ILLINOIS

UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

PRODUCTION NOTE

University of Illinois at
Urbana-Champaign Library
Large-scale Digitization Project, 2007.

Technical Report No. 358

SYSTEMATICITY AND SURFACE SIMILARITY
IN THE DEVELOPMENT OF ANALOGY

Dedre Gentner
University of Illinois at Urbana-Champaign

Cecile Toupin
University of California at Berkeley

December 1985

Center for the Study of Reading

TECHNICAL
REPORTS

CENTER FOR THE STUDY OF READING

Technical Report No. 358

SYSTEMATICITY AND SURFACE SIMILARITY
IN THE DEVELOPMENT OF ANALOGY

Dedre Gentner
University of Illinois at Urbana-Champaign

Cecile Toupin
University of California at Berkeley

December 1985

University of Illinois
   at Urbana-Champaign
51 Gerty Drive
Champaign, Illinois 61820

Bolt Beranek and Newman Inc.
10 Moulton Street
Cambridge, Massachusetts 02238

This page is intentionally blank.

Abstract

This research investigates the development of analogy: in
particular, we wish to study the development of systematicity in
analogy. Systematicity refers to the mapping of systems of
mutually constraining relations, such as causal chains or chains
of implication. A preference for systematic mappings is a
central aspect of analogical processing in adults (Gentner, 1980,
1983). This research asks two questions: (a) does systematicity
make analogical mapping easier; and (b) if so, when
developmentally do children become able to utilize systematicity.

Children aged 5-7 and 8-10 acted out stories with toy
characters. Then they were asked to act out the same stories
with new characters. Two variables were manipulated:
systematicity, or the degree of explicit causal structure in the
original stories, and the transparency of the object-mappings.
Transparency was manipulated by varying the similarity between
the original characters and the corresponding new characters; it
was included in order to vary the difficulty of the transfer
task. If children can utilize systematicity, then their transfer
accuracy should be greater for systematic stories.

The results show (a) as expected, transparency strongly
influenced transfer accuracy: for both age groups, transfer
accuracy dropped sharply as the object correspondences became
less transparent; (b) for the older group, there was also a
strong effect of systematicity and an interaction between the two

variables. Given a systematic story, nine-year-olds could
transfer it accurately regardless of the transparency of the
object correspondences.

Systematicity and Surface Similarity

in the Development of Analogy

Analogy is a central process in learning and discovery. For
example, Sadi Carnot's great work on the principles of heat is
pervaded by an analogy between heat and water: the 'fall' of
heat from high temperature to low temperature is compared to the
fall of water from high elevation to low elevation. Just as
Carnot used this analogy to think through the mechanical action
of heat, so a student learning water can use the same analogy to
come to understand ideas like "The power released when heat flows
between two bodies varies with the difference in temperature
between them" (Buckley, 1979). But notice that to make this
analogy useful the learner must focus on certain kinds of matches
between the two domains (e.g., Clement, 1981, 1982; Collins &
Gentner, in press; Forbus & Gentner, 1986; Kempton, in press;
VanLehn & Brown, 1980). A learner who interpreted the analogy to
mean that heat is wet or transparent like water might be worse
off with the analogy than without it. The power of an analogy in
learning is in the system of relations that can be mapped.

Focus on systems of mutually constraining relations is a
central aspect of adult competence in processing analogy
(Gentner, 1980, 1983). Adults not only have the ability to map a
system of relations, but show a marked preference for such
mappings (Gentner & Landers, 1985). This bias towards mapping

systems seems to reflect a tacit preference for coherence and
mutual constraint in analogical mapping. This research asks two
questions: (a) does the presence of systematic relations make
analogical mapping easier; and (b) if so, when developmentally do
children become able to utilize this systematicity.

The plan of the paper is as follows. We first give a brief
review of the literature on analogical development. Then we
present structure-mapping and the systematicity principle.
Finally, we describe our research tracing the development of
systematicity in analogy.

