicit and explicit; and unconscious and conscious (see Figure 2).

They argue that the understanding and use of implicit knowledge processes poses a considerable value creation factor. At the same time, the concept of non-explicit knowledge is one of the most ill defined concepts in management literature (Despres and Chauvel 2000, Busch and Richard et al. 2001, Li and Gao 2003). Thus, there is an agreement that non-explicit knowledge is important, but there is no agreement on what it actually is. Memory and cognitive psychology can offer decades on research findings on implicit memory and knowledge. Thus, a linkage between concepts from memory and cognitive psychology on the one hand and concepts from knowledge science and management on the other might clarify the concept of non-explicit knowledge. A sharp definition of different forms of non-explicit knowledge will also allow the measurement of individual and organizational forms of non-explicit knowledge for performance prediction and evaluation purposes. Also, they conducted an experiment to find empirical support for the assumption that there exists a difference between conscious and unconscious access to structural knowledge and declarative knowledge (i.e. explicit knowledge).

A simplified representation of their 2D model is shown in Figure 1(b) where vertical and horizontal axes correspond to consciousness and cordifiability, respectively.

2.1.3 Nonaka's 2D Knowledge Space

Nonaka and Takeuchi (1995) proposed a two dimensional space of knowledge creation where the *epistemological dimension* (or codifiability) and the *ontological dimension* ('knowledge level') were took into consideration (see Figure 1(c)). 'Knowledge level' refers to the level of organization such as individual, group, organization, and inter-organization. This knowledge space was prepared for discussing a knowledge creation process (or dynamics) as shown in the next section. Here, it should be noted that only individuals create knowledge, and an organization itself cannot create knowledge without individuals but can support creative individuals or provide contexts for them to create knowledge.

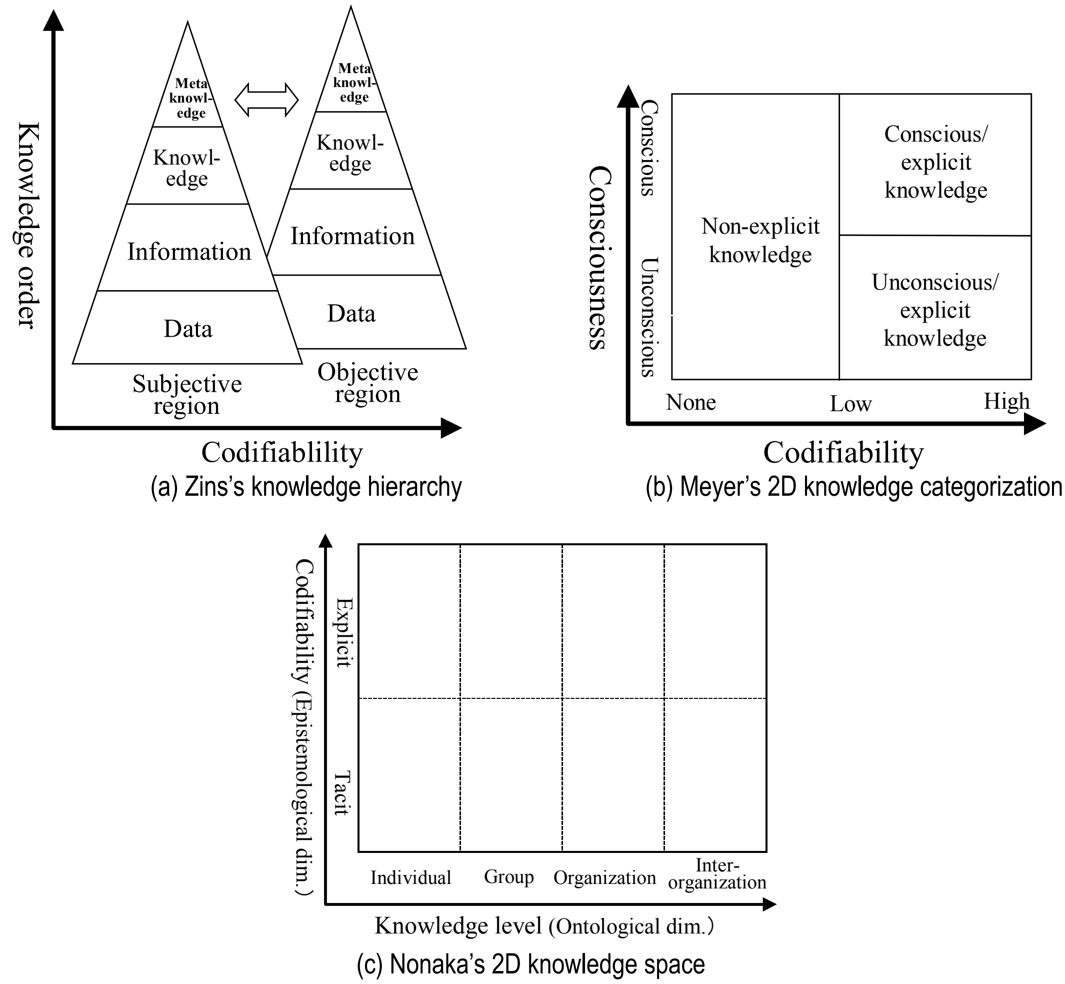

Figure 1 Various knowledge space models

2.1.2 Meyer's 2D Knowledge Categorization

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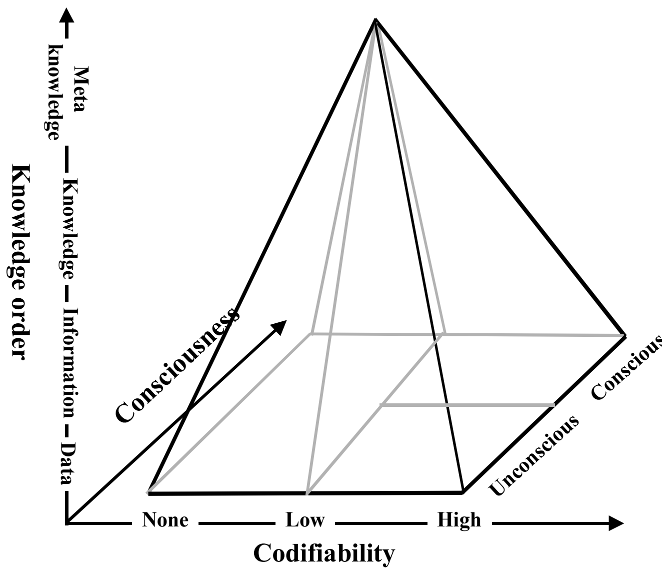
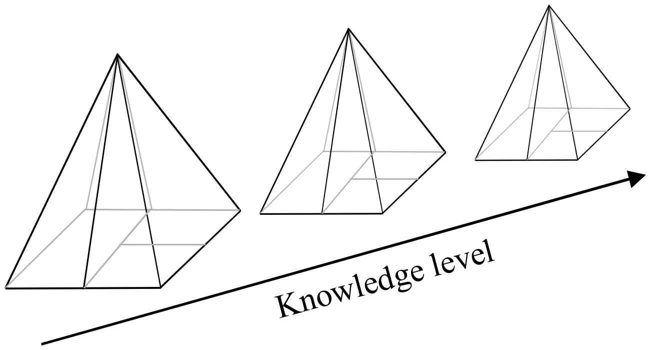
2.1.4 Integrated Knowledge Space

From the models described above, we can identify the four dimensions knowledge order, codifiability, consciousness, and knowledge level. Among these dimensions, the first three are concerned with the epistemological aspect and the last one the ontological aspect of knowledge. By combining two models from Figures 1(a) and 1(b), we can form a 3D knowledge space as an epistemological model, which is called a *knowledge pyramid* due to its shape (see Figure 2(a)). The three axes of a knowledge pyramid are knowledge order, codifiability, and consciousness. It should be noted that the objective region shown in Figure 1(a) is superimposed on the codifiable (right-sided) part of the knowledge space in Figure 2(a), because objective knowledge is a product of codification of subjective knowledge as denoted above.

