Analogical Processing: A Simulation and Empirical Corroboration[1]

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Abstract

This paper compares the performance of the *Structure-Mapping Engine* (SME), a cognitive simulation of analogy, with two aspects of human performance. Gentner's *Structure-Mapping theory* predicts that soundness is highest for relational matches, while accessibility is highest for surface matches. These predictions have been borne out in psychological studies, and here we demonstrate that SME replicates these results. In particular, we ran SME on the same stories used in the psychological studies with two different kinds of match rules. In analogy mode, SME closely captures the human soundness ordering. In mere-appearance mode, SME captures the accessibility ordering. We briefly review the psychological studies, describe our computational experiments, and discuss the utility of SME as a cognitive modeling tool.

1 Introduction

Analogy is a complex process. Given a current context, it consists of being reminded of a "similar" experience or concept, establishing the proper correspondences between this knowledge and the current situation, judging the match for soundness and appropriateness, and then using these correspondences. As with any complex process, it is essential to form the right decomposition and strive to understand the subtleties of each component of the process.

This work examines the variables that determine the *accessibility* of a similarity match and its *inferential power* or *soundness.* To test our hypotheses, we start with a theoretical model, Gentner's *Structure-Mappping theory* of analogy, and use a computational simulation to show how the predictions of the model compare with independent, empirical data. By embedding a theory in a computational model which is used for prediction, we can see whether the predictions follow logically from the implemented form of the theory (see Anderson, 1983; Van Lehn, 1983). This constrains the interpretation of observations.

Cognitive simulation studies can offer important insights for understanding the human mind. They serve to verify psychological theories and force one to pin down aspects which might otherwise be left unspecified. They also offer unique opportunities to construct idealized subjects, whose prior knowledge and set of available processes is completely known to the experimenter. Unfortunately, cognitive simulation programs tend to be special-purpose and/or computationally expensive. In this paper we discuss our use of the *Structure-Mapping Engine* (SME) as an aid in research on a general theory of analogy. SME is a computer simulation of analogical processing based upon Gentner's Structure-Mapping theory. It avoids the difficulties typically found in cognitive simulation programs by being both flexible and efficient. SME provides a "tool-kit" for constructing matchers consistent with Gentner's theory. This enables us to generate and explore a space of plausible algorithms for analogical processing and compare these against subjects' performance. In this paper, we aim to show the utility of SME's tool-kit approach, its viability as a cognitive model, and demonstrate the validity of its theoretical foundation, the structure-mapping theory.

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2 The Structure-Mapping Theory

The theoretical framework for our studies is Gentner's *Structure-Mapping theory* of analogy (Gentner, 1980, 1983, 1987), which outlines the implicit rules by which people interpret and reason with analogy and similarity. The underlying hypothesis of the Structure-Mapping theory is that an analogy is a device for importing the relational structure of one domain (the *base*, source of knowledge) to another, less familiar domain (the *target*). It provides rules for analogical mapping and demonstrates how mapping may be used to make inferences about the new domain. These rules state that information is mapped from the base to the target in the following manner:

1. Discard object descriptions not involved in higher-order relations.
2. Attempt to preserve relations between objects.
3. Use *systematicity* to determine which higher-order relations are mapped. This rule is important for deciding what inferences to make and how strongly these inferences should be believed.

The systematicity principle is central to analogy. It maintains that analogy conveys a system of connected knowledge, rather than a mere assortment of independent facts. The systematicity principle is a structural expression of our tacit preference for coherence and deductive power in analogy (Gentner, 1987).

An important feature of Gentner's theory is that it is *structural.* The rules depend only on the structural properties of the knowledge representation and are *independent* of specific domain content.

In addition to articulating the rules for analogical mapping, the structure-mapping theory functions as a core theory for a broader treatment of the processes of analogy and similarity. Identification of these processes, as defined by Gentner (1987), enable us to decompose analogical processing into three distinct, yet interdependent, stages. First, a suitable base domain must be *accessed* from memory. Once base and target representations appear in working memory, the *mapping* stage establishes

Table 1: Similarity Classes (Gentner, 1987).

Type	# shared attributes	# shared relations	EXAMPLE
Literal Similarity	Many	Many	Milk is like water.
Analogy	Few	Many	Heat is like water.
Abstraction	Few	Many	Heat flow is a through-variable.
Anomaly	Few	Few	Coffee is like the solar system.
Mere Appearance	Many	Few	The glass tabletop was blue as water

the proper analogical correspondences between the two domains. Finally, the mapping is examined to determine *soundness*, and when appropriate, applicability and consistency with the task at hand. This work examines the variables that affect the *accessibility* of a similarity match and it *inferential power* or *soundness*.

2.1 Similarity Types

Gentner's theory is unique in that it breaks down the often vague terms of "analogy" and "similarity" into a continuum of similarity categories. These categories are characterized according to the distribution of relational and attributional predicates that are mapped during the analogical process (see Table 1). Analogy and literal similarity lie on a continuum of degree-of-attribute-overlap. Likewise, there is a continuum between analogies and abstractions. Both involve overlap in relational structure, but vary in the degree of concreteness of the base domain. We use these classifications below to analyze the factors influencing accessibility and soundness.

3 The Structure-Mapping Engine

The *Structure-Mapping Engine* (SME) (Falkenhainer, Forbus, & Gentner, 1986) is a computational tool for studying analogical processing which simulates the structure-mapping process. Given representations of a base and target, SME constructs all consistent interpretations of the given analogy, providing a numerical evaluation score for each. SME has significant advantages over programs based on traditional matching algorithms. Like the Structure-Mapping theory, SME is domain independent. Because it produces all consistent interpretations of an analogy, one can easily see structurally consistent alternatives to the best match. At the same time, SME's algorithm is very efficient — it does not backtrack. Most importantly, SME provides a flexible "tool-kit" for constructing matchers consistent with the different kinds of comparisons sanctioned by Gentner's theory. This enables us to quickly test, refine, and compare a large space of different conjectures about analogical processing.

The construction of interpretations is guided by *match rules* that specify which facts and entities might match and estimate the believability of each possible component of a match. To build a new matcher one simply loads a new set of match rules. These rules are the key to SME's flexibility. *Match constructor rules* guide what individual predicates and entities are allowed to map between the two domains. As with the match constructor rules, match evaluation is programmable: the quality of each match is found by running *match evidence rules* and combining their results. Using one set of rules, SME may be configured to perform analogical matches. Using other rule sets, SME can be made to perform mere-appearance matches or literal similarity matches. In our experiments using SME, we currently use three types of rule sets, depending on the phenomenon being investigated. One set of rules focuses on object descriptions and is called the "mere-appearance" rules. In contrast, the "true analogy" rule set prefers relations, while the "literal similarity" rules match both relations and object descriptions.

In this study, we used the mere-appearance (MA) and true analogy (TA) rules. The mere-appearance rules serve to measure the degree of superficial, descriptive similarity between the two domains. The match constructor rules for the MA set only allow matches between lower-order predicates - object attributes and first-order relations - not between higher-order relations. The evidence rules for the MA set give a weight of 0.5 for each match between descriptive attributes and a weight of 0.4 for matches between first-order relations. The true analogy rules measure the degree of relational overlap between two domains. The TA match constructor rules allow matches between relational predicates having the same name and discriminate against attributional matches, only allowing them if the attributes play a role in some higher-order relation. The evidence rules provide evidence for a match if the predicates matched have the same name, if they are of similar order,[2] and if their arguments may potentially match,[3] all in the 0.2 to 0.5 range. One important evidence rule is the systematicity rule, which causes the weight of a match between two items to increase in proportion to the amount of higher-order structure matching above them.

Proper understanding of the evaluation scores is important for correct interpretation of these studies. The scores are unnormalized. A score of 20 may be high for one analogy, while low for a different analogy. The evidence weights provide an ordering between alternate interpretations within a single mapping task. They only measure the relative merits of different targets and the merits of different interpretations for a single target. One of our current research goals is the construction of a structural evaluator that would produce scores corresponding to a single, fixed scale. With the evaluator, SME would then be able to rate two completely different similarity matches as being equally good, regardless of how different their domain descriptions were in size.

To date, over 40 analogies have been run on SME. These examples serve to provide evidence for the Structure-Mapping approach to the theory of analogical processing. SME rapidly produces intuitively plausible results. For details, see (Falkenhainer, et. al, 1986).

4 Comparing Simulation with Human Performance

The psychological results we are modeling concern the natural processes of spontaneous reasoning by analogy and similarity: that is, the process whereby a person who is thinking about some current situation is reminded of some prior similar situation which he may decide to use in reasoning about the current situation. In this research we asked (1) what governs spontaneous access to analogy and similarity, and (2) once an analogy has been processed, how do we judge its inferential soundness (ie., whether it is rigorous enough to have predictive utility)?

To analyze the factors affecting accessibility and soundness in

[2] We define the *order* of an item in a representation as follows: Objects and constants are order 0. The order of a predicate is one plus the maximum of the order of its arguments.

[3] The arguments of two predicates may potentially match if corresponding arguments are syntactically compatible (e.g., both are entities).

(a) Mean Rating of Soundness.

(b) Proportion of base stories recalled given different kinds of matches.

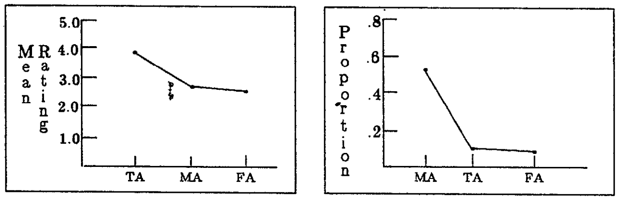

Figure 1: Results of the Rattermann and Gentner Study.

analogical processing, we start with recent empirical findings and discuss how these fit within the structure-mapping framework. We then use the implementation to simulate the same process in the hope that a rigorous simulation of the theory correctly parallels the empirical results.

4.1 Empirical Findings

Recent studies by Gentner & Landers (1985) and Rattermann & Gentner (1987) ask what governs spontaneous access to analogy and similarity and what governs the subjective soundness of analogy and similarity. According to Structure-Mapping theory, systematicity should play a key role in the determination of soundness; no predictions are made for accessibility. The method was designed to resemble a natural memory situation. Subjects were given 32 short stories to read and remember. Of these 32, 18 were key stories; the remaining 14 were fillers, designed to add more difficulty to the task. After a week, the subjects returned and performed two tasks: (1) a reminding task, and (2) a soundness rating task.

The reminding task consisted of reading a new set of 18 stories which matched the original 18 in various ways: mere-appearance matches, which match in object descriptions and first-order relations, true analogies, which match in first-order and higher-order relations, and false analogies or anomalies, which matched only in first-order relations. Each subject received only one matching target story for each of the 18 original key stories. Subjects were told that if the new story reminded them of any of the original stories, they should write out that original story in as much detail as possible.

After completing the reminding task, subjects went on to the soundness task. Subjects were given pairs of stories and asked to judge each of the story pairs for the inferential soundness of the match. The explanation for soundness was given as: "...when two situations match well enough to make a strong argument" (Gentner, 1987). They were told to rate each pair on a scale of 1 to 5, with 5 being "sound" and 1 being "spurious".

The results of the study are presented in Figure 1. As predicted by structure-mapping theory, a strong preference for true analogies was found in the soundness-rating task. These results suggest that relational structure is important in determining the subjective "goodness" of an analogy. However, as evidenced by the higher score for TA's than FA's, it is not just shared relations but shared higher-order relations that are important in determining inferential power.

The study provided surprising results for access. Although subjects rated true analogies as being most sound, they tended to not retrieve true analogies during the reminding task. Instead they were most likely to access superficial, mere-appearance matches

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 that 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 deer instead.

Target Story - 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.

Target Story - 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 tailfeathers on it.

Figure 2: Story Set Number 5.

These results suggest that superficial similarities, including object descriptions, play an important role in access. However, higher-order relational similarities do promote some access, as indicated by the fact that true analogies were retrieved more often that false analogies. Our conclusion is that access and inference are governed by a very different set of rules.

4.2 Computational Simulation

Human performance in the Rattermann & Gentner study was compared to SME's performance on similar tasks. For five of the story sets that were used in their study, the base stories, true analogy targets and mere-appearance targets,[4] were encoded and presented to SME (a total of 15 stories, making 10 matches). The encoder had no knowledge of the results of human performance when writing the representations. Different rule sets were used, corresponding to the similarity types of mere-appearance and true analogy. One of these stories will be discussed in detail, showing how SME was used to simulate a test subject.

Story set number 5, shown in Figure 2, revolves around a story about a hawk named Karla. Two similar, target stories were used as potential analogies for the Karla narration. One was designed to be truly analogous and describes a small country named Zerdia (TA5). The other was designed to be only superficially similar and describes an eagle named Zerdia (MA5).

To test the relative accessibility of the base story for the two target stories, we ran SME using the mere-appearance match rules. This measured their degree of superficial overlap and thus, according to our prediction, the relative likelihood of their accessibility. The output of SME for the MA task is given in Figure 3, which shows that the eagle story (evaluation = 7.7) has a higher mere-appearance match rating than the country story (evaluation = 6.4). Thus, if the surface-accessibility hypothesis is correct, the MA target "Zerdia the eagle" should have demonstrated a higher accessibility rating for the human subjects than

[4]The false analogies were not simulated, since they provided little insight beyond that given by the TA and MA results.

Analogical Match from *Karla* **to** *Zerdia the country (TA5).*

```
Rule File: appearance-match.rules
Number of Match Hypotheses: 12
Number of GMaps: 1

Gmap #1:
   (HAPPINESS-HUNTER HAPPINESS-GAGRACH)
   (ATTACK-HUNTER ATTACK-GAGRACH)
   (WARLIKE-HUNTER WARLIKE-GAGRACH)
   (DESIRE-FEATHERS DESIRE-SUPERCOMPUTER)
   (HAS-FEATHERS USE-SUPERCOMPUTER)
   (OFFER-FEATHERS OFFER-SUPERCOMPUTER)
   (TAKE-FEATHERS BUY-SUPERCOMPUTER) (WEAPON-BOW WEAPON-BOW)
 Emaps:   (KARLA1 ZERDIA12) (FEATHERS3 SUPERCOMPUTER14)
          (CROSS-BOW4 MISSILES16)  (HUNTER2 GAGRACH13)
 Weight: 6.411572
```

Analogical Match from *Karla* **to** *Zerdia the eagle (MA5).*

```
Rule File: appearance-match.rules
Number of Match Hypotheses: 14
Number of GMaps: 1

Gmap #1:
   (OFFER-FEATHERS OFFER-FEATHERS) (BIRD-KARLA BIRD-ZERDIA)
   (ATTACK-HUNTER ATTACK-SPORTSMAN)  (SEE-KARLA SEE-ZERDIA)
   (HAS-FEATHERS HAS-FEATHERS) (TAKE-FEATHERS TAKE-FEATHERS)
   (DESIRE-FEATHERS DESIRE-FEATHERS)  (WEAPON-BOW WEAPON-BOW)
   (WARLIKE-HUNTER WARLIKE-SPORTSMAN)
   (PERSON-HUNTER PERSON-SPORTSMAN)
 Emaps.   (FEATHERS3 FEATHERS9) (CROSS-BOW4 CROSS-BOW10)
          (HUNTER2 SPORTSMAN8)  (KARLA1 ZERDIA7)
 Weight: 7.703568
```

Figure 3: SME's Analysis of Story Set 5, Using the MA Rules.

the TA target "Zerdia the country".

To obtain soundness ratings for story set 5, we again ran SME on the above stories, this time using the true-analogy (TA) match rules. The output of SME for the TA task is given in Figure 4. Notice that "Zerdia the country" (evaluation = 22.4) was found to be a better analogical match to the original Karla story than "Zerdia the eagle" (evaluation = 16.8). Thus, according to Gentner's systematicity principle, it should be judged more sound by human subjects.

4.3 Observation versus Prediction

Tables 2 and 3 show the empirical as well as computational results for the five stories used in our simulation. Table 2 provides soundness ratings along with SME's evaluation scores when TA match rules were used. The +'s in the columns labeled "TA > MA?" indicate a higher evaluation score for the true analogy than for the mere-appearance match, by our subjects (column 4) or by SME (column 7). Here, as in Table 3, the results from SME should be read only to establish the *direction* of the difference: whether TA or MA receives a higher evaluation score within the same story set.[5] For example, we cannot say that story 9 is rated as being a more sound analogy than story 18 simply because SME gives story 9 a higher score. Comparing columns 4 and 7, we see that, using analogy rules, SME was able to qualitatively match

[5]Recall that the evidence score used here can only be used to compare matches that have the same base domain. Therefore it is meaningful to compare scores across the rows, but not down the columns.

Analogical Match from *Karla* **to** *Zerdia the country (TA5).*

```
Rule File: true-analogy.rules
Number of Match Hypotheses: 54
Number of GMaps: 1

Gmap #1:
   (CAUSE-PROMISE CAUSE-PROMISE) (SUCCESS-ATTACK SUCCESS-ATTACK)
   (HAPPINESS-HUNTER HAPPINESS-GAGRACH)
   (HAPPY-HUNTER HAPPY-GAGRACH) (REALIZE-DESIRE REALIZE-DESIRE)
   (DESIRE-FEATHERS DESIRE-SUPERCOMPUTER) (CAUSE-TAKE CAUSE-BUY)
   (OFFER-FEATHERS OFFER-SUPERCOMPUTER) (NOT-ATTACK NOT-ATTACK)
   (FAILED-ATTACK FAILED-ATTACK) (ATTACK-HUNTER ATTACK-GAGRACH)
   (TAKE-FEATHERS BUY-SUPERCOMPUTER) (PROMISE-HUNTER PROMISE)
   (CAUSE-OFFER CAUSE-OFFER) (FOLLOW-REALIZE FOLLOW-REALIZE)
   (NOT-HAS-FEATHERS NOT-USE-SUPERCOMPUTER)
   (CAUSE-HAPPY CAUSE-HAPPY) (HAS-FEATHERS USE-SUPERCOMPUTER)
   (CAUSE-FAILED-ATTACK CAUSE-FAILED-ATTACK)
 Emaps:   (HIGH23 HIGH17) (FEATHERS20 SUPERCOMPUTER14)
          (CROSS-BOW21 MISSILES15) (HUNTER19 GAGRACH13)
          (KARLA18 ZERDIA12) (FAILED22 FAILED16)
 Weight: 22.362718
```

Analogical Match from *Karla* **to** *Zerdia the eagle (MA5).*

```
Rule File: true-analogy.rules
Number of Match Hypotheses: 47
Number of GMaps: 1

Gmap #1:
   (PROMISE-HUNTER PROMISE) (DESIRE-FEATHERS DESIRE-FEATHERS)
   (TAKE-FEATHERS TAKE-FEATHERS) (CAUSE-OFFER CAUSE-OFFER)
   (OFFER-FEATHERS OFFER-FEATHERS) (HAS-FEATHERS HAS-FEATHERS)
   (REALIZE-DESIRE REALIZE-DESIRE)
   (SUCCESS-ATTACK SUCCESS-ATTACK) (NOT-ATTACK NOT-ATTACK)
   (FOLLOW-SEE-ATTACK FOLLOW-SEE) (SEE-KARLA SEE-ZERDIA)
   (FAILED-ATTACK SUCCESSFUL-ATTACK) (CAUSE-TAKE CAUSE-TAKE)
   (ATTACK-HUNTER ATTACK-SPORTSMAN)
 Emaps:   (FAILED22 TRUE11) (KARLA18 ZERDIA7)
          (HUNTER19 SPORTSMAN8) (FEATHERS20 FEATHERS9)
          (CROSS-BOW21 CROSS-BOW10)
 Weight: 16.816530
```

Figure 4: SME's Analysis of Story Set 5, Using the TA Rules.

human soundness preferences quite well.

Table 3 shows the results from the human subjects' recall task, along with SME's evaluation scores using MA match rules. Again, SME was able to duplicate human performance as indicated by the +'s in the "MA > TA?" columns.

Note that in Table 2 SME gives its highest evaluation to the true analogy in every case but one: in story 21 the MA match wins over the TA match. SME's performance on story 21 under true analogy rules concerned us, since we had expected the TA match to win over the MA match in every case. However, when we looked more closely at the human data, we discovered that the human subjects also broke their usual pattern: when rating this story set they failed to show their usual preference for analogy over mere appearance in soundness. As Table 2 shows, the difference between TA and MA is significant for the other four story sets, but nonsignificant for story set 21. Examination of the stories revealed that we had erred in constructing this set: the "true analogy" target required a many-to-one object mapping with the base. Both our human subjects and our simulation had reacted to this inconsistency by giving the TA match a much lower than average score.

Table 2: SME Run as a True Analogy Matcher.
A "+" indicates the difference is significant and "?" indicates the difference is non-significant, as determined by a t-test. Recall that the differences between SME's evaluation scores are only useful as <0 or >0; they cannot be compared across rows.

STORY #	HUMAN SUBJECTS' SOUNDNESS RATINGS				SME RUN AS A TRUE ANALOGY MATCHER		
	TA	MA	DIFFERENCE (TA-MA)	TA > MA?	ON TA PAIRS	ON MA PAIRS	TA > MA?
5 Karla, hawk	4.2	2.0	2.20	+	22.36	16.82	+ (5.54)
9 steak;dog	4.4	3.0	1.40	+	27.85	11.66	+ (16.19)
17 pioneer	4.6	2.5	2.10	+	26.46	20.23	+ (6.23)
18 teacher	3.8	2.0	1.80	+	22.90	19.42	+ (3.48)
21 Acme, IRS	3.5	3.1	.40	?	16.35	26.28	- (-9.93)

Table 3: SME Run as a Mere Appearance Matcher.

STORY #	HUMAN SUBJECTS' PROPORTION OF BASE STORY RECALLED				SME RUN AS A MERE APPEARANCE MATCHER		
	MA	TA	DIFFERENCE (MA-TA)	MA > TA?	ON MA PAIRS	ON TA PAIRS	MA > TA?
5 Karla, hawk	.67	0	.67	+	7.70	6.41	+ (1.29)
9 steak,dog	.44	.11	.33	+	12.09	8.56	+ (3.53)
17 pioneer	.44	.22	.22	+	11.00	7.59	+ (3.41)
18 teacher	.22	.11	.11	+	11.90	8.09	+ (3.81)
21 Acme, IRS	.78	.11	.67	+	7.75	6.71	+ (1.04)

5 Discussion

The results of comparing SME with human performance are promising. First, psychological evidence indicates that people use systematicity and consistency to rate the soundness of a match. SME replicates this pattern in analogy mode. Second, access in people is governed by surface properties. As predicted, SME replicates human access patterns when in mere-appearance mode. In fact, we have tried SME on over 40 different analogies (including those cited here), and it rapidly produced humanly plausible results on all of them. The results of SME qua "ideal subject" on these analogical tasks provides strong convergent evidence for the Structure-Mapping theory.

SME is extremely representation-sensitive. We believe that this is psychologically plausible, in that human analogical processing is limited by their representations. Unfortunately, it raises the spectre of tailoring the representations to get desirable results. We have tried to reduce tailorability by several routes. First, we have tested SME with representations produced by AI reasoning programs which were not designed for analogical reasoning (Falkenhainer, et. al, 1986). Second, when hand-coding is necessary (as in these studies), we used several cross-checks. First, representation conventions were defined in advance. Second, we sometimes used several independent encoders and compared results. Third, we told the encoders nothing about the human results. The results of story set 21 suggests we were somewhat successful. At first it appeared that SME's low evaluation of the TA match was a bug. Only later, when examining the human data, did we discover that the same pattern held there.

Although several AI analogy programs exist (e.g., Winston, Carbonell, Kedar-Cabelli), few are intended as cognitive simulations (exceptions include Burstein 1983, Pirolli & Anderson, 1985). To our knowledge, no simulation has been successfully compared as extensively with human performance as SME. Moreover, we know of no other general-purpose matcher which successfully simulates two *distinct* kinds of human similarity. Our results suggest that the principles of Structure-Mapping can provide a detailed account of human analogical processing. Using these principles, it appears that SME's architecture provides considerable leverage for cognitive modeling.

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References

Anderson, J., *The Architecture of Cognition*, Harvard University Press, Cambridge, Mass, 1983.

Burstein, M. H., "Concept formation by incremental analogical reasoning and debugging", *Proceedings of the 1983 International Machine Learning Workshop*, Monticello, IL, June 1983.

Carbonell, J.G., "Learning by Analogy: Formulating and Generalizing Plans From Past Experience," in *Machine Learning: An Artificial Intelligence Approach*, R.S. Michalski, J.G. Carbonell, and T.M. Mitchell (Eds.), Morgan Kaufman, 1983a.

Falkenhainer, B., K.D. Forbus, D. Gentner, "The Structure-Mapping Engine," *Proceedings AAAI*, August, 1986.

Gentner, D., "The Structure of Analogical Models in Science", BBN Tech. Report No. 4451, Cambridge, MA., Bolt Beranek and Newman Inc., 1980.

Gentner, D., "Structure-Mapping: A Theoretical Framework for Analogy", *Cognitive Science* **7**(2), 1983.

Gentner, D., "Analogical Inference and Analogical Access" to appear in A. Preiditis (Ed.) *Analogica: Proceedings of the First Workshop on Analogical Reasoning*, Pitman Publishing Co., 1987 (in press).

Gentner, D., & R. Landers, "Analogical Reminding: A Good Match is Hard to Find". In *Proceedings of the International Conference on Systems, Man and Cybernetics*. Tucson, Arizona, 1985.

Kedar-Cabelli, S., "Purpose-directed analogy", *Proceedings of the Seventh Annual Conference of the Cognitive Science Society*, 1985.

Pirolli, P. L., & Anderson, J. R., "The role of learning from examples in the acquisition of recursive programming skills", *Canadian Journal of Psychology* **39**, 240-272, 1985.

Rattermann, M.J. & D. Gentner, "Analogical Reminding", submitted to the *Ninth Annual Conference of the Cognitive Science Society*, July, 1987.

Van Lehn, K., "Felicity Conditions for Human Skill Acquisition: Validating an AI-based Theory", Xerox Palo Alto Research Center Technical Report CIS-21, 1983.

Winston, P. H., "Learning and reasoning by analogy" *CACM* **23**(12), 1980.

Winston, P. H., "Learning new principles from precedents and exercises". *Artificial Intelligence* **19**, 321-350, 1982.