Development of Analogy

Since children are major consumers of education, it is
important to know what they do with instructional and
experiential analogies. Unfortunately there is a great deal of
evidence suggesting that young children do not use analogies in
the powerful systematic way that adults do. Experimental studies
show a marked developmental change in children's fluency at
interpreting metaphors. A four-year-old asked "Can a person be
sweet?" answers literally: e.g., "Not unless he was made out of
chocolate" (Asch & Nerlove, 1960). Similarly, young children are
poor at matching sentences with metaphorically related pictures
(Dent, 1984; Kogan, 1975) and at choosing appropriate
metaphorical completions for sentences (Gardner, Kircher, Winner,
& Perkins, 1975). Young children tend to produce and select
attributional interpretations to nonliteral comparisons. This

pattern contrasts sharply with the adult preference for relational interpretations. For example, given the comparison "A cloud is like a sponge," five-year-olds produce interpretations like "Both are round and fluffy." Adults produce relational interpretations: e.g., "Both can hold water for some time and then later give it back" (Gentner, 1980; Gentner & Block, 1983; Gentner & Stuart, 1983). Further, adults rate analogical comparisons as more apt when they can find relational interpretations than when they can find only attributional interpretations. Children show no such preferences; they are equally happy with relational and attributional interpretations (Gentner, 1986; Gentner & Landers, 1985). These and many other experimental results seem to indicate that the ability to perform figurative comparisons develops gradually and late (Inhelder & Piaget, 1958).

However, it has been pointed out that a number of factors enter into the assessment of metaphoric and analogical ability (Gentner, 1977; Reynolds & Ortony, 1980; Vosniadou, 1985). Young children differ from older children in their command of the vocabulary, in their knowledge of the domains, and in their pragmatic understanding of when non-literal interpretations are permissible. This means that in many situations, especially with verbal interpretation tasks, there is danger of underestimating the young child's metaphorical ability and of conflating other

developmental trends with the development of true analogical ability.

In order to isolate development of analogy from other developmental trends, we must first delineate the essential processes that define analogy and metaphor. Then we can determine the course of development of analogy. In particular, we can ask when in development children become able to take advantage of systematicity.

Structure-mapping and Systematicity

The theoretical framework for this research is the structure-mapping theory of analogy (Gentner, 1980, 1982, 1983; Gentner & Gentner, 1983). This theory describes the set of implicit rules by which people interpret analogy and similarity. An analogy is a mapping of knowledge from one domain (the base) into another (the target), according to the following rules.[1] Objects in the base are placed in correspondence with objects in the target:

$$M: \quad b_i \longrightarrow t_i$$

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

(1) Attributes of objects are dropped:

$$e.g., [RED (b_i)] \longrightarrow [RED (t_i)].$$

(2) Relations between objects in the base tend to be mapped across:

$$e.g., COLLIDE(b_i, b_j) \longrightarrow COLLIDE(t_i, t_j)$$

(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(b_i, b_j), COLLIDE (b_j, b_k)] -->

CAUSE [PUSH(t_i, t_j), COLLIDE (t_j, t_k)]

Figure 1 shows an example analogy: the Rutherford analogy

between the solar system and the hydrogen atom. Let us ask what

this analogy conveys to the person hearing it for the first time.

Assuming that the person has the prior knowledge about the solar

system shown in the top network, the person must

- set up the object correspondences between the two domains:

sun --> nucleus and planet --> electron.

- discard object attributes, such as YELLOW (sun).

- map base relations such as MORE MASSIVE THAN (sun, planet)

to the corresponding objects in the target domain.

- observe systematicity: i.e., discard isolated relations,

such as HOTTER THAN (sun, planet), and keep relations such

as MORE MASSIVE THAN that are governed by higher-order

constraining relations which can themselves be mapped.

Here, the higher-order system is

e.g., IMPLIES [MORE-MASSIVE-THAN (sun, planet),

REVOLVE-AROUND (planet, sun)].