When we add an ontological dimension to the 3D knowledge space shown in Figure 2(a), we have 4D knowledge space model shown in Figure 2(b). The 3D knowledge space model is useful to consider a knowledge process on a single knowledge level (e.g. an individual) whereas the 4D knowledge space model is necessary to investigate an organizational knowledge process.



(a) 3D knowledge space (Knowledge pyramid)



(b) 4D knowledge space

Figure 2 3D and 4D knowledge space

2.2 Knowledge Process Model

Nonaka and Takeuchi (1995) proposed the concept of a *knowledge creation-spiral* for the dynamics of organizational knowledge creation. The spiral is characterized by two kinds of dynamics: a cycle of knowledge conversion between tacit and explicit knowledge (i.e. a cycle among socialization, externalization, combination, and internalization) that is called 'SECI model', and the elevation the spiral from a lower ontological level to a higher ontological level. These are shown in Figure 3.

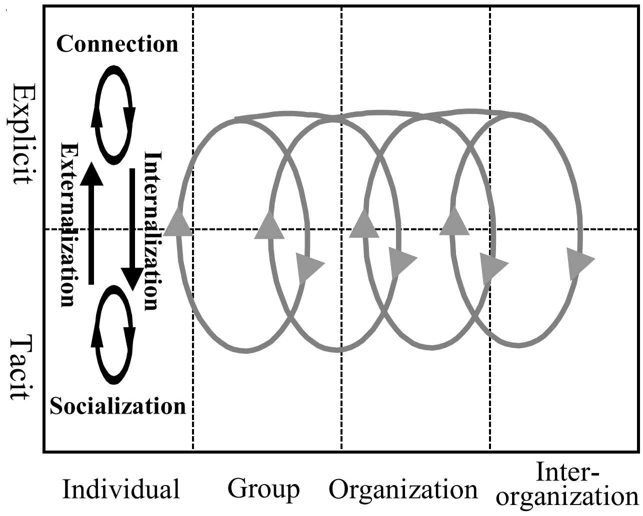


Figure 3 **Knowledge creation spiral**

Zins (2006) argued that every empirical perception is composed of two basic components: raw material and *a priori* concepts. *A priori* concepts give meaning to the diversity of the raw material and compose it into one unified thematic unit. Thus, *a priori* concepts can function as a driving force to compose the raw material into knowledge at a higher order. In this paper, we assume that the *a priori* concepts include top-down thinking such as perspective, viewpoint, intension, hypothesis, model, framework and so on. These concepts function as a driving force for composing raw materials by the cyclic conversions between different types of knowledge through bottom-up thinking such as reflection, specification, induction, abduction and so on. With dynamic interaction between the driving force and the functions of composition, the interior of a knowledge pyramid is organized (i.e. extended and elaborated) gradually from lower knowledge to upper knowledge. This epistemological model of knowledge processes in a knowledge space is shown in Figure 4. In the figure, it should be noticed that 'a priori', ‘higher ordering’ and ‘insight cycle’ form an *epistemological knowledge creation spiral* while Nonaka’s spiral is an ontological knowledge creation spiral.

In the ontological knowledge process model shown in Figure 5, the ontological spiral as proposed by Nonaka and Takeuchi is important. However, the investigation of interactions between epistemological and ontological spirals is beyond the scope of this paper.

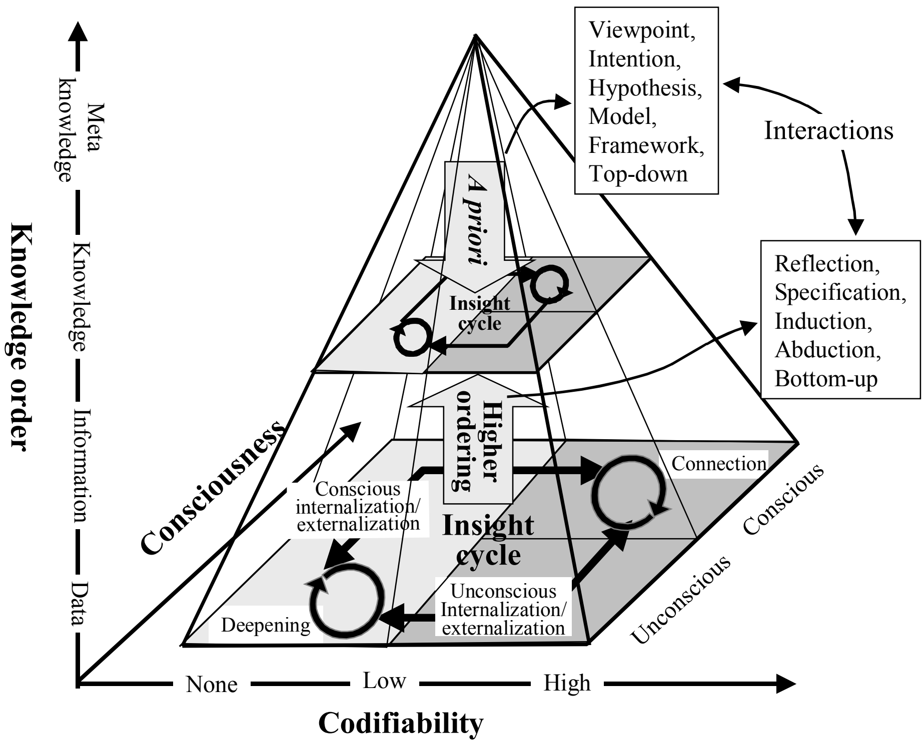


Figure 4 An epistemological knowledge process model

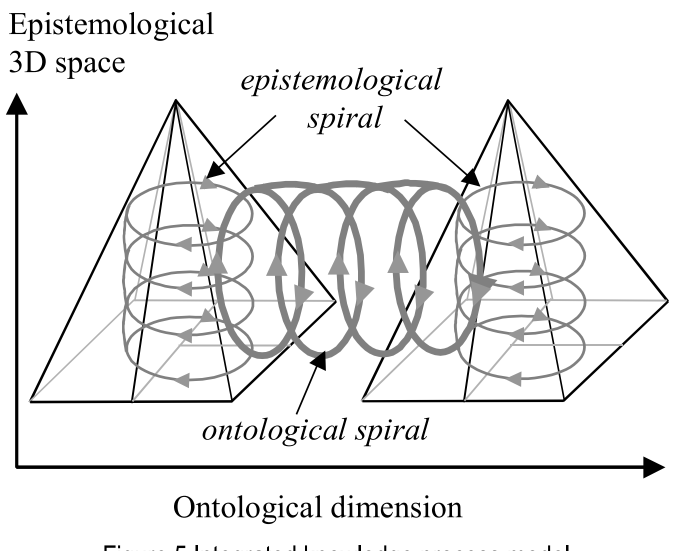
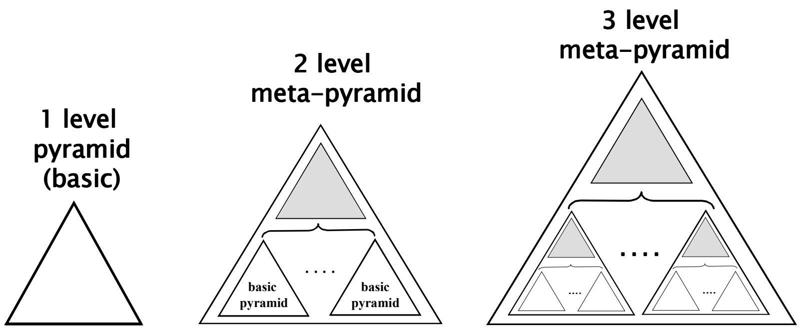


