In *Proceedings of the International Conference on Systems, Man and Cybernetics*,
Tucson, Arizona, November 1985.

ANALOGICAL REMINDING: A GOOD MATCH IS HARD TO FIND

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Abstract

Analogy is a powerful technique in commonsense reasoning. For example, a person reasoning about molecular collisions spontaneously brings up the analogy of a wrestler hitting the ropes, and uses it to solve the problem. Here we ask how such analogies are accessed: What determines which comparisons people will think of spontaneously? Artificial intelligence researchers have generally assumed that analogical access is governed by the same factors as analogical reasoning: i.e., that long-term memory access is via shared higher-order relations such as causality (e.g., Schank, 1982). However, there is psychological evidence that people often fail to notice potential higher-order analogies.

To find out what governs access, we put people in the position of trying to access analogy and similarity matches from long-term memory and asked which kinds of comparisons were easiest to retrieve. Subjects first read a large set of scenarios. Two weeks later, they were given new scenarios to read. Some of these were true analogs of the first scenarios; others were spurious matches, sharing low order predicates but not higher-order relational structure. Subjects were asked to write out any prior scenarios that came to mind while they were reading the new scenarios. Afterwards, they rated all the pairs for soundness: i.e., how well the inferences could be carried from one scenario to the other.

The results are surprising from the point of view of causal indexing. Although subjects rated the true analogies as much more sound than the spurious matches, their spontaneous access was much higher for the spurious mere-appearance matches. The matches that came to mind most easily were the ones they themselves judged to be least useful in reasoning. This suggests that analogical access is based on qualitatively distinct processes from analogical inferencing.

Analogy and similarity are an important part of everyday reasoning. People spontaneously discover and use analogies as mental models (Gentner, 1980; Collins & Gentner, 1983, 1986; Lakoff & Johnson, 1983). For example, they think of a cloud as like a sponge (Stevens, Collins, & Goldin, 1979), of a thermostat as like a gas pedal (Kempton, 1987), or of an electric circuit as like a hydraulic system (Gentner & Gentner, 1983). Aside from its importance in reasoning about the physical world, analogical reasoning plays a major role in legal argumentation and in human planning.

In science, analogies help learners gain an intuitive grasp of abstract scientific models (Gentner, 1980, 1982). For instance, to understand electric circuits many people think about an analogy between electric circuits and water pipes, reservoirs and pumps. A person can transfer some of his knowledge about the base domain of water pipes, reservoirs, and pumps, to the target domain of electric circuits (Gentner & Gentner, 1983). In this way, he can understand electric circuits better, and solve problems about them.

To understand analogy in commonsense reasoning, we require an account of how analogy is accessed and of how it is used. This research attempts to separate the variables that determine the *accessibility* of an analogical match from those that determine the *predictive power* of the match. Structure-mapping theory (Gentner, 1980, 1982, 1983, 1986) describes the rules by which people reason with an analogy once it is accessed. We begin by summarizing this theory, before going on to discuss how analogy is accessed. According to structure-mapping theory, an analogy is a device for mapping the relational structure from one system of knowledge (the base) onto a new system (the target). Objects from the base are placed in correspondence with objects in the target:

M: bi --> ti

Predicates are mapped from the base to the target according to the following mapping rules:

- (1) Attributes of objects are dropped: e.g.,

  [RED (bi)] -/-> [RED (ti)].

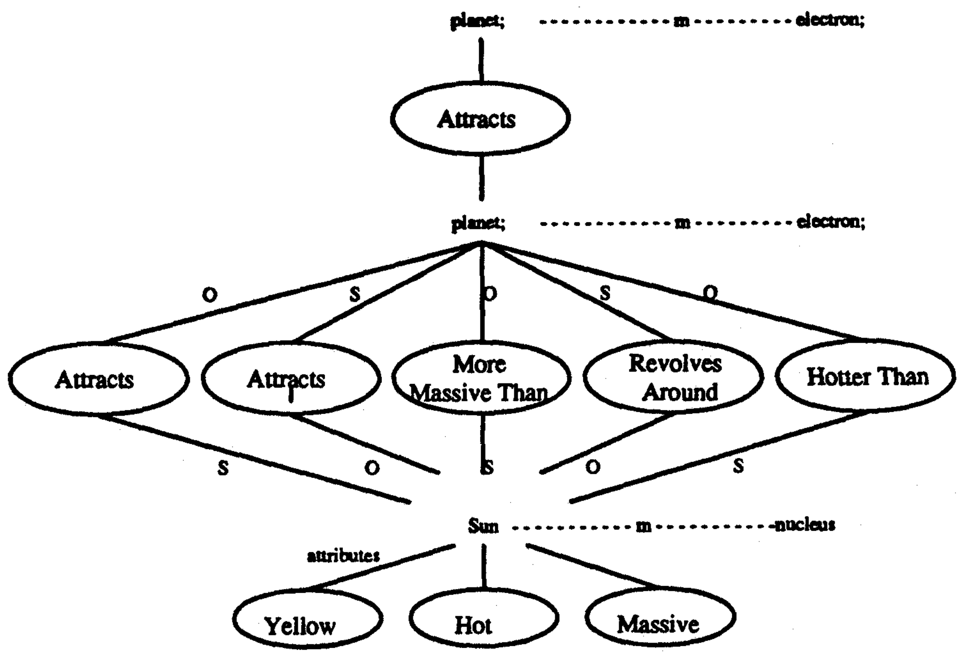
- (2) Certain relations between objects in the base are mapped across: e.g.,

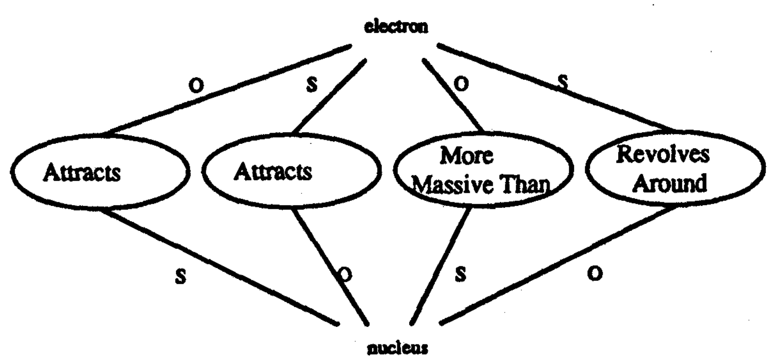
  COLLIDE (bi, bj),
  ---> COLLIDE (ti, tj)

- (3) The particular relations mapped are determined by systematicity, as defined by the existence of higher-order constraining relations which can themselves be mapped: e.g.,

  CAUSE [PUSH (bi, bj),
  COLLIDE (bk, b1)]
  ------>
  CAUSE [PUSH (ti, tj),
  COLLIDE (tk, t1)]

In the case of true analogy, only relational predicates are mapped. In the case of literal similarity, both relational predicates and object-attributes are mapped. In the case of a mere-appearance match, object-attributes and a few first-order relational predicates will be carried across. The rules given here are for true analogy.





The Rutherford analogy between the atom and the solar system provides a good illustration of the structure-mapping principles. As Figure 1 shows, the analogy operates to set the objects of the base domain (the solar system) in one-to-one correspondence with the objects of the atom. Object attributes, such as YELLOW (sun) and MASSIVE (sun) are dropped. Relations between objects, such as MORE MASSIVE THAN (sun, planet) and REVOLVES AROUND (planet, sun) are mapped across to the atom, making the object substitutions sun - - - nucleus and planet - - - electron. However, not all relations are mapped; for example, the relation HOTTER THAN (sun, planet) is not mapped to the atom. This is because of the systematicity principle. As we will discuss later, the higher-order causal structure in the solar system and the atom links the two relations MORE MASSIVE THAN and REVOLVES AROUND. This systematicity principle reflects a tacit preference for coherence and deductive power. It is what gives analogy its inferential power.

Structure-mapping theory has received a great deal of convergent support. Although there are differences in emphasis, the theories of Burstein (1983), Carbonell (1983) and Winston (1981) all show the basic elements of one-to-one mappings of objects, with carryover of predicates. Moreover all these researchers have moved towards something like the systematicity principle, or to a special case of systematicity: e.g., Carbonell focuses on plans and goals as the high-order relations that give constraint to a system, and Winston focuses on causality. Within psychology, the accounts of Gick & Holyoak (1983), Read (1984), Reed (1984) and Rumelhart & Norman (1981) share some notion of analogy as mapping, and in many cases have used the precise structure-mapping framework. Thus we have a fairly good understanding of the subjective rules of analogical *inferencing*.

Analogical *access*, however, is a different matter. We know very little about how people notice analogies. When faced with a target problem or situation, what are the factors that cause a person to spontaneously think of some piece of stored knowledge? The dominant position in artificial intelligence research is that access occurs via shared causal relations or other higher-order relations. Schank's (1982) *causal indexing* proposal for reminding is perhaps the strongest statement of this view, but the work of Winston (1981), and Carbonell (1983) also suggests such a view. The basic idea behind causal indexing is that we access memory by matching predictive causal structures of memory and the present situation. Thus, causal indexing implies that the accessibility of an analogy is governed by the same principles that determine how inferentially useful or predictive the analogy is: i.e., *systematicity*, the degree to which the base and target domains share their higher-order causal structure.

However, there are indications from psychological research that access may not follow causal matching. One sign of trouble is that potentially useful analogies are often missed. In research done by Reed, Ernst, and Banerji (1974) and by Gick and Holyoak (1980, 1983), subjects tried to solve a very difficult problem. Just prior to receiving the problem, they read some material that was in fact analogous to the problem plus solution. When told about the analogy, almost all the subjects were able to solve the problem. Yet, only about a third of the subjects spontaneously noticed the analogy, in spite of the fact that the problem immediately followed the story. This research shows that an analogy can be difficult to notice even when it would be extremely useful for solving a problem. Their A second indication that casual matching may not be the correct view come from work on transfer of training (Brown & Campione, 1984). For example, Ross (1984) found that subjects were more likely to access a rule if their current context resembled the context in which they had learned the rule. His work suggests that analogical access is influenced by overall similarity, not just similarity in causal structure.

The present study seeks to resolve the question of what determines analogical access. To clarify the discussion, let us decompose analogical reasoning into three parts: access, mapping and inferential power. *Access* is the process of matching a base situation in memory with a given target situation a person is faced with. In other words, it is the process of a given target situation reminding a person of a base situation in his memory. Structure-mapping theory is concerned with mapping and inferential power. *Mapping* occurs after a base situation has been accessed from memory. In mapping, two subprocesses occur: the objects and predicates of the base are carried onto corresponding elements of the target according to the rules given above. One of the most important aspects of mapping is the implicit cognitive rule called the systematicity principle. Briefly, the systematicity principle states that only those predicates that belong to a system constrained by higher-order predicates will be carried across (Gentner, 1982, 1983). The systematicity principle in mapping reflects people's tacit preference for coherence and deductive power. In cases where a highly systematic relational structure can indeed be mapped into the target domain, we have a powerful analogy. Because the base and target share their higher-order structure, significant inferences can be transferred from the base situation to the target situation. This brings us to the third aspect of analogy, inferential power. According to structure-mapping theory, it is sytematicity which determines the inferential power of an analogy. The experiment presented here tested this prediction that systematicity determines the power of soundness of a match. In addition, it investigated the effects of different kinds of matches on accessibility.

In this study, we aimed to create a naturalistic long-term memory access situation. We first gave our subjects a large number (32) of stories to read and remember. Then, one week later, we brought them back, showed them a new set of stories and to tell us if they were reminded of any of the original stories. Finally, they rated the story pairs for inferential power or soundness. The stories were carefully designed to embody different kinds of similarity matches. The kinds of similarity between base and target were varied as follows:

1. Surface Similarity: similarity among the objects in the original scenarios and the objects in the text scenarios.

2. First-Order Similarity: similarity among the vents and first-order relational predicates between the original and test scenarios.

3. Higher-Order Similarity: similarity in the higher-order relational structure-either causal structure or other kinds of constraining structure-between the original and test scenarios. Using these three levels of predicate-matching, we constructed pairs of scenarios that were alike on specific levels. The kinds of matches, as shown in Table 1, were:

- 1. Mere appearance match: A pair which is alike on the first two levels (object-attributes and some first-order relations)

- 2. True analogy: A pair which is alike on the two higher levels (first order relations and higher-order relations).

- 3. False analogy: A pair which is alike only in first-order relations, with the higher-order relations different.

Table 1: Similarity Pattern of BASE-TARGET pairs

Target	Objects Similar to objects in BASE story.	1st-order predicates similar to those of BASE.	Same higher-order structure as BASE.
True Analogy		X	X
Mere Appearance	X	X	
False Analogy		X	

Two measures were obtained for each pair of scenarios:

- (1) The accessibility of the first story given the second, i.e., how well the second story serves as a cue for the first.

- (2) The inferential or predictive power of the analogy between the stories, as rated by the subjects.

Our predictions were:

1. that the *soundness*, or predictive power, of a comparison would be governed by its systematicity: the degree to which the likeness between base and target is one of a mutually constraining set of higher order relations.

2. that accessibility would be heavily influenced by surface attribute overlap. Therefore, in measures of spontaneous access, mere-appearance matches should outperform true analogy.

3. and that therefore, the rules of access are different from those of predictive power.

Method

Subjects. The subjects were 30 students from the MIT Psychology Department.

Materials. The experimental material consisted of 18 sets of stories, four stories per set. In addition, there were 14 filler stories and 5 stories used a samples for the instructions. Each of the 18 sets of stories had one BASE story and three TARGET stories resembling the BASE story in certain precise ways. The three types of TARGET were as follows.

1. True Analogy (TA) TARGET. The TA TARGET had different objects (such as main and minor characters, places, and instruments) than the BASE. But its first-order predicates were all similar or identical to those of the BASE. Finally, The TA TARGET has a higher-order structure identical to that of the BASE.

2. Mere appearance (MA) TARGET. The MA TARGET had a superficial similarity to the BASE; objects and first-order predicates were similar or identical to those of the BASE but the higher-order structure consisting of causal and temporal predicates was different.

3. False Analogy (FA) TARGET. The FA TARGET had only first-order predicates similar to those of the BASE. Its objects, as well as its higher order structure, were different from those of the BASE.

Table 2 shows an example set of four scenarios: a base scenario plus one example of each of the three kinds of matches.

Table 2: Sample Story Set

BASE story Karla, an old hawk, lived at the top of a tall oak tree. One afternoon, she saw a hunter on the ground with a bow and some crude arrows that had no feathers. The hunter took aim and shot at the hawk but missed. Karla knew the hunter wanted her feathers so she glided down to the hunter and offered to give him a few. The hunter was so grateful that he pledged never to shoot at a hawk again. He went off and shot a deer instead.
True Analogy Once there was a small country called Zerdia that learned to make the world's smartest computer. One day Zerdia was attacked by its warlike neighbor, Gagrach. But the missiles were badly aimed and the attack failed. The Zerdian government realized that Gagrach wanted Zerdian computers so it offered to sell some of its computers to the country. The government of Gagrach was very pleased. It promised never to attack Zerdia again.
Mere Appearance Once there was an eagle named Zerdia who donated a few of her tailfeathers to a sportsman so he would promise never to attack eagles. One day Zerdia was nesting high on a rocky cliff when she saw the sportsman coming with a crossbow. Zerdia flew down to meet the man, but he attacked and felled her with a single bolt. As she fluttered to the ground, Zerdia realized that the bolt had her own tail feathers on it.
False Analogy Once there was a small country called Zerdia that learned to make the world's smartest computer. Zerdia sold one of its super computers to its neighbor, Gagrach, so Gagrach would promise never to attack Zerdia. But one day Zerdia was overwhelmed by a surprise attack from Gagrach. As it capitulated the crippled government of Zerdia realized that the attacker's missiles had been guided by Zerdian super computers.

For the sake of consistency, the TA an FA TARGETS were constructed to have the same objects, and the MA and FA TARGETS were constructed to have the same higher order structure.

Although each type of TARGET has a different pattern of similarity to the BASE, every effort was made to make the wording of the TARGET stories in each set as homogeneous as possible without sacrificing readability of the stories.

Procedure: Reminding Task. There were two sessions. At the first session, each subject read a booklet of 32 very short stories. Each booklet consisted of the same 18 BASE stories and 14 filler stories. Thus, except for the order, all subjects read the same set of 32 stories. They were told to read carefully and remember the stories. At the second session, six to eight days later, subjects received a workbook of 18 TARGET stories. Each workbook consisted of 6 MA TARGETS, 6 TA TARGETS, and 6 FA TARGETS, in random order. Thus each subject received one third each of the three kinds of matches. To counterbalance which type of match occurred in which stories, there were three groups of subjects.

For each TARGET story read, subjects wrote down any BASE story they were reminded of. They were instructed as follows:

"For every story you read today, please notice whether you are reminded of any of the stories from the previous session. If you are, please write down the story you are reminded of. If you are reminded of more than one story, write the one that is the best match for the current story...

Be sure to include as many details as you can remember - if possible, the names of characters, their motives and what happened."

Procedure: Judging Task. The judging task was given to subjects after they had completed the matching task, at the end of the second session. In this task, subjects read the same 18 pairs of stories they had received in the reminding part of the study, and rated each pair for the "soundness" of the match between the two stories. The first story in each pair was one of the BASE stories from the first session. The second story in each pair was the matching TARGET story they read this week. Thus, each subject rated 1/3 MA, 1/3 TA, and 1/3 FA matches. Subjects remained in the same counterbalancing groups as in the reminding task.

The instructions for judging soundness were as follows:

"This part of the experiment is about what makes a good match between two stories or situations. We all have intuitions about these things. Some kinds of resemblances seem important, while others seem weak or irrelevant. Here's an example:

Suppose you and a friend were having an argument about politics. And your friend brought up another situation, say, the way a car works, and said the situations are fundamentally the same. You might agree that his car example matches well with the political situation, and see the argument he is making. This is what we mean by a *sound match*. Or, you might reject his example; you might feel that although the situations look the same, the resemblance is actually just superficial. We call this a *spurious match.*

In this part of the experiment, we want you to use your intuitions about soundness - that is, about when two situations match well enough to make a strong argument. ... If the pair of stories match this way, give them a high rating."

Scoring: Judging Task. The scoring of the judging task simply required recording the subjects numerical ratings of the soundness of the 18 pairs of stories. Then average ratings for MA, TA and FA comparisons were computed.

Scoring: Reminding Task. To score the reminding task we had to judge whether the subjects had indeed successfully retrieved the original stories (as opposed to just guessing, for example). To do this, two judges read each of the workbooks and scored subjects' descriptions of the BASE stories they were reminded of were scored in three ways:

(1) *Overall Score.* Two judges scored on a 1-5 scale, how well subjects recalled each BASE story. This was done by comparing each description a subject wrote with the correct BASE story. The scoring scheme the judges uses was as follows:

- 5= excellent story recall; the description mentions all the important elements of the BASE and contains a great amount of detail as well.

- 4= very good recall; the description mentions all the important elements of the BASE and contains some detail.

- 3= good recall; the description mentions all important elements of the BASE but contains little or no detail.

- 2= fair recall; the description mentions a few of the important elements of the story but some are missing or wrong.

- 1= poor recall; the description mentions something from the BASE story but we can't be sure subject genuinely recalled the BASE.

- 0= nothing or different story.

The independent scores assigned by the two judges agreed 75.5% of the time. 22% of the time, the scores they assigned disagreed by 1, 2.5% by 2.

(2) *Flat Scoring.* This score attempted to score for any genuine recall at all, without worrying about whether the recall was of high quality. We grouped all descriptions that had received an overall score of 2 or better. Thus, a subject's total flat score over all 18 BASE-TARGET pairs would be the number of descriptions he wrote that received an overall score of 2 or higher.

(3) *Last Sentence Keyword Score.* A keyword was chosen in advance from the final sentence in each BASE story. Subjects scored 2 for using this keyword or a good synonym in their description, 1 for using a dubious synonym, and 0 otherwise.

Results

Judging Task. Figure 2 shows the results of the judging task. As predicted by structure-mapping theory, subjects judged the true analogies (the only pairs that shared higher-order structure) to be sound (mean rating). They judged the pairs lacking in shared systematic structure to be unsound.

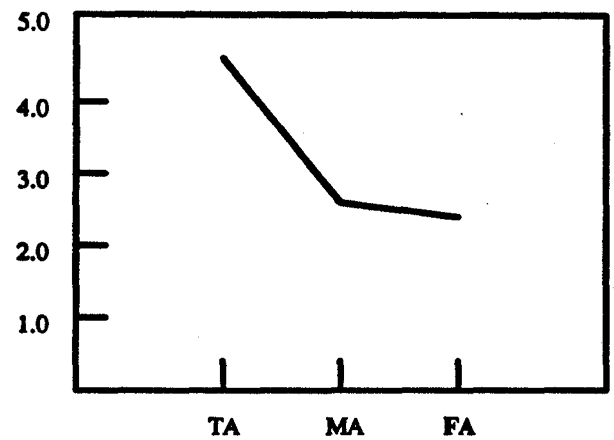


Figure 2: Quality of Match

These patterns were confirmed by t-tests. The differences between TA and MA and Between TA and FA are significant ($p<.001$ in each case), and the difference between MA and FA is not significant ($p=.802$). These results show quite clearly that TA BASE-TARGET pairs are judged to be more sound than the other types. The MA and FA pairs were considered equally spurious.

The difference between false analogies and true analogies is particularly interesting for structure-mapping theory, for they demonstrate the importance of systematicity in judgments of analogical soundness. The fact that subjects were more willing to base causal inferences on true analogies than on false analogies confirms that shared higher-order relations are important in analogical thinking.

Reminding Task. The results of the reminding task are quite different. Under all three scoring methods, mere appearance matches are by far the best recall prompts. Figure 3 abc shows the results for overall recall score, keyword scoring and flat scoring.

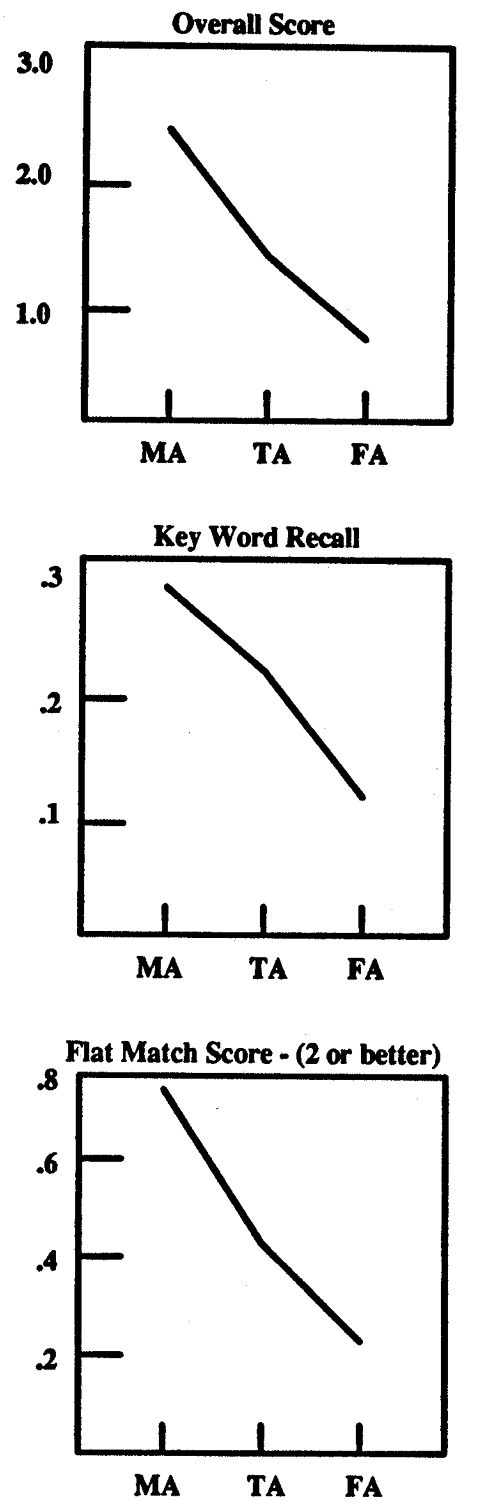


Figure 3: Recall Scores for Original Stories

Both overall analyses of variance and T-test indicate that all of the differences - MA-TA, MA-FA, and TA-FA - are significant for both overall and flat matching scores ($p<.001$ in all six tests). The results for the Keyword scoring are similar. Again, there was a main effect of matching condition on keyword score $F(2,54)=3.725$, $p<.05$. But individual t-tests show only the MA-FA difference is significant, $p<.05$.

Discussion

The results for the two parts of the experiment show that similarity matches are important in determining both accessibility and inferential power of analogies. However, the kinds of similarity matches are different for the two cases. In our reminding task, mere appearance matches were the easiest type of comparison to notice, true analogies were about twice as hard and false analogies about three times as hard. If memory is accessed by causal indexing (i.e., by searching on the basis of the higher-order structure of a TARGET situation) then the True Analogy TARGETS would have been the best cue for the BASE stories. But this was not the case. Evidently, access to memory is governed by surface similarity between the BASE and TARGET.

On the other hand, on soundness ratings the true analogy BASE-TARGET pairs were rated significantly higher than the other two types. Mere Appearance BASE-TARGET pairs were not rated significantly higher that False Analogy pairs. Thus, although surface appearance matches were the easiest for people to spot, they were judged by the same people to be poor comparisons. True analogies are the most difficult to notice, but have the greatest inferential power and usefulness.

Thus this experiment provides strong support for each of our original conjectures:

- (1) Accessibility is governed by literal or surface similarity, not similarity of higher-order structures.

- (2) Inferential power is governed by similarity of higher-order structures.

- and therefore that

- (3) Accessibility and inferential power follow different rules.

Our conclusion concerning inferential soundness is that structure-mapping theory is correct here: shared higher-order relational structure is the most important variable. Our conclusion concerning access is that surface similarity between base and target is a strong determinant of the accessibility of a comparison. This is consistent with the work of Gick & Holyoak (1983) and of Ross (1984).

These results suggest that, contrary to the dominant intuition in artificial intelligence, *analogical access* and *analogical inference* are governed by very different rules. This calls into doubt the causal indexing view held by many researchers in artificial intelligence.

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