Actual use of analogies in remarkable scientific discoveries

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This study uses an interview method to investigate how scientists use analogies in actual remarkable scientific discoveries. The observed cases of analogy are classified into six classes according to the two criteria of similarity and transfer, only four of which classes actually include the observed cases. Each typical case of three of the four classes is shown and explained in relation to the availability of the goal of the analogy and other forms of reasoning. One of the three cases is especially considered a case of analogy with the reformation of knowledge based on thematic abstraction, whose dynamic process has not fully been investigated.

Introduction

Analogical reasoning has been pointed out to be one of the most promising mental resources for abduction[1] which brings out an important scientific discovery. There have been in fact a considerable number of studies on analogical thinking. Almost all of them, however, employed an *in vitro approach* (Dunbar, 1995) which was based on cognitive experiments. As a result, they failed to investigate the actual spontaneous use of analogy, especially that as used in real-world laboratories, where the process of an analogy might extend over a much longer period than in artificial settings such as psychological experiments. On the other hand, some studies, whose number is quite small, adopted an *in vivo approach*: Dunbar, for example, collected data on actual scientific thinking in four laboratories based on observations of a participant for 10 months, and analyzed the reasoning of the scientists in real-world contexts (Dunbar, 1995). He found that the three laboratories in which analogies were commonly used could make real gains in their scientific work, whereas the one laboratory that failed to engage in analogical thinking could not. He insisted that analogical reasoning was a potent source of conceptual change or emergent thinking. His study, however, is considered to have two shortcomings: (1) it fails to provide cases of the whole process of analogical reasoning observed in a real-world laboratory, which process may be more dynamic and complicated than that observed in a cognitive experiment and (2) it did not fully capture the types and cognitive mechanisms of analogical reasoning used in scientific discoveries because it is considered to have been concerned mainly with the metaphors used in social interactions, such as an explanation of one's own idea to others, rather than with analogical reasoning itself. This study, however, applies an interview method to provide the cases of analogies that some researchers in different fields used to make actual important scientific discoveries. The following are considered to be the questions concerning analogy that should be answered in studies on analogical reasoning:

1. How is the source retrieved as a potentially relevant analogue and on what similarity is it based? On what similarity is the mapping from the source to the target based?
2. How is the portion of knowledge about each retrieved source searched for and transferred to the target?

This study intends to classify all the cases collected from the above two viewpoints and to investigate what types of analogy were used in real-world laboratories and how they contributed to scientific abduction.

[1] In this paper, abduction is assumed to include the whole process of generation, modification and verification of explanatory hypotheses, whereas in AI it usually means a backward search of the knowledge which explains certain facts.

Method

Two methods can be adopted as the *in vivo approach*: participant observation and interview. Observation is considered to provide more reliable data than interview (Dunbar, 1995; Ericsson & Simon, 1993), because interview necessarily depends on the memories of interviewees. Then, why was the interview method adopted in this paper in spite of its relatively low reliability? The reasons are as follows.

- The interview method allows data to be collected from researchers in various fields, making it possible to consider the differences among fields as well as those among individuals or laboratories. With a participant observation, data can only be collected from researchers in one or two fields. Dunbar, in fact, collected data in only one major field.
- In many cases, the process of scientific abduction extends over a quite long period. It may be true that analogy is made instantly, but the incubation (or preparation) and justification of analogy generally need a long period of time. An interview method is also useful in this respect because the period of a research project is not relevant. In fact, all three of the cases of analogy explained in the next section lasted for much more than the 10 months over which Dunbar had made participant observations.

Interviewees

Twenty two leading Japanese researchers in the fields of natural science and technology were interviewed: their research fields were mainly material science, biotechnology, ecology and theoretical astronomy. The interviewees were selected from among the researchers whose achievements had been highly estimated by their colleagues based on the *consensual assessment technique*. As a result, the following researchers were selected.

- A leader or a chief researcher in a public or national major research project.
- A productive and creative researcher who had been awarded by academic societies in the recent several years.

Interview method

Retrospective reports are said to suffer from the relatively low reliability caused by the vagueness of interviewee's memories (Dunbar, 1995; Ericsson et al., 1993). To compensate for such a weakness, therefore, only the research projects satisfying both of the following two conditions were selected: (1) the research process was recorded in relative detail and (2) the research project had been completed recently or was in progress. In addition, the following efforts were made.

- The author examined all the available research records provided by the interviewees themselves and by their co-researchers.
- In some cases, the author checked the consistency of the data provided by the interviewee himself/herself and the data provided by his/her co-researchers. The two types of collected data turned out to be basically consistent. In all three cases of analogy explained in the next section, the data were collected from more than one researcher per project, and their consistency was checked and confirmed.
- The author had the interviewees themselves reconfirm whether the results of analyzing the data seemed appropriate or not. The result of an analysis was excluded from consideration when it was regarded as inappropriate.

Interview procedure

The interview procedure consisted of three tasks: a pre-interview, the interview itself, and a post-interview. In almost every case, the interviewer repeated the interview and post-interview with the same interviewee several times.

Pre-interview The interviewer (the author) presented the questionnaire to every interviewee in advance. Each interviewee was asked to select some cases appropriate for the purpose of the interview among his/her recent research projects and to provide the special knowledge of his/her field (in the form of a review or original paper and other research material) that was necessary for the interviewer to understand his/her explanation. In addition, he/she was required to present his/her own past research data and records which the interviewer used to consider the plausibility of the interview data.

Interview Each interviewee was first asked to dictate the outline of his/her own research and thinking processes for the cases selected. That was followed by questions and answers between the interviewee and the interviewer. All the data were recorded on tape.

Post-interview All the protocol data were analyzed by the method explained below. Every interviewee was asked to confirm whether the results of analysis were appropriate or not from the technical viewpoint of his/her research. In some cases, the interviewer asked the interviewee's research colleagues to confirm whether the interviewee's reports were consistent with their memories and whether the interviewee's thinking processes reported were unique to the interviewee or might be commonly observed among the researchers in the field.

Method of analysis

All the data recorded were first transcribed and then recomposed in chronological order. The contents of each verbal protocol were classified into respective research themes, then each theme was classified into abduction processes, each of which was consistent in content. The cases of analogy were elicited from among various forms of reasoning observed in each abduction process. All the cases were analyzed from the viewpoints of the two questions concerning analogy explained in the first section and classified into six classes as explained below.

Criteria of classification The two questions concerning analogy have often been used as criteria for classifying analogies in previous studies and are also used here.

First, the cases of analogy can be classified according to the types of similarity used both in the retrieval of a potentially relevant source and in the mapping. Three types of similarity are widely known to be used in the retrieval (and mapping) process: object-level, relation-level, and pragmatic similarity. The relation-level similarity which is irrelevant to the goal of analogy, however, is considered to be hardly used as a retrieval cue because a target involves only a few causal relations. In fact, the results of analysis reveal that the relational similarity was never used as a retrieval cue in all the cases observed. Relation-level similarity is, therefore, excluded here: object-level and pragmatic similarities will be used as classifiers. Object-level similarity is called *category-based similarity* in this paper, because the object which is generally used as a retrieval cue in scientific abduction is the category of natural kinds.[2] In addition to the two similarities, another type of similarity was actually used: *category-formational similarity*, which means that a potential source is mapped to the target based on the category newly created in the process of the analogy.

Second, the cases of analogy can be classified according to the types of search for the knowledge which is potentially transferred. The mechanism of deciding which portion of knowledge is to be transferred, however, has rarely been investigated, although some theories on re-

[2] Note that category-based analogy in some cases is also goal-directed or goal-derived. The question here is whether the goal of a target is, in fact, used as a *retrieval cue* or not.

trieval and mapping such as SME (Falkenhainer, Forbus, & Gentner, 1989) and ARCS (Thagard, Holyoak, Nelson, & Gochfeld, 1990) have been proposed. This is considered to be because the knowledge structure of a source is assumed to be explicitly given in most previous studies. The knowledge structure of concern of both the source and the target can, however, dynamically change in the process of an analogy. To clarify this, the following two classifiers will be newly introduced: search for the transferable knowledge based on causality and that based on meta-constraint.

All the cases observed will be, therefore, classified into six classes according to the three types of similarity and the two types of transfer. In addition, it should be analyzed whether *thematic abstraction*[3] (Suzuki, 1994) was actually used in the process of analogy, because the abstraction is considered to be closely related with the reformation of knowledge or conceptual change while an analogy is being made.

Results and analyses

There were many intra-laboratory and interlaboratory similarities in the spontaneous use of analogy in abduction. Hence, a number of trends have emerged from the interview data, although the amount of the data is insufficient for statistical analysis.[4] These trends will be explained and the observed cases of analogies will be classified into the six classes identified.

Classification of analogies

The analogies observed are explained mainly according to the types of similarity used in retrieval (and also in mapping).

Goal-directed analogy In this class of analogy, a potentially relevant source analog is retrieved by using a goal which has been fully clarified through other types of reasoning (including meta-reasoning) prior to the analogy: the goal itself is used as a retrieval cue.[5] A typical example is shown in Figure 1, although the figure provides a summary rather than the raw protocol data.[6]

The detailed explanation of the abduction based on analogy uses the following notations. A target domain is denoted by t. K_t is a set of facts specific to the target. A source domain is the one retrieved as a potential analogue of the target domain t, which is denoted by s. K_s is a set of facts specific to the source, the same as K_t. G_t is the goal of the target.

First, a domain with G_s, which is a counterpart of G_t, is retrieved as a potentially relevant analogue, where G_s is equivalent to G_t with respect to the objects and relations of concern. Speaking of the case shown in Figure 1, G_t is "a (molecule of) sebum penetrates the interior of a single fiber" and G_s is "a molecule of insecticide penetrates the interior of a single fiber." Hence G_s is similar to G_t in that a certain molecule penetrates the interior of a single fiber. Second, K'_s, the portion of K_s, that causally explains G_s and that shares the equivalent facts with K_t, is searched for. As for the case in Figure 1, K'_s is "the molecule of concern is soluble" which shares the property of *solubility* with K_t. In addition, K''_s which is causally explained by K'_s is searched for. As for the example, K''_s is "the molecule of concern is gelable and thus trapped firmly." Finally, the union of K'_s and K''_s is transferred into K_t. This case is also classified into the analogy with causality-based transfer, because it uses the causalities in searching for the relevant knowledge, *i.e.* K'_s and K''_s.

Note that *two-stage similarity match* (the comparison of goals and that of potentially relevant shared facts) is often observed in this analogy and that the two matches are exactly opposite in the direction of comparison (the comparison of goals is made from target to source while that of facts is made from source to target).

This analogy requires that the goal of a target be clarified before the analogy, because the whole process is goal-directed and goal-derived.[7] The reasoning before the analogy may contribute more to abduction than the analogy itself. Note that the relevant similarity and causality are not explicit to an analogist in advance but gradually made salient in the process of an analogy: they are dynamically determined in the light of the goal of an analogy while they are fixed in SME.

This class of analogy is often used in inventing a method for realizing a goal[8] or in speculating whether a relatively simple phenomenon is likely to occur. About half of the observed analogies belong to this class: the number of the cases is 10.

Category-based analogy In this class of analogy, a source analogue is retrieved by using a category of natural kinds (Glucksberg & Keysar, 1990). It is because the information available before the analogy is not sufficient: either the goal of a target or the causality of a source is not so clear as in the goal-directed analogy. Of the seven cases observed, four were reported by the two researchers who were compelled to make abduction by using fragmentary data, which seems due to the characteristics of their research fields: the fields of one researcher are paleontology and ecology, and that of the other is geology. A typical example is shown in Figure 2, which example illustrates the following characteristics of the class of analogy.

[3]It means a thematically and functionally organized abstraction based on the goal of analogy.

[4]Statistical analysis, which is a future work, is needed to decide to which factors (research field/laboratory strategy/individual tendency) each observed trend is attributed.

[5]This class of analogy is considered similar to *purpose-directed analogy* in (Kedar-Cabelli, 1985).

[6]The raw protocol data of each explained case cannot be reported in this paper because they have a large quantity and, in some cases, are not permitted to become open.

[7]For example, in the case where a method for changing the scattering frequency of an electron was transferred to a target whose final goal is to develop a new type of transistor, the goal of "changing the scattering frequency" was already identified by backward reasoning and meta-reasoning prior to the analogy.

[8]In this case, the two-stage similarity match is not necessarily needed: only a goal-directed similarity is required.

Theme: To develop a new type of detergent which can remove stains from cotton fabric.

Problem: The researcher assumed sebum to be the potential cause of stains on cotton fabric: he focused on the sebum. He regarded it as a primary problem to locate sebum in a cotton fabric, because that had not been done at that time.

Situation before analogy: Almost all researchers believed that sebum was on the surface of a single fiber. The researcher himself, therefore, tried with a scanning electron microscope to find molecules of sebum on the surface of a single fiber, but in vain. Then he and his colleagues doubted the idea that sebum was on the surface of a single fiber and assumed that sebum penetrated the interior of a single fiber: he formed the assumption heuristically by shifting his attention to the microscopic structure of the interior of a single fiber.

Analogical reasoning: He tried to evaluate the assumption based on analogy: he looked up a paper saying that a certain molecule can penetrate a single fiber. As a result, he could find a paper saying that a single fiber consists of crystal and amorphous domains and that a molecule of insecticide can penetrate the amorphous domain. It also says that this results from the fact that a molecule of insecticide is soluble and, therefore, gelable. Then he analogically decided that a molecule of sebum could also penetrate the interior of a single fiber because it is also soluble: the objects of concern of the two analogical domains share the property of *solubility*. In addition, the paper says that a molecule of insecticide may be firmly trapped inside a fiber because it is gelable. It was, therefore, predicted that a molecule of sebum might be trapped firmly.

Figure 1: A case of goal-directed analogy.

Theme: To locate the spawning ground of the nautilus.

Situation before analogy: Only a few things were known about the nautilus: (1) several infant individuals were observed only around coral reefs while some dying individuals were found in wider areas, (2) the nautilus prefers Crustacea as a food, and (3) it is probable from the result of an isotopic experiment that the nautilus inhabits relatively deep ocean.

Analogical reasoning: The researcher recalled Broadclub cuttlefish as an analogue of the nautilus, because both species belong to the same category of *cephalopod*. At the moment, he analogically supposed that the spawning ground of the nautilus is a coral reef, the same as that of Broadclub cuttlefish. Then he considered the plausibility of the assumption by constructing a structure of explanation on Broadclub cuttlefish and transferring it to the domain of the nautilus. The following two facts were known about Broadclub cuttlefish: one is that Broadclub cuttlefish inhabits the open sea and the other is that it spawns in coral reefs. He built an explanation as follows. The above two facts imply that the habitat and the spawning ground are different. This, in turn, supports the following meta-constraint, because a coral reef is, in general, like a labyrinth: if the number of spawns is small, the spawning ground itself should work as a shelter for the spawns. Because the habitat of the nautilus was also assumed to be the open sea, he was convinced that it spawned in coral reefs as well, which supports both of the above meta-constraint and the facts about the nautilus known in those days.

Figure 2: A case of category-based analogy.

1. A kind of category (hierarchical classification of chemical substances and species) was used as a retrieval cue.
2. Two ways of searching for or evaluating potentially transferable knowledge were observed: one is based on causality, the same as in goal-directed analogy, and the other is based on constructing a plausible structural explanation consistent with some *meta-constraints*, which is shown in Figure 2.

The above are considered to derive from the facts that (1) the goal of a target is unavailable as a retrieval cue and (2) only the weaker constraints on analogy, not the strong causality of a source, are available[9] so that an analogist is compelled to patchwork some fragmentary data or known facts into a structural explanation. This is considered to be attributed to the characteristics of research fields like ecology and geology, in which only a little information and weaker constraints are available, rather than to an individual's tendency in reasoning. But this is still an open problem. The process of searching knowledge by using meta-constraints has been observed only in this class of analogy.

Note that a category used is implicitly relevant to the goal of the analogy because an expert knows that such a category is available in the light of the goal and of his/her experiences in using the category as a similarity. The category used is, therefore, not a surface similarity (Holyoak & Koh, 1987) but a kind of goal-derived category (Glucksberg et al., 1990) or thematic abstraction. Interestingly, a category was regarded as a ***structural dissimilarity*** (Holyoak el al., 1987) in some situations while it was used as a similarity in similar situations, depending on the goal of the analogy. For example, a method of assigning an unknown substance to a known molecule in a single-crystal state could not be analogically derived from the methods of assigning the substance to the same molecule in other states, such as poly-crystal and dissolved states. The interviewee knew as an expert that the difference in state was sometimes fatal to analogical transfer of such an assigning method, although it caused no problem for some other purposes. The discrimination of surface/structural similarity is, therefore, considered to depend on the goal of analogy: the distance between domains, which is discussed in (Dunbar, 1995), is difficult to define generally without considering the goal of the analogy.

Category-formational Analogy This class of analogy has not fully been investigated in previous studies mainly based on psychological experiments. In this anal-

[9] Of course, the weak causality of a source is also used.

Theme: To construct a theory which explains the unique behavior of star clusters.

Situation before analogy: There was a theory which aimed to explain the unique behavior of clusters by regarding a cluster as an isothermal gas sphere like a fixed star (that is, the source analogue was a model of the internal constitution of stars). Most researchers in those days, however, recognized this analogy as a fallacy, because a cluster remarkably differs from a star in that the former is a discrete system whereas the latter is a continuous one. The concept of *self-gravitation* was used mainly in the theory of the internal constitution of stars.

Analogical reasoning: The researcher assumed that the unique behavior of clusters was caused by the fact that clusters are self-gravitational systems. He considered that if the assumption was right, self-gravitation (*i.e.*, the similarity) would influence the unique behavior of clusters far more drastically than the difference between discreteness and continuity (*i.e.*, the dissimilarity). So he considered that the theory of the internal constitution of stars would be available. To take the effects of self-gravitation into account, however, the linear theory (on an isothermal gas sphere) had to be replaced by another theory (on a heterothermal gas sphere). Then he introduced both Prigogine's theory on non-equilibrium thermodynamics and the linearized stability theory, and succeeded in creating the new concept of *selfgravo-thermodynamics*. He found that clusters and stars are quite similar from this viewpoint: he modified the theory of the internal constitution of fixed stars from the viewpoint. In the analogical transfer, however, the modified theory had to be still more modified, although partially: for example, the scattering of photons, which is the main energy transfer mechanism within a star, is replaced by the collisions of particles within a cluster, both of which are equivalent from the viewpoint of internal energy transfer mechanism. These differences brought some critical dissimilarities in the end: the most significant one is that only the *core* of a cluster suffers from gravitational collapse while the *whole* of a star does so and finally grows into a black hole.

Figure 3: A case of category-formational analogy.

ogy, a source analogue is connected with and mapped to a target by using a category like in the category-based analogy. This analogy, however, differs from the category-based analogy in that a new category is being created in the process of analogy in the former while the category used is static or fixed in the latter. That is because a target has a weaker connection with a source analogue in the former analogy than in the latter one. The number of cases is only 2, both of which were reported by the researchers in theoretical astrophysics. A typical example is shown in Figure 3, which suggests the following important points.

1. There had existed a similar but fallacious analogy before this analogy. The source was retrieved by using the pre-existing category of *self-gravitation*, but its relevancy could not be assured by the category, because the connection between the two domains was not salient.
2. A category of *selfgravo-thermodynamics*, which was used as a cue for the mapping rather than the retrieval[10] was formed in the process of analogy by newly introducing other theories and by extending the pre-existing category which had been specific to the source. As a result, the connection between the target and the source was established. The newly formed category is considered a kind of thematic abstraction because the pre-existing category was thematically reorganized into the category in light of the goal of the analogy.
3. The transfer of knowledge was almost an embedding based on causality, but the process of modifying the transferred knowledge was quite complicated. Thematic abstraction is considered to have also been used here because the category of *internal energy transfer mechanism* is not so much a common category as an ad hoc one tailored for this modification.
4. The researcher testified that the dissimilarity between clusters and stars had been made much of after the analogical transfer while the similarity had been important at the beginning.

The most important in this case is that the whole analogy is driven by thematic abstraction. The abstraction enables the reformation of knowledge according to the goal of analogy, which provides the similarity between the domains. This dynamic process of analogy in actual scientific abduction has not fully been clarified in SME, ACME (Holyoak & Thagard 1989) or ARCS.

The author believes that the fourth point can be attributed to the characteristics of the research field of theoretical astrophysics, because this phenomenon was more or less observed in both cases, although this is still an open question.

Effects of analogies

Table 1: The classification of the observed cases (each figure denotes the number of the cases).

	transfer based on causality	transfer based on meta constraint
goal-directed	10	0
category-based	3	4
category-formational	2	0

Both the classification of the observed cases and the comparison between the classes of analogy are summarized in Table 1 and Table 2. Of the three classes based on the similarity criterion, the goal-directed analogy is close to deduction because both the retrieval of a potential source and the search for potentially transferable knowledge are carried out by using both the goal of a target and the causality of a source. This class of analogy, therefore, requires that its goal be clear and specific. If the goal and the causality used are not problem-specific, this analogy

[10]This is because the source has already been retrieved by using the pre-existing category.

Table 2: The comparison of the three classes of analogy.

classes of analogy	availability of a goal	retrieval cue	types of transferred knowledge	related form of reasoning
goal-directed	high	goal	method or simple phenomenon	deduction
category-based	↕	common-category	method or structural explanation	construction of a belief network
category-formational	low	newly formed category	theory	theory application

may be the what is called deduction.[11] This analogy is, therefore, considered to have the least possibility of leading to mental leaps. The category-based analogy is considered to realize the construction of a belief network (Pearl, 1988) based on knowledge transfer: some fragments of knowledge and their links are newly introduced to a target and some uncertain beliefs concerning the target are made more certain by the analogy. The category-formational analogy is close to theory application: a theory can be transferred and applied to a target by newly introducing an abstract viewpoint which can play the role of a bridge spanning two domains, and by extending the original theory. In the last two classes of analogies, the goals are less clear and specific than in the goal-directed analogy. These analogies are, therefore, considered to have more potential of causing mental leaps than the goal-directed one. The differences among the three analogies may depend on the difference in the degree of clarification of a goal and in the availability of the goal as a retrieval cue.

General discussions

This study applies an interview method to investigate how scientists use analogies, not in artificial settings such as psychological experiments, but in actual scientific contexts. This paper first provides some remarkable cases of analogies used in real-world laboratories and reveals that each of the cases, especially that of the category-formational analogy, shows a more dynamic and complicated process as a whole than that observed in cognitive experiments. The author then classified all the cases collected according to the two criteria: the types of similarity and the types of transfer. As a result, it was revealed that four classes of analogy, one of which has not fully been investigated, were used in actual scientific abduction, which differ in the effects on abduction. All these were not fully clarified in (Dunbar, 1995; Holyoak & Thagard, 1995).

The results of analysis reveal that all the cases of analogy in actual scientific abduction are more or less goal-directed or goal-derived. As a result, this study does not postulate the initial process of forming many unnecessary mappings, which could not be actually observed, as postulated in SME, ACME and ARCS. In two classes of analogy, thematic abstraction turns out to be much used: it enables the reformation of knowledge (including the similarity itself). This study is considered to differ from most previous studies in this respect because they could not fully clarify the dynamic and complicated process of analogy with respect to the reformation of knowledge based on thematic abstraction.

Of course this study has some problems. In particular, the interview method suffers from relatively low reliability. Some efforts were therefore made to compensate for this weakness. There is, however, somewhat of a gap between what people actually think and what people are conscious of while they are thinking. Hence, it is one of the future works to collect data by participant observation and to compare them with the data of the present study.

[11] Many cases in which problems were solved by using general causality were, in fact, classified into deductive problem solving in the analysis.

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