Figure 5 Integrated knowledge process model

2.3 Meta-Pyramid

A knowledge pyramid represents a certain unit of a knowledge process (or knowledge work). The knowledge-scientific study is characterized as a knowledge process studying a knowledge process: namely, a *meta-knowledge process*. Therefore, the structure of a knowledge scientific study assumes a compound hierarchy of knowledge processes (or a nesting structure among knowledge pyramids). This compound hierarchical structure is called a *meta-pyramid* as shown in Figure 6, where each knowledge pyramid is expressed with a triangle for simplicity. The simple triangle shown in Figure 6(a) represents a basic pyramid. In Figure 6(b), the knowledge pyramids laid out on the bottom level are basic pyramids that are raw material for a second level-knowledge process, whereas the knowledge pyramid laid out in the second level corresponds to a knowledge scientific study that is indicated by a dark triangle. The structure of the 3-level meta-pyramid shown in Figure 6(c) is more complicated, because there are two level meta-pyramids in the bottom level that are raw material for the top level knowledge pyramid. Various combinations among several kinds of meta-pyramids are possible as shown below.



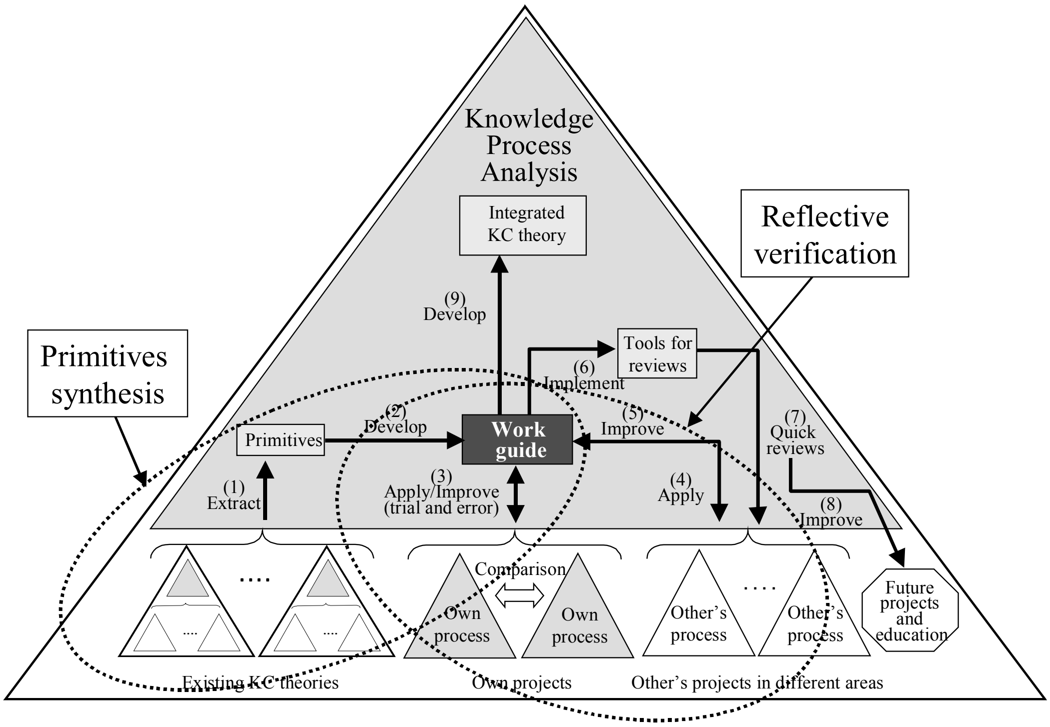
(a) (b) (c)

Figure 6 Basic pyramid and meta-pyramid

3. Knowledge Process Analysis

3.1 Tasks for Knowledge Process Analysis

The Meta-pyramid described above is very convenient for characterizing a knowledge scientific study. We employ it for expressing the structure of KPA in general as much as possible (see the upper area in Figure 7). The structure of KPA is characterized as the second or the third level pyramid. Our approach to KPA consists of nine tasks: (1)-(9). Precedence relationships among these tasks are shown in the figure. Details on each task are described in the lower table in Figure 7. Tasks corresponding to *primitives synthesis* and *reflective verification* also are shown with ellipses in Figure 7.



No.	*Task*	*Details*
(1)	Extract Primitives	Extracting primitives from existing KC theories, which are used for viewpoints for KPA
(2)	Develop a Work Guide	Developing a work guide for reviewing a knowledge process in an exploratory way as a concrete workflow that clarifies 5W1H of a knowledge process to be analyzed
(3)	Review Own Knowledge Processes	Reviewing own knowledge processes (or own projects) according to the work guide, where reflective analyses are very important for understanding and verifying the meaning of primitives
(4)	Apply the Work Guide	Applying the workflow to other knowledge processes in various fields to extend it
(5)	Improve the Work Guide	Improving the work guide based upon experiences for the cases
(6)	Implement Tools	Implementing tools for reviews of knowledge processes when the work guide is improved sufficiently
(7)	Accumulate Cases	Accumulating a lot of cases quickly using the tools
(8)	Find Future Improvements	Getting insights to improve future projects and education
(9)	Obtain an Integrated KC Model	Obtaining an integrated knowledge creation model finally

Figure 7 Structure and tasks of KPA

3.2 Extraction of Primitives

In general, a KC theory can explain certain aspects of research activities but not the whole process. Therefore, we need to employ several theories in order to develop a work guide for knowledge process analysis. Therefore, we focus on the following ideas (please compare original publications for details).

3.2.1 The Theory of Tacit Thought

Polanyi (1983) proposes the concept of tacit knowledge. The most famous sentence is "I shall reconsider human knowledge by starting from the fact that we can know more than we can tell. This fact seems obvious enough; but it is not easy to say exactly what it means…" He employs the example of face recognition: We cannot tell how we recognize a face we know.

He also states similar things about research: "It is commonplace that all research must start from a *problem*. Research can be successful only if the problem is good; … but how can one see a problem? For to see a problem is to see something that is hidden. It is to have an intimation of the coherence of hitherto not comprehended particulars. The problem is good if this intimation is true; it is original if no one else can see the possibilities of the comprehension that we are anticipating. … It makes sense if we admit that we can have a *tacit foreknowledge* of yet undiscovered things." He takes as an example the Copernicans and states "This is indeed the kind of foreknowledge the Copernicans must have meant to affirm. During one hundred and forty years before Newton proved the point…"

Tacit foreknowledge is one of the most fundamental concepts for KPA. Regarding tacit foreknowledge, both aspects are important: what can be seen as a problem, and how it can be seen.

3.2.2 Equivalet Trasformation Theory

Ichikawa (1970) proposed a methodology for creative thought called the equivalent transformation theory. The most fundamental concepts of this theory are *equivalence finding* and *equivalent transformation*. Both concepts are expressed in a diagrammatical form in Figure 8. In his book, he emphasizes that creation is more or less based on these concepts. The meaning of the figure is as follows. Instances of the original system are equivalently transformed to instances in the target system. This is done from certain selected viewpoints under an equivalence dimension and certain constraints by eliminating some conditions from the original system and adding some conditions to the target system. He also distinguishes two types of routes for thought: an *analog route* and a *digital route*. An analog route is characterized as intuitive, qualitative, and imaginary thought, while a digital route logical, quantitative, and real. Also he states that both routes are indispensable for creation; at first an analog route and then a digital route. For example, an analog route corresponds to the Copernicans' tacit foreknowledge and a digital route to Newton's proof. Finding not only an analog route but also a digital route is often triggered by *serendipity* or an accidental discovery through insight (Robert, 1989).

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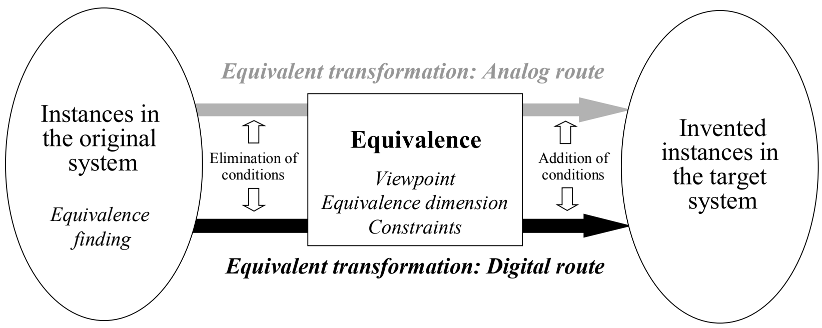

Figure 8 **Equivalent transformation**

3.2.3 Knowledge Management Theory

While Polanyi (1983) proposed the knowledge dichotomy of explicit and tacit dimensions in studying mainly European individual scientists, Nonaka and Takeuchi (1995) systematically exploited Polanyi's concept in developing business knowledge, and emphasized the role of the tacit dimension of knowledge in the processes of organizational knowledge creation in Japanese manufacturing companies (Li and Gao 2003). The dynamic spiral-type conversions (i.e. *SECI model*) between explicit knowledge and tacit knowledge pose a convenient analytical framework for knowledge activities in *dynamic organizational knowledge creation*.

Nonaka's theory consists of four major elements (see Figure 9): (1) the SECI model as stated above; (2) individual and shared context (or '*Ba*') in which knowledge is created, shared, and utilized, and which can be physical, virtual, or mental; (3) *knowledge assets* as inputs and outputs of a knowledge-creating process; and (4) *knowledge leadership* that provides enabling conditions conductive to the process. These four elements interact with each other in managing by creating new knowledge continuously.

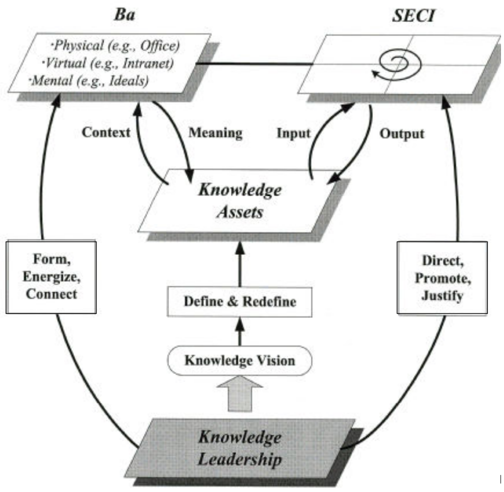

Figure 9 Major elements of Nonaka's theory (Nonaka, Toyama et al. 2000)

3.2.4 Non-Explicit Knowledge-Process Support

The concept of tacit knowledge plays a central role in organizational performance. However, it is at the same time one of the most vague concepts in management literature and it is unclear whether Polanyi, who proposed the concept of tacit knowledge and Nonaka, who introduced it into knowledge management, are actually referring to the same thing. Meyer et al. (2007) tried to link the concepts of individual *tacit*, *implicit*, and *explicit* knowledge with findings from memory, cognition and knowledge sciences by developing a two dimensional model of *knowledge categorization*, where *consciousness* is one of dimensions and *tacitness* (or *codifiability*) is the other as shown in Figure 1(b). They also proposed basic concepts that are important for non-explicit knowledge–process support: *social networks*, *knowledge inventories*, and *knowledge exchange*. These concepts are illustrated in Figure 10.

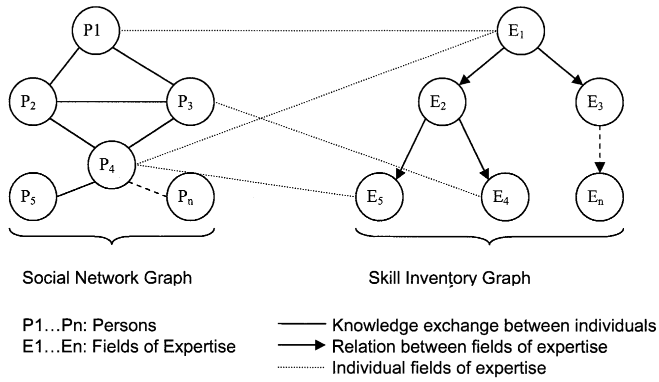

Figure 10 Social network, knowledge inventory, and knowledge exchange (Meyer et al., 2007)

3.2.5 KJ Method

Kawakita (1975) proposed the KJ method, which is famous in Japan as an effective label-based method for organizing ideas and solving problems. It contains four steps: label making (i.e. *exhaustive idea externalization*), label grouping and title making (i.e. *multi-stage abductive idea organization*), spatial arrangement and chart making (i.e. *diagrammatic mapping*), and explanation. These steps are explained below and schematically illustrated in Figure 11 (Sugiyama and Misue, 1990):

(1) ***Label making***: We start with a supply of labels or note cards on which ideas or information (text or image etc.) relevant to our problem are written. We collect and record ideas until we feel we have exhausted all necessary information.

(2) ***Label grouping and title making***: The labels are spread on a large sheet and are read several times. If there are labels that seem to belong together, they are grouped. This process is repeated until two-thirds of the cards are arranged in groups. Then, group titles describing the essence of all cards in a group are created. Once a group-title is made, its corresponding cards are stacked with the title clipped on its top. Next, we arrange the groups in larger groups in the same manner. This iterative process is terminated if the number of groups is reduced to less than ten.

(3) ***Special arrangement and chart making***: If an arrangement with a consistent representation of all groups is obtained, all sub-groups are spread in the same manner. After completing this spatial arrangement, we draw a chart by showing the relationships using various symbols and signs.

(4) ***Verbal or written explanation***: The chart is then described verbally or in writing. As a general rule, the explanation should lead to a team effect of idea generation.