Insert Figure 1 about here.

Systematicity. Part of our understanding about analogy is

that it conveys a system of connected knowledge, not a mere

assortment of independent facts. The systematicity principle is

included for formalize this tacit preference for coherence and

deductive power in analogy. The systematicity principle states

that a base predicate that belongs to a mappable system of

mutually interconnecting relations is more likely to be imported

into the target than is an isolated predicate. A system of

relations refers to an interconnected predicate structure in

which higher-order predicates enforce constraints among lower-

order predicates.[2]

The systematicity principle requires a mappable relational

chain. If the predicates, and especially the higher-order

relations, of the base chain are not valid in the target, then

another chain must be selected. Thus, a relational chain--such

as a causal chain--in the base that matches a relational chain in

the target constitutes good support for its members. Winston

(1982) gives an insightful demonstration of the need for such

importance-dominated matching.[3]

By promoting deep relational chains, the systematicity

principle operates to promote predicates that participate in

causal chains and in other constraint relations. It is an

essentially syntactic mechanism that guarantees that the set of

candidate mappings will be as interesting--in the sense that a

mutually interconnected system of predicates is interesting--as the knowledge base allows.

Ease of mapping. Our discussion so far has been couched in terms of the implicit standards for a good analogical mapping. Empirical studies have borne out the prediction that systematicity is one of the implicit rules for a good analogical mapping. Adults focus on shared systematic relational structure in interpreting analogy. They tend to include relations and omit attributes in their interpretations of analogy, and they judge analogies as more apt if they share systematic relational structure (Gentner, 1980; Gentner & Block, 1983; Gentner & Landers, 1985; Gentner & Stuart, 1983). From this we can conclude that systematicity is a desideratum in analogy; it is one of the criteria by which an interpretation is devised and by which the analogy itself is judged.

But we want to go beyond the prior evidence here to suggest that systematicity may also play an active role in guiding the on-line mapping process. We conjecture that the presence of higher-order constraints helps guide the mapping of lower-order relations and provides a check on the correctness of the mapping. An error made in mapping a particular relation from base to target is more likely to be detected quickly if there is a higher-order relation which relates that lower-order relation to other knowledge.

To see how this could work, imagine a learner who hears the Rutherford analogy, "The atom is like the solar system," for the first time. Let us assume that the learner knows something about the solar system and little or nothing about the structure of the atom, and must map information from his model of the solar system. We contrast the case in which the learner has a systematic representation of the solar system with that in which he does not. In each case, we will assume the learner makes one mistake in mapping predicates from base to target. Then we will contrast the two cases--the systematic knowledge case and the nonsystematic knowledge case--to show how systematic knowledge enables the learner to repair mapping errors.

Figure 2 shows two representations of the solar system/atom analogy: a systematic representation (Figure 2a) and a nonsystematic representation (Figure 2b).

Insert Figure 2 about here.

Suppose that the learner momentarily switches the objects when mapping the MORE MASSIVE THAN predicate and ends up with

MORE MASSIVE THAN (electron, nucleus).

At this point the learner is in danger of ending with a garbled and inaccurate notion of the structure of the atom. Now let us take the two cases in turn.

Systematic knowledge case. For the learner who has a
systematic model of the base domain, there is a higher-order
causal relation that can be mapped from base to target. This
gives the learner a way of spotting the error. For at this point
he has the following derived propositions in the target:

1. MORE MASSIVE THAN (electron, nucleus)

2. REVOLVE AROUND (electron, nucleus) (We assume both
   learners have mapped this lower-order relation correctly.)

3. CAUSE [MORE MASSIVE THAN (electron, nucleus),
   REVOLVE AROUND (electron, nucleus)]

The last assertion is the causal chain that the learner
derives by plugging in his (partly erroneous) lower-order
mappings to the higher-order CAUSE relation. This chain can be
compared to the similar causal statement that the learner knows
from the base domain:

- CAUSE [MORE MASSIVE THAN (sun, planet),
  REVOLVE AROUND (planet, sun)]

Comparing these two chains, the learner can see an
inconsistency. In the base domain, the less massive object
revolves; in the target, the more massive object revolves. One
way to resolve the inconsistency is to recheck the object
mappings, giving the learner an opportunity to correct his error.
Thus systematic knowledge of the base domain should allow the
learner to detect and repair an incorrect local mapping.

Nonsystematic knowledge case. The learner's derived
representation of the target domain has only the two lower-order
relations:

1. MORE MASSIVE THAN (electron, nucleus)

2. REVOLVE AROUND (electron, nucleus)

There is nothing to alert him to an error in mapping these
relations. Without systematic structure to map from the base
domain, the learner simply has a disconnected set of low-order
predicates. Thus he is unlikely to notice and repair a mapping
error.

Based on this reasoning, we conjecture that the presence of
systematic relational structure should provide an on-line check
on the correctness of the individual lower-order predicate
mappings. Thus, systematicity should increase the transfer
accuracy of an analogical mapping. Another factor that should be
important during the on-line mapping process is the transparency
of the object-correspondences. Transparency is defined as the
ease of determining the object correspondences and predicate
mappings for an analogy or similarity match. Transparency is
high when surface similarity correlates well with structural
similarity. There is evidence that transfer accuracy is greater
for high-transparency analogies (Reed, 1985; Ross, 1986). We
predict that transparency will have a strong effect on transfer
accuracy. To the degree that it is easy to determine how the
objects in the base correspond with the objects in the target,

the transfer of predicate structure from base to target should be easier.

This line of reasoning leads us to three predictions concerning analogical mapping:

1. Transparent object-correspondences promote accurate mapping.

2. Systematic knowledge of the base domain leads to more accurate analogical mapping.

3. The effect of systematicity will be stronger the more difficult (the less transparent) the analogical mapping.

The Development of Systematicity

In this research, we investigated the development of systematicity in analogical mapping. We wished to discover when children become able to benefit from the presence of a system of mutually constraining relations in carrying out an analogy. To do this, we used a technique we called cross-mapping to vary the transparency of a set of analogical mappings. Then we gave children either systematic or nonsystematic base scenarios to map, as described below. The question was whether the degree of systematicity would affect children's ability to perform analogical transfer. If children's accuracy is improved by the presence of systematically connected knowledge structures, this is evidence that they can appreciate systematicity, whether or not they are able to articulate this appreciation explicitly. Our method was designed to avoid the confoundings inherent in

requiring a verbal interpretation. The children were simply asked to act out stories using toy dolls and animals. The analogical step was that the children had to transfer a story plot from one set of characters to another. An important aspect of the methodology is that we do not require our subjects to articulate the higher-order information. Children are compared only in their accuracy at acting out the low-order event predicates, which are identical in systematic and nonsystematic stories. Thus any developmental differences in the effects of systematicity here are likely to reflect true cognitive differences, and not merely differences in facility with language.

In order to fully test the effects of systematicity, we wanted to include a wide range of mapping difficulty. This brings us to the second theoretical question addressed in the study: the effects of varying the transparency of the object correspondence between base and target. To achieve this variation, we varied the surface similarity between the characters and the test characters. There were three levels of transparency: (a) high transparency—test characters look highly similar to corresponding original characters; (b) moderate transparency—test characters look quite different from corresponding original characters; and (c) low transparency—test characters look similar to non-corresponding original characters (the cross-mapped case). The cross-mapped case is predicted to

be very difficult, because the object similarities between base and target are deliberately misleading. A given test character looks like one of the original characters, but plays a different role in the story. An example will help make the three transparency conditions clear. Suppose that in the original story the hero was a chipmunk, the hero's friend was a robin and the villain was a horse. Then the roles in the three kinds of mapping conditions might be

	ORIGINAL	HIGH	MEDIUM	LOW
HERO	chipmunk	squirrel	elephant	zebra
FRIEND	robin	bluebird	shark	squirrel
VILLAIN	horse	zebra	cricket	bluebird

The design included age and systematicity as between-subjects variables and transparency as a within-subjects variable. We predicted that children's accuracy in enacting the second story would be greatest in the high-transparency mapping condition and lowest in the low-transparency cross-mapped condition, where the natural object mappings had to be resisted. Besides this prediction, there were three questions of interest:

- whether transfer accuracy would be higher for systematic stories than for nonsystematic stories
- if so, when such systematicity effects would show up developmentally
- whether systematicity would interact with mapping difficulty.

This last question is particularly interesting from our theoretical perspective. For if the presence of systematic higher-order relations helps the child preserve the relational structure she is trying to map, then the more difficult the mapping the greater the potential benefit of systematicity.

Method

Subjects

The subjects were 72 children, 36 four- to six-year-olds and 36 eight- to ten-year-olds, recruited from schools and preschools in Cambridge, Massachusetts. They were randomly assigned to either the systematic or the nonsystematic condition. Approximately equal numbers of males and females were included within each of the two experimental conditions, within each age group.

Materials

Stories. Nine short stories were constructed, each involving three characters and depicting a series of actions which led to a final outcome. There were two versions of each story: systematic and nonsystematic. The structure of the stories was as follows: (a) an introductory section, which introduced the characters; (b) an event sequence, with an outcome; (c) a moral (in systematic versions only). For each story, the event sequence was a set of 10 to 15 sentences depicting a series of events and an outcome. This section was identical in the systematic and nonsystematic story types. The

story types differed only in their introductory sections and in whether they contained a moral. Table 1 shows sample stories.

Insert Table 1 about here.

For both kinds of stories, the introductory section was one or two sentences long and contained (a) some descriptive information about the protagonist (e.g., "There once was a very handsome chipmunk.") and (b) some relation between the protagonist and one of the other two characters (e.g., "The chipmunk was friends with the cow."). The relation between the characters was the same in the systematic and nonsystematic story types. However, the information about the protagonist differed between the two story types. In the systematic stories, the description of the protagonist concerned a relevant habit or relational trait (e.g., "The chipmunk was very jealous"). In the nonsystematic stories the description attributed a neutral trait (e.g., "The chipmunk was very good-looking."). For both systematic and nonsystematic stories, the introductory sections were designed to define the roles of the characters. This meant that, to set up a transfer test, we could simply read the child the introduction with the new character assignments; this determined the rest of the story.

Aside from the difference in the introduction, the systematic stories differed from the nonsystematic stories in

possessing a moral: a final sentence that expressed a moral and linked the protagonist's initial character trait to the story outcome (e.g., "The chipmunk realized that he shouldn't be so jealous, because it is better to have more friends." No moral was added to the nonsystematic stories. The systematic stories, with a mean word length of 200 words, were somewhat longer than the nonsystematic stories (with a mean word length of 170 words), chiefly because of the presence of the moral. Half the children received systematic stories; the other half, nonsystematic stories.

Story-telling stimuli. Sixty-three toy dolls and animals were used to depict the characters. Of these, there were 27 pairs of animals that were independently judged by three judges to be 'similar-looking,' and nine animals that were judged to be 'different-looking' from one another and from any of the paired animals. A small number of props were used to aid in the story-telling. For each story, one or two rectangular, colored felt pieces were used to mark key locations, such as a house or road. For some stories, one or two additional toys, such as a wagon or plastic food, were used as props.

Mapping conditions. For each target story, three further stories were constructed using different sets of characters. These three story types reflected three mapping conditions corresponding to high, medium or low transparency:

- S/S: Similar Characters / Similar Roles (High

   Transparency)

- D: Different Characters / Similar Roles (Medium

   Transparency)

- S/D: Similar Characters / Different Roles (Low

   Transparency)

In the S/S condition, the test characters looked like the

characters in the original story, and they played the same role

as their counterparts in the original story. In the D condition,

the test characters bore no resemblance to any of the characters

in the original story. In the S/D condition, the test characters

resembled those in the original story, but were given different

roles from their look-alike counterparts in the original story.

This was predicted to be the most difficult mapping condition.

Table 2 shows the object mappings for all nine stories.

Insert Table 2 about here.

The mapping condition could have been varied by giving all

children the same base story and then varying the target story.

As Table 2 shows, we decided instead to vary the original base

story that the children heard. Thus, a child in the S/S

condition and a child in the S/D condition would receive

different original stories, but the same target story. This was

done in order to achieve strict comparability on the test phase.

Since the child can receive help or extra practice when necessary

in acting out the original stories, any small differences in the

ease of comprehension of the original stories are less likely to

affect the overall results than would differences in the test

stories. Thus the base stories varied according to systematicity

(systematic or nonsystematic) and mapping condition (S/S, D, or

S/D), for a total of six kinds of base stories (see Table 2).

All children received three stories in each of the three

mapping conditions, for a total of nine stories. The assignment

of stories to mapping condition was counterbalanced across groups

of children. The mapping conditions (S/S, D and S/D) were

presented in three different orders, according to a Latin square

design. There were two orderings--one the reverse of the other--

for the stories themselves. Thus, children were divided into 12

groups according to their Systematicity Condition, Mapping Order

and Story Order. However, the essential experimental variables

were Age (2 levels, between), Systematicity (2 levels, between)

and Mapping Condition (3 levels, within).

Procedure

Children were read aloud the stories and asked to act them

out with toy animals. Once they had acted out a story, they were

asked to act out the same story again, only with new characters.

A practice session using a four-line story about two characters

was used to acquaint subjects with their task. During the

practice session, children were encouraged to tell the story and

speak the dialogue. The experimenter demonstrated the two-fold task for the child if necessary. The experiment began once a child demonstrated the ability to perform the transfer task successfully without help. The experimental procedure was the same for each story and was divided into two parts: the Story Phase and the Test Phase.

Story phase. The experimenter began each story by introducing the three story characters (e.g., 'Here is the moose.'). The experimenter made sure that the child could correctly name the toys before proceeding. With the story characters in view, the child was then instructed to listen carefully to the story. After the experimenter finished reading the story aloud, props, including location markers, were introduced: e.g., the 'wheelbarrow' or the 'lake.' Some individual variation in the use of props was allowed, as long as the child used each prop consistently. The child then acted out the story, using the characters and props. If the child made omissions or errors, the experimenter corrected them and asked the child to again act out the story. Once the child demonstrated the ability to act out the original story correctly without help, the Test Phase began.

Test phase. The experimenter then asked the subject to act out the same story again, but with three new characters. The three original story characters were removed from view and the new test characters were introduced: e.g., 'This is the

squirrel.' Location markers, such as the 'lake,' were left in the same position, and props were gathered and set before the subject to use. The child was then instructed to listen carefully to the beginning of the story with the names of the new characters. The experimenter read aloud the introductory section and repeated it if desired. Then the child was told to act out the rest of the story.

The stories were designed so that the introductory section set the roles of the characters in such a way as to determine the rest of the story for a child who had performed the character-mapping correctly. During the test phase, the experimenter did not provide the subject with any information regarding mapping assignments, omissions, or errors. However, the experimenter could give neutral prompts, such as "What happened next?" or "Who is doing that?" In addition, the experimenter would repeat the correct name(s) of the character(s) or the introductory section on request.

The Story and Test Phases were carried out in the same way for each story. Children were given three stories in a test session, with a two-minute distractor task of coloring or putting together a puzzle between stories. Each child participated in three test sessions, spaced at least a day apart.

Scoring. For each story, the sentences were grouped into six core propositions representing the major events and the outcome. The moral in the systematic stories constituted a

seventh proposition that was scored separately. In scoring,
propositions were treated as wholes. If an error was committed
with respect to any one character or action contained in a
proposition, the proposition was considered incorrect. Thus, for
each subject there were six possible correct propositions per
story. The same six propositions were scored for systematic and
nonsystematic stories.

Three scoring procedures were used: Strict, Lenient and Key
Sentence scoring. However, since all gave the same results, we
describe only the strict scoring procedure. In the strict
scoring procedure, a proposition was scored as correct if the
child either verbally or nonverbally depicted each of its events
with the correct assignment of actors. Two types of errors were
scored: omissions and incorrect answers. A proposition was
scored as an omission if the subject verbally omitted any action
or character contained in that proposition AND failed to
adequately demonstrate the inclusion of the action or character
through nonverbal actions. A proposition was scored as incorrect
if any character or action contained in that proposition was
incorrectly identified AND the subject failed to correctly
identify the character or action in question through nonverbal
actions.

Results

The results are shown in Figure 3. These results show:

1. as predicted, object-mapping transparency had strong
   effects on transfer accuracy for both age groups.
2. systematicity benefited only the older group.
3. the benefits of systematicity were strongest in the most
   difficult mapping condition.

Insert Figure 3 about here.

A 2 x 2 x 3 mixed-measures analysis of variance of Age
(Between) X Systematicity (Between) X Mapping Condition (Within)
showed main effects of Age [$F(1,68) = 14.93$, $p < .001$],
Systematicity [$F(1,68) = 6.28$, $p < .05$], and Mapping Condition
[$F(2,136) = 29.01$, $p < .000001$]. There was also the predicted
interaction between Systematicity and Mapping Condition [$F(2, 136) = 3.89$, $p < .05$].

Although both Mapping Condition and Systematicity show main
effects, their developmental patterns differ. Mapping Condition
shows strong effects for both age groups. As predicted, the
children performed best with the easy S/S mapping, intermediate
with the D mapping, and worst with the misleading S/D mapping.
Planned comparisons confirmed that Mapping Condition had
significant effects on both age groups.

In contrast, Systematicity showed significant effects only in the older group. For the older children, performance was significantly better on systematic stories [t(34) = 2.48, p < .01]. This was not true for the younger children; they derived no significant advantage from systematic plot structure [t(34) = 1.08, NS].[4]

The last prediction was that Systematicity should have its greatest effects on the most difficult mappings (since these are the mappings in which the children cannot rely on object similarity to perform the transfer). This prediction was confirmed by the Systematicity X Mapping Condition interaction noted above. More to the point, planned comparisons within the older group (the only group affected by Systematicity) confirmed that Systematicity was significant only in the S/D condition. Thus the presence of systematic relational structure created a significant improvement only in the most difficult mapping condition.

It might be wondered whether the systematicity advantage in transfer was simply a memory phenomenon. We know that the degree of structure and organization plays a role in how well material can be remembered (e.g., Bower & Clark, 1969; Bransford & Johnson, 1972; Mandler, 1967); perhaps the eight-year-olds were simply better able to remember the systematic stories during the mapping task. Then the systematicity advantage would tell us nothing about mapping, but only reaffirm the superiority of

organized structures in memory. There are three arguments against the memory interpretation of the data. First, the children were uniformly able to perform the original story enactments--i.e., the enactments using the initial set of characters. Since this, too, was a memory task, any difference in memory for the original stories should have shown up here. Recall that the transfer enactment is done immediately after the initial story enactment, so there should be little opportunity for forgetting. Second, the interaction between systematicity and mapping condition discussed in the preceding paragraph shows that the effects of systematicity were specific, rather than an across-the-board advantage. Third, and most important, all children regardless of systematicity condition performed nearly perfectly on the high-transparency transfer task. When the transfer mappings were easy, children could demonstrate nearly perfect memory for the original story in both the systematic and nonsystematic condition. Thus we conclude that the differences in transfer accuracy are not due to differential forgetting but arise during the mapping process itself.

These results suggest that systematicity indeed plