Analogy-Making:
Psychological Data and Computational Models

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1. What is Analogy?

There is no general agreement on what is analogy-making: is it a type of reasoning or a type of perception?

Analogy can be viewed as a type of reasoning where knowledge is transferred from one situation (called source or base) to another one (called target) on the basis of some kind of similarity between both situations, i.e. on the basis of the judgment that the two situations are essentially identical with respect to the task at hand. This is the currently prevailing view on analogy (Gentner, 1983, 1989, Holyoak and Thagard, 1995).

Analogy can also be viewed as a kind of high-level perception, where one situation is perceived as (in terms of) another one (Hofstadter, 1995).

From my perspective, both aspects are relevant and important and therefore analogy might be considered as a bridge between reasoning and perception thus playing a special role at the core of human cognition.

2. Analogy and similarity

One of the difficult questions is when two situations can be considered as analogous. There are at least three criteria (called syntactic, semantic, and pragmatic constraints) which have to be applied together (Holyoak & Thagard, 1989, 1995):

- structure correspondence between the two situations, i.e. the pressure to find a one-to-one mapping between the elements of both situations and to preserve the relations between them (e.g. correspondence between the structure of relations in a family and the structure of hierarchical relations in a organization), and
- semantic similarity between the elements of both situations (e.g. teachers test the pupils, and professors examine the students – teachers are semantically similar to professors, pupils – to students, and test – to examine),
- correspondence established between the most important aspects of both situations with respect to the goal of the reasoner (e.g. in the context of a deal values and ownership are important but not the current locations of the objects being exchanged).

Depending on the degree of satisfaction of each of these criteria analogy my evolve into other kinds of similarity. So if two objects have the same attributes and relational structure (e.g. two cars which are the same model of the same brand) analogy evolves into literal similarity; if they share only attributes, but not the relational structure, i.e. there is a high semantic similarity, but no structure correspondence (e.g. a lamp is like the sun as both emit light) analogy evolves into mere appearance (Gentner, 1989).

3. Types of analogy.

Depending on whether or not the base and the target belong to the same subject domain two different types of analogy are defined: *cross-domain analogy* (or between-domain, or inter-domain analogy) and *intra-domain analogy* (or within-domain analogy, or case-based reasoning).

Analogical problem solving can be initiated

- by an explicit hint to use a particular case (provided by a teacher) as a source for analogy (*forced analogy*),
- by spontaneous retrieval of a source from memory and noticing the analogy between this case and the target. In the present work only the last case is investigated: (*spontaneous analogy*),
- by a reasoner's explicit decision to try to solve a difficult problem by an (a priori unknown) analogy and generating (constructing) various sources by systematic transformations (*constructive analogy*).

Analogy is used in various contexts: in problem solving (solving a new problem by analogy to an old one), in argumentation (using an old case as an argument that in the new situation the same should be done), in explanation (explaining a new concept or theory using an analogy to a well known concept or theory), etc. In the case of problem solving the base for analogy could be the problem solution of an old problem, or the derivation of that solution. The latter case is called derivational analogy.

4. Basic Psychological Findings.

4.1. Experiments on Retrieval

It is a well known experimental fact that people usually have difficulties retrieving spontaneously a source analog, especially a remote-domain analog (Gick & Holyoak, 1980, 1983), and this is probably the main difficulty in human analogical problem solving (only 20% success in their experiments).

However, Holyoak and Koh (1987) demonstrated that spontaneous analogical transfer in fact occurs even between remote domains like the Radiation Problem (Dunker, 1945) and a lightbulb story (to fuse the filament in a bulb using a laser or ultrasound).

Experiments performed by various researchers (Ross 1984, 1987, 1989a, 1989b, Gentner & Landers, 1985, Holyoak & Koh, 1987) demonstrated clearly that the main factor affecting the retrieval process is the overall semantic similarity between source and target, i.e. the number of shared features. In other words in most cases the superficial dissimilarity may prevent people from retrieving a story which is structurally very similar to the target.

Base	**army**	**laser fragile glass**	**laser insufficient intensity**	**ultra-sound fragile glass**	**ultra-sound insufficient intensity**
Target	**radiation**	**radiation**	**radiation**	**radiation**	**radiation**
% success	**20**	**69**	**33**	**38**	**13**

Table 1. Comparing the percentage of successful retrieval of the base story depending on the structural and superficial similarities between base and target.

Gick & Holyoak (1983) demonstrated that the availability of a scheme (a more general and abstract description of a class of problems) aids in the retrieval of the corresponding source.

4.2. Experiments on Mapping

A number of studies investigate human difficulties in establishing correct correspondences between the source and the target. It is particularly difficult to find correspondences between analogs from two different and remote domains. Even provided with the source and explicitly hinted, some subjects fail to use the analogy: about 25% of the subjects in experiments performed by Gick and Holyoak (1980, 1983) on the Dunker problem.

It was demonstrated that the degree of structural consistency between source and target affects the ease of establishing such a correspondence but it was also shown that the similarity between the objects and relations involved in the analog situations is important as well (Gentner & Toupin, 1986, Holyoak & Koh, 1987, Ross, 1987). In particular, it was demonstrated that cross-mapping (similar objects playing different roles in the situations) impairs establishing a correct correspondence between source and target and that more similar relations are put in correspondence more easily.

4.3. Priming and Context Effects

Kokinov (1990) has demonstrated *priming effects* on analogical problem solving, that is that the preliminary state of memory (active concepts, other problems and thoughts) influences the accessibility and retrievability of sources. Moreover, it has been demonstrated that these priming effects decrease in the course of time and disappear after 20-25 minutes. Another study (Kokinov & Yoveva, 1996) has demonstrated *context effects* on analogical problem solving, i.e. the perception of casual objects from the environment can also influence the way the problem is being solved. This means that analogy-making is a dynamic context-sensitive process.

5. Models of Analogy.

There is a more or less general agreement on the subprocesses of analogy-making (Hall, 1989): perceiving and/or formulating the problem, retrieval of a source analog, mapping the source onto the target, transfer of knowledge from the source to the target (making inferences), evaluation of the inferences, and learning (memorizing the inferences or the mappings, induction of more general schemata, reorganizing the memory organization in order to achieve easier analog retrieval in the future).

There is, however, a great deal of disagreement on the mechanisms performing these subprocesses as well as on their interactions. Some researchers isolate one particular subprocess (most often the mapping process, but also the retrieval process) and try to model it, while others believe that all these subprocesses run in parallel and interact with each other and therefore they cannot be modeled separately.

Thus the classic Structure-Mapping Theory (SMT) proposed by Gentner (1983) is a theory of mapping only. Moreover Gentner (1989) claims that different guiding principles are used in retrieval and mapping and therefore different mechanisms are responsible for them. The SMT suggests that mapping is based on structural similarities between the two domains, which is operationalized as mapping based on identical relations between the objects in the two domains (ignoring the objects themselves and their attributes) and preserving the hierarchical organization of these relations (giving priority to higher-order relations) which is called the *systematicity principle.* One problem with SMT is its restriction to identical relations which requires both domains to be represented in a very specific way, i.e. STM lacks flexibility.

Holyoak and Thagard (1989, 1995) have also proposed a theory of mapping which, however, relies on the three types of constraints listed above: syntactic (similar to Gentner's structure-mapping idea), semantic and pragmatic. They use a connectionist network to solve this constraint satisfaction problem in a parallel manner. This model is much more flexible allowing similar relations (not only identical ones) to be mapped, but the computational task becomes too complex (forming all possible pairings) even for a parallel solution.

Thagard, P., Holyoak, K., Nelson, G., and Gochfeld, D. (1990) have proposed a constraint-satisfaction model of retrieval called ARCS, which is basically similar to ACME but has a preliminary phase which is based solely on superficial similarity – the number of shared predicates. Gentner, D. and Forbus, K. (1991), Forbus, K., Gentner, D. and Law, K. (1995) have proposed a model of retrieval MAC/FAC which is based on semantic similarity judgments between target and base.

Hofstadter (1995), Hofstadter and Mitchell (1994), Mitchell (1994), French (1995) have developed the CopyCat and TableTop models of analogy-making which integrate the first two phases of analogy – perception and mapping. They have demonstrated that the interaction between perception and mapping makes the systems much more flexible as the mapping will not depend on the manually encoded problem descriptions, but will construct their own representations of the task depending on the results of the perceptual process. The systems are stochastic and so they produce different results on different runs thus demonstrating flexible behavior. These systems, however, lack long-term memory for solved problems and thus they do not retrieve any base from memory, but rather they compare every two problems given to them by the user.

Recently Hummel and Holyoak (in press) have proposed a model of analogy-making which integrates retrieval and mapping and which is based on a hybrid architecture integrating distributed connectionist representations with symbolic representations.

6. AMBR: An Integrated, Context-Sensitive Model of Analogy-Making

The AMBR model (Kokinov, 1994) integrates many of the analogy-making subprocesses: retrieval, mapping, transfer, evaluation, and (to certain extend) learning. This model lacks perceptual possibilities and is fed up with the problem description by the user (as in most analogy-making models, except CopyCat and TableTop), but we are currently working on an extension of the model called PEAN which should integrate perception as well.

The integration of various analogy-making subprocesses is considered to be crucial for the success of analogy modeling in AMBR, because this processes run in parallel and interact

with each other thus guiding and restricting each other's behavior. Thus, for example, the memory process changes dynamically the relevance factor of each memory element (based on new input from perception and on the internal connections between the memory elements) and these changes influence the work of other processes as mapping and transfer by increasing the importance for the corresponding element to be mapped or transferred. This interaction makes also possible to combine flexibility with efficiency – allowing potentially every possible mapping, but restricting the actually attempted mappings to the ones which are relevant to the particular context. For example, AMBR is much more flexible than SMT and ACME in allowing two relations to be considered as similar when a superclass of them can be found at any level of the hierarchy (STM restricts to the Zero-level requiring identity, and ACME restricts to the First-level allowing immediate neighborhoods to be mapped), at the same time only a few possible mapping hypotheses are formed (in contrast to ACME where all possible pairings are considered) – the ones that have high relevance to the context as computed by the memory mechanisms. On the other hand, each successful mapping or transfer activates new memory elements triggering new changes in the relevance factors computed dynamically by the memory process.

A second important feature of AMBR is that reasoning is a dynamic context-sensitive process, influenced both by the preliminary state of the mind of the reasoner and by the changes in the environment. AMBR has demonstrated the same kind of priming and context effects found in psychological experiments (section 4.3). Thus given one and the same target problem AMBR produces different results on different occasions depending on the preactivated concepts and stories as well as on the elements of the environment being perceived during the problem solving process.

A third important feature of AMBR is that it is a general reasoning mechanism whose particular cases are deduction, induction and analogy, i.e. if it happened to be the case that the retrieved base is a general case or schema than AMBR performing the mapping and transfer by the same mechanisms will perform a deduction, and if it happened to be the case that the retrieved base is a particular case of the problem at hand than the same mechanisms will produce an inductive inference, while in all other cases it will make analogical inferences.

AMBR is built on a general cognitive architecture, DUAL. Cognitive processes emerge from the collective behavior of many simple micro-agents in this architecture. Each agent is hybrid one having a symbolic and a connectionist part. The symbolic part represents a small piece of (declarative and/or procedural) knowledge while the connectionist part represents its relevance in the current context. Both parts play important roles in every cognitive process.

7. Conclusions

Analogy-making is a basic human ability which lies at the heart of human cognition. It is typical both for everyday commonsense reasoning and for highly creative thinking. Analogy is often used in problem solving, argumentation, explanation, etc. It is closely related to other basic cognitive processes such as perception, similarity judgment, metaphor.

Cognitive science understanding of this phenomenon and its modeling are in their early stages and it is far from solving the mystery of analogy-making that has excited scientist since Socrates and Aristotle, but it is challenging and interesting to work in this field.

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