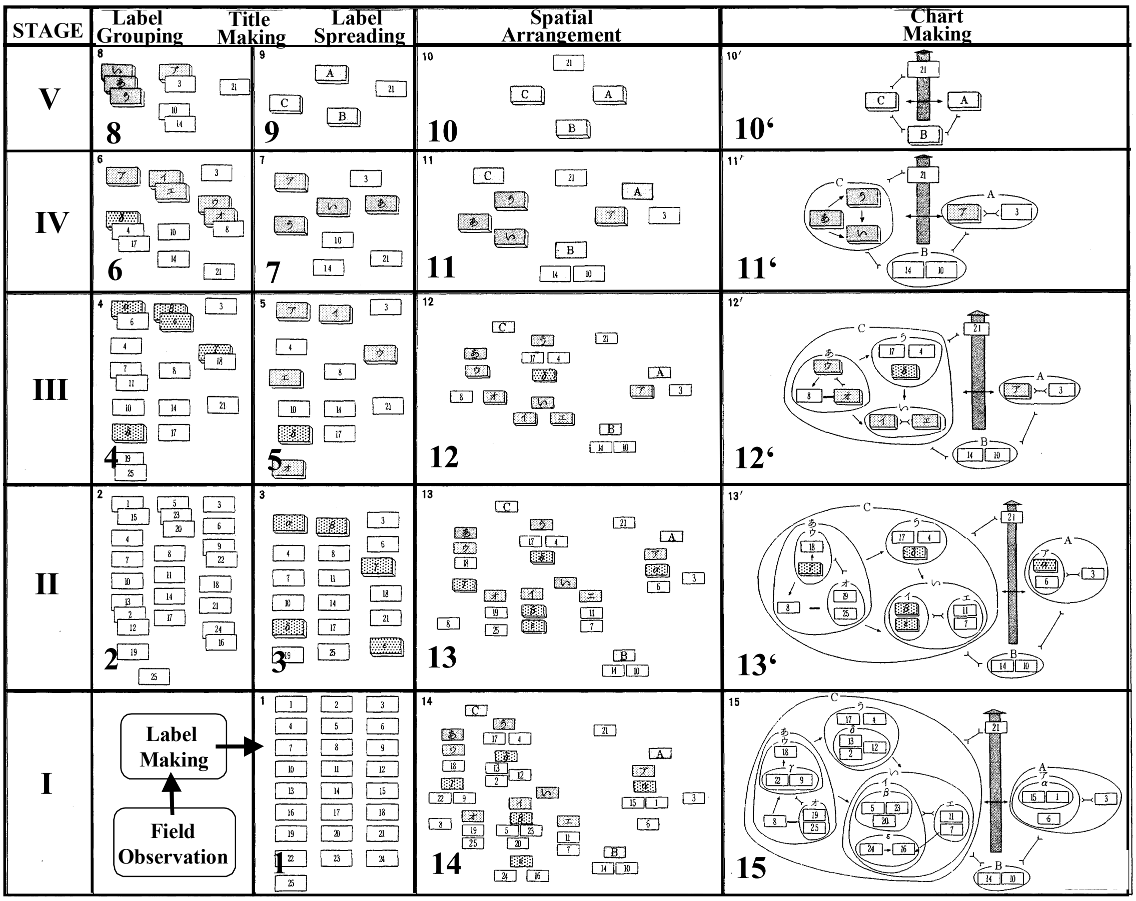

Figure 11 Process of the KJ method

3.2.6 Concept Synthesis

In Finke, Ward et al. (1992), the idea of *concept synthesis* is introduced: If one forms a new word, e. g. 'pet-bird', by connecting the two words 'pet' and 'bird', a new property such as 'a pet-bird can speak' often emerges. Thus, concept synthesis is characterized by the emergence of new properties in the mind.

3.2.7 Serendipity

Roberts (1989) pointed out the importance of an *accidental discovery* in science and called it *serendipity*.

Table 1 shows all selected primitives. It should be noted that they are mutually independent except for two pairs of similar primitives marked in the figure. This might imply that the selection of primitives is successful although it is not based on clear criteria but is rather intuitive at the moment. We have to further clarify he criteria in future research.

Table 1 Primitives selected

KC Theory	Primitive
Tacit dimension (Polanyi)	Tacit foreknowing
Equivalent transformation (Ichikawa)	Equivalence finding Equivalent transformation (ET) ET thinking flow: Analog route ET thinking flow: Digital route
KC Management (Nonaka et al)	Organizational knowledge dynamics: SECI model 'Ba' (individual and shared context) Knowledge leadership Knowledge assets
Non-explicit knowledge process support (Meyer)	Knowledge categorization Social network Knowledge exchange Knowledge inventory
Creative cognition (Finke et al)	Concept synthesis
KJ method (Kawakita)	Exhaustive idea externalization Multi-stage abductive idea organization Diagrammatic mapping
Serendipity (Roberts)	Accidental discovery

Table 2 Steps of the work guide

Item		Step	Details	5W1H
Spanning Space	1	Course or phases of a project	The progress or course of a project is reviewed along the time axis. A diagram is drawn up to see the overall view of persons involves in the project and the duration of each person's research activity.	WHO, WHEN, WHAT
	2	Social network	The social structure of a project and its dynamics are clarified in diagram form. From the diagrams drawn as steps 1 and 2, the phases of a project including SECI modes are identified.	WHO, WHERE, HOW
Underlying Context	3	Individual and shared context	The individual context of each member (actor) is remembered and described as a list. Also, the social context of each member is remembered and described as a list.	WHO, WHERE, WHY
Knowledge Statics & Dynamics	4	Individual knowledge	Individual project-relevant knowledge for each member of the research team is assembled as a list based on the dimensional model of knowledge types.	WHO, WHAT, HOW
	5	Knowledge exchanges	Knowledge exchanges among all related persons are identified and assembled as a cross section table.	WHO, WHAT
Problem Setting & Solving	6	Analog route	Who can see a problem at first and how he/she can see the problem are identified to clarify an analog route or tacit foreknowledge. Moreover, how this problem is shared among members is also clarified.	WHO, WHAT, HOW, WHY, WHEN
	7	Digital route	A research project can be completed only if one can logically bridge a gap between the start and end points of an analog route; i.e. a digital route. Here a digital route is recalled precisely.	WHO , WHEN, WHAT, HOW
Total Process Map	8	Overall thinking flow map	It is desirable to illustrate both analog and digital routes schematically on the whole as a diagram, from which one can get much information about a project.	WHO , WHEN, WHAT, HOW, WHY
Integrated Model	9	Integrated KC model	It is expected that one can develop a newer and more general model for knowledge creation by analyzing a lot of cases and adding primitives.	WHAT, HOW, WHY, WHEN, WHERE

3.3 Work Guide

Synthesizing the above concepts, knowledge creation through tacit knowledge processes is influenced by the following factors: the course or phases of the project, the social network the actors are embedded into, the individual context of actors, their individual (tacit) knowledge involved, the knowledge exchanges among the actors, the digital and analogue route of problem setting and solving, leading to an overall flow of thinking of all participants. Several of such analyses can be integrated into an overall model of knowledge creation, which can serve as a foundation for other or future projects in the same setting. A proposed work guide composed of nine steps as shown in Table 2, where which elements of 5W1H can be clarified in each step also is presented.

Relationships between the primitives shown in Table 1 and the steps shown in Table 2 are illustrated in Figure 12, where relationships indicate possible insights from viewpoints of related primitives in each step. The steps of the work guide are selected in terms of comprehensiveness, easiness to remember, ease-of-use, and at-a-glance understandability. The arrows in Figure 12 mean the precedence relations among tasks of the work guide that is recommended based on the authors' experience.

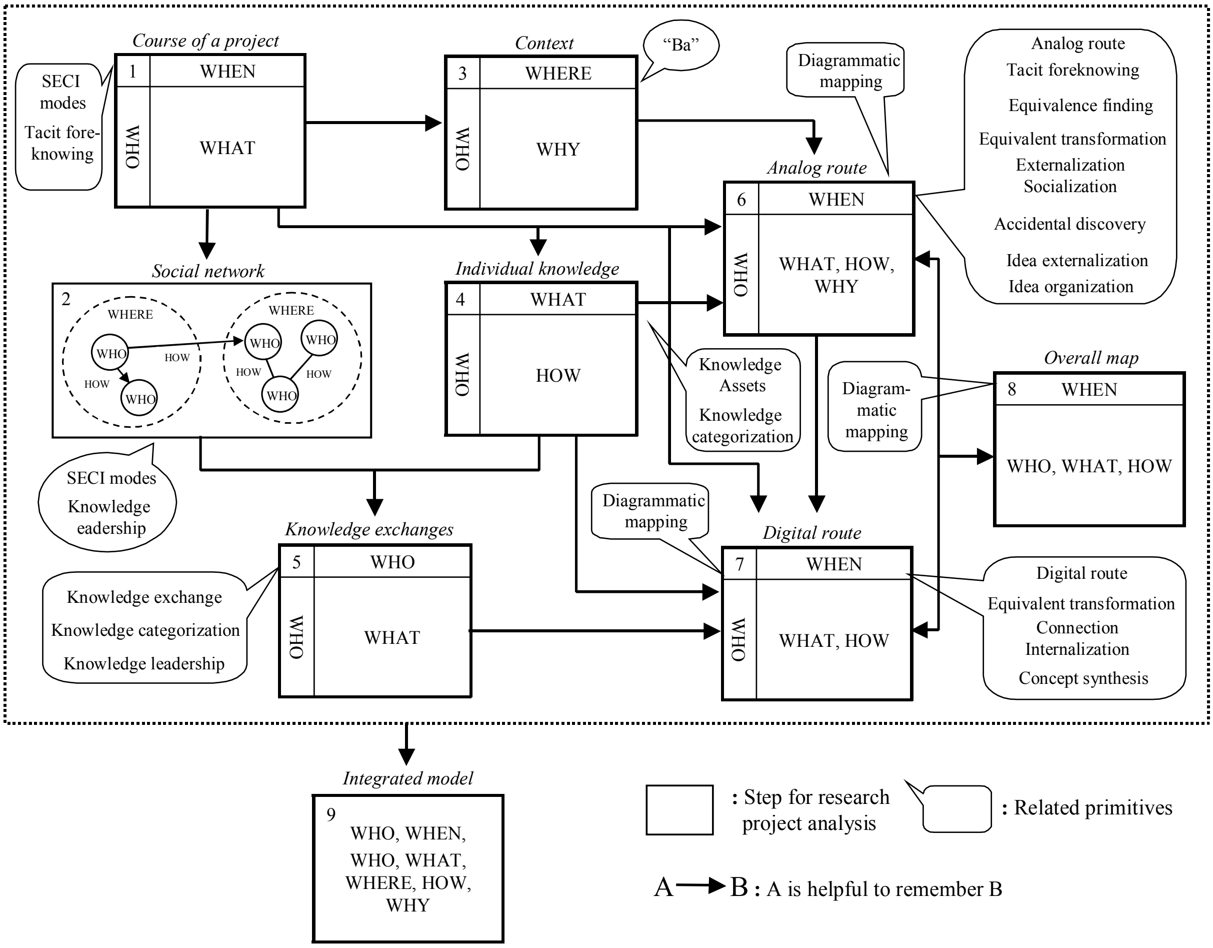

Figure 12 Relations between primitives and tasks

In the following section, we will report excerpts from an explorative application of a few steps of the above framework within a scientific project as page limitations prevent a display of all findings. The application of the framework is in so far explorative, as issues of objectivity remain largely unaddressed and data collection was conducted ex-post after project completion. This first application should analyze overall practicability of data collection and analysis. Issues of objective data collection and computation will have to be addressed in the future.

4. Analysis of a Research Project

The framework was applied to a small research project entitled "Creating New Puzzles by Abstraction and Conversion" (See Sugiyama et al (2004) and Sugiyama et al (2005) for further reference). Its aim was the elaboration of a novel paradigm for user interfaces, with a special emphasis on attractive features that popular toys possessed. For this purpose, we took a systematic approach referred to as abstraction and conversion. The basic idea of the approach is to abstract and convert existing puzzles into other media such as graphs, blocks, sounds, and robots, while preserving their logic (See Figure 13). Analysis of operations of the puzzles led to abstract or mathematical models. Based on these models, puzzle generators were implemented and various types of puzzles were produced.

The supervisor of the project, who subjectively undertook the different assessments, took the nine steps of the analysis. An excerpt of his analyses is outlined in the following sections.

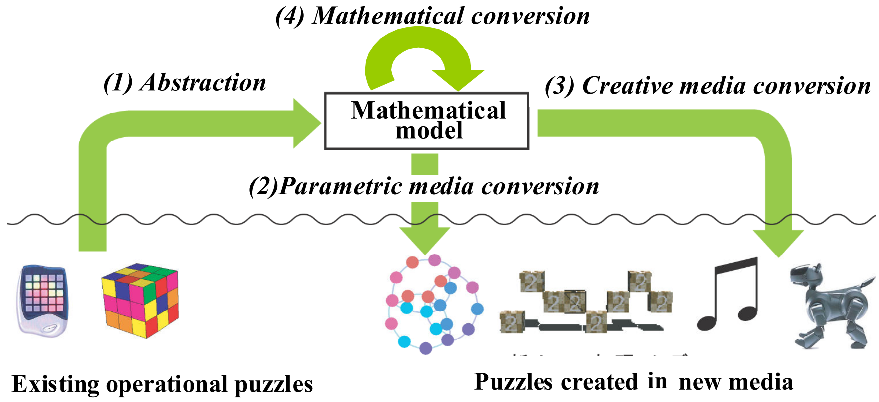

Figure 13 Basic ideas for creating new puzzles

4.2 Course of the Project and Social Network

Clarifying the time sequence of the project and the social network among related persons is most important as first step of the analysis since they provide the fundamental axes of a project space. This is done by arranging persons involved and the duration of each person's activity in a diagram (see Figure 14), identifying project phases and the corresponding modes of the SECI model. In this case, phases identified are: (1) preparation, (2) generation of basic ideas, (3) socialization, (4) formalization, (5) explosion, (6) presentations and publications, and (7) advancement to a new research. Ten persons *A* to *J* in four domestic and one abroad research organizations related to each other: *A* is a PhD candidate supervised by *B*; *B* is a leader of the project; *C*, *D*, and *F* are master students supervised by *B*. Six persons *A*, *B*, *C*, *D*, and *F* are project members. It can be seen that there are two key members *A* and *B*: *A*'s ideas or tacit foreknowledge initiated this project and *B*'s ability for formalization clarified the problem.

In Figure 15, the overall social network and knowledge flow among all related persons for the whole project duration are presented. From Figure 15, we can recognize the importance of knowledge flows of declarative knowledge and hints from outside professionals: They affected the outcome of the project essentially. This means that keeping a good social network is very important to pursuit research effectively and efficiently.

4.2 Context Analysis

According to Nonaka's 'Ba'-theory, context or environment is the most essential factor for a research project. Individual and shared context of project members is presented in Figure 16.

With regard to the contexts, *A*'s individual context seems to be most critical for the project, which can be stated according to the following eight factors:

Social context: Any revolution or novel paradigm was desired in the research domain of 'user interface'.

Pressure: Member *A* had to accomplish his PhD researchs.

PhD research subject: *A*'s PhD research subject was 'user interface with the engagement effects'. This puzzle research formed a part of his thesis.

Stimulation: *A* was stimulated when he was on leave to the famous research institute ATR for three months.

Hints: The research topic of 'toy interfaces' was a good hint for his research. It affected him to seek the possibility of interfaces with more logical bases than existing toy interfaces such as 'doll interfaces' and 'miniature gardens'.

Intuition: *A* graduated at an art university and has a good artistic sense.

Skills: *A* has superior programming skills.

Successful experience: In the implementation of the spring layout algorithm used for graph puzzles, *A* had a successful experience.

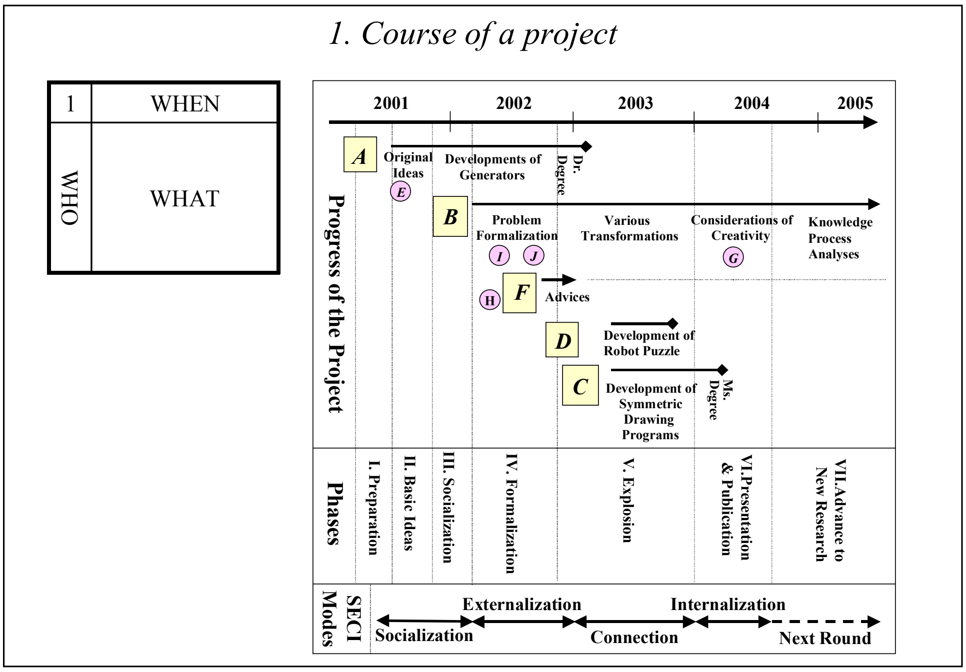

Figure 14 Course of the project: step 1

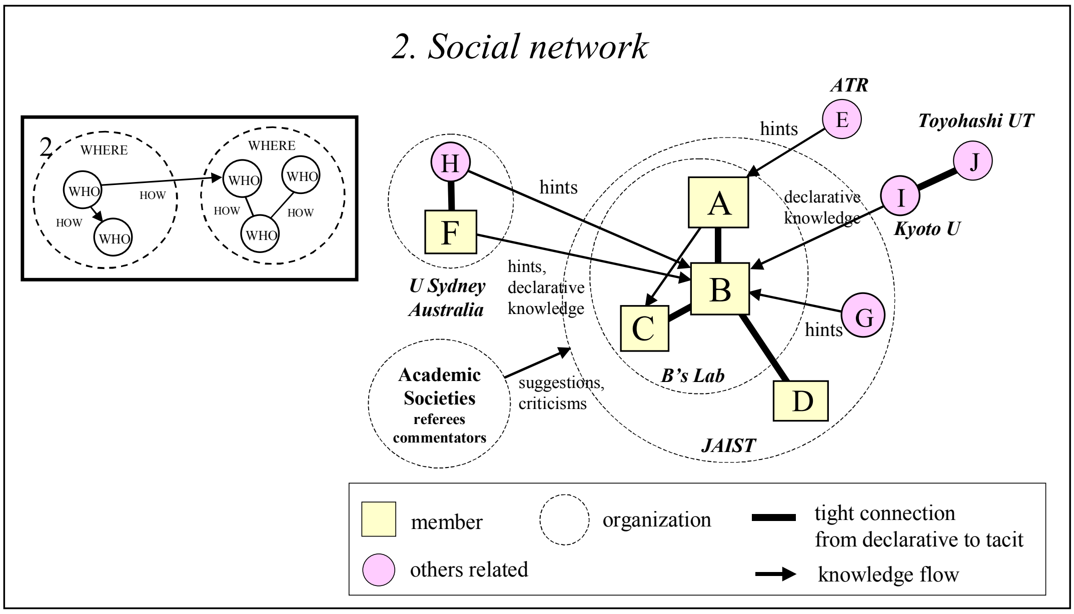

Figure 15 Social network: step 2

3. Context

3	WHERE
WHO	WHY

Per-son	*Affiliation at That Time*			*Context at That Time*
A	KS Lab	JAIST	Dr Student	***A*** **is** ***B*****'s Dr student. He graduated an art university. He has good artistic senses and programming skills but is not familiar with physics, mathematics etc. His subject for Dr thesis is "User interfaces with engagement effects." His motivation is very high for getting Dr degree. He was a visiting student to ATR for a half of year where** ***E*** **supervised him.**
B	KS Lab	JAIST	Professor	***B*** **is** ***A*****'s,** ***C*****'s, and** ***D*****'s supervisor. His knowledge and experience are fitting for progressing this research project.**
C	KS Lab	JAIST	Ms Student	***C*** **is** ***B*****'s student. He has good analytic senses and programming skills but slightly individual. His subject for Master thesis is "Symmetric graph drawing for permutation puzzles."**
D		JAIST	Ms Student	***D*** **is** ***B*****'s student for the sub theme. He has interests for manipulating robots.**
G		JAIST	Professor	**He is** ***B*****'s colleague in JAIST. His research domain is creativity support.**

Figure 16 Individual and shared context: step 3

4. Individual knowledge

4	WHAT
WHO	HOW

Person	*Explicit Knowledge*		*Non-explicit knowledge*			
				Cognitive component of tacit knowledge		
	Declarative knowledge	*Conscious Access to structural knowledge*	*Acquired skills and procedural knowledge*	*Unconscious access to declarative knowledge*	*Unconscious access to structural knowledge*	*Tacit procedural knowledge*
A	Spring algorithm	How to utilize spring algorithm	Programming skills for developing generators	Logic of puzzles	Equivalent transformation thinking	Artistic senses
B	Graph drawing algorithm, Geometry, Graph theory	Mathematical formalizations	Mathematical derivations	Logic of puzzles	Systems integration and analysis	System thinking
C	Tutte algorithm	-------	Programming skills	-------	-------	-------
D	AIBO control	-------	Integration of IT tools, Programming	-------	-------	-------
G	General design theory	-------	-------	-------	-------	-------

Figure 17 Individuals knowledge: step 4

5. Knowledge exchange

5	WHO
WHO	WHAT

to / from	*A*	*B*	*C*	*D*	*G*
A	-------	**Foreknowledge, Basic ideas**	**Source code of PP generators**	------	----
B	**Mathematical formalization, Theoretical results**	-------	**How to solve symmetric layout problem**	**Set of proble m solving**	----
C	-------	**Symmetric layout program, Improvement of generator**	-------	------	----
D	-------	**Robot puzzle**	-------	-------	----
G		**Let S know ETT**	-------	-------	----

Figure 18 Knowledge exchange: step 5

4.3 Individual Knowledge and Knowledge Exchange

It is possible to state what kind of specific declarative knowledge and skills an individual contributed to a project, and what kind of weak declarative knowledge manifested itself during the course of a project. Figures 17 and 18 show the details of individual knowledge and knowledge exchange, respectively: i.e. both tables indicate static and dynamic knowledge inventories. In Figure 17, we can see that both explicit and non-explicit knowledge of *A* and *B* is the kernel of accomplishing the research. For *A*'s knowledge, the important elements are the spring algorithm (used for generating the layouts of graph puzzles), splendid programming skills, and a good artistic sense, while for *B*, important elements are expertise knowledge of wide theoretical domains such as graph drawing algorithms, geometry, and graph theory; his ability of formalization, derivation, and analysis; and his sense for system integration. In Figure 18, it can be seen that most knowledge was exchanged through *B*. This means that *B* coordinated the project activities well and took knowledge leadership.

4.4 Process Map: Analog and Digital Routes

As stated previously, Ichikawa's analog route and Polanyi's tacit foreknowledge are conceptually similar. Tacit foreknowledge (or seeing a problem) is most important for research and is intuitively found by an individual, where a creative mind is indispensable. Ichikawa's digital route (or solving a problem) is logically constructed step by step to find possible routes from the start point to the target point of the analogue route, where experts who have the ability for the coordination and promotion of research are indispensable. The presentation of the digital and analogue route are integrated into a *total thinking flow map* (or process map) of both analog and digital routes for the project (see Figure 19). In the map, relationships among members, research activities and basic concepts (or primitives) are presented, where we distinguish between equivalent transformations in an analogue route and a digital route and they are denoted as a-ET and d-ET respectively. From the map, we can easily recognize concrete instances (or evidences) of the primitives based on our own experience.

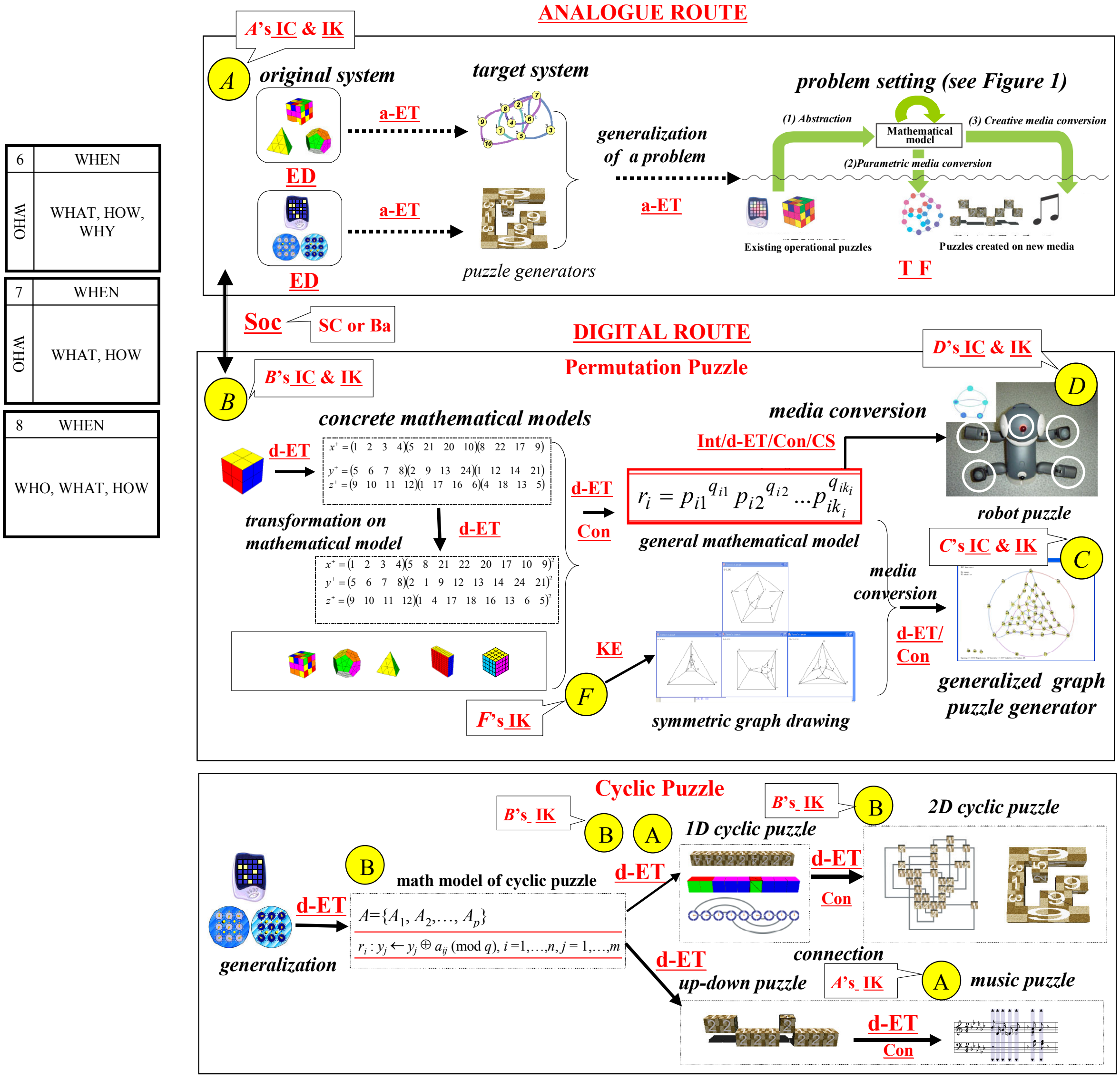

Figure 19 Thinking flow map: steps 6-8

(TF: tacit foreknowledge, a-ET: equivalent transformation in analogue route, d-ET: equivalent transformation in digital route, IC: individual context, SC: social context, IK: individual knowledge, Soc: Socialization, Ext: externalization, Con: connection, Int: internalization.)

4.5 Process Summary

From the overall analysis (Sugiyama, 2007), we gain the following insight into the processes of the project:

1. *A* acquired a *tacit foreknowledge* in two steps: In a specific and in a more general way (compare the *analog route* in Figure 8). In this stage, *A* did not know how to obtain a mathematical model of puzzles both specifically and generally, although *A* had already developed a tentative puzzle generator intuitively.
2. When *A* reported his idea to *B*, *B* assessed it as a good research problem. This is the only reference to the *socialization* phase of the *SECI model*.
3. After the socialization, *B* formalized and analyzed the problem utilizing mathematical concepts, leading to improved results. In this way, *A* experienced the importance of mathematical analysis for the *digital route*.
4. It is possible to interpret each small *equivalent transformation* in terms of the small-step modes of SECI model: i.e. *externalization*, *connection* and *internalization*.
5. The transformation of abstract models into a robot puzzle can be understood as a *concept synthesis*. The new

concept ‘Rubik’s cube robot’ led to the emergence of new puzzles that synthesize two concepts.

6. *Idea exhaustion* was not enough in this research. We have to challenge further possibilities of converging the puzzle into other media.
7. Although a strong *serendipity* was not observed in the process of both routes, *A* had a hint for the study of puzzles when he stayed at ATR. This might be a case of week serendipity.

5. Conclusions

We have presented a way to construct a framework for knowledge process analysis (KPA), where a knowledge pyramid and a meta-pyramid have been introduced, and a knowledge process model has been developed. We have applied this framework to analyze concrete research projects in an exploratory way and elaborate it through the accumulation of case studies. This study is based on a methodology consisting of knowledge process modeling, primitives synthesis, and reflective verification. We have described details of this methodology and presented the result of a case study. It can be concluded that fruitful products such as a novel methodology, a practical work guide, a tool for KPA, insights for improving future research projects/education, and the integration of existing knowledge creation theories can be expected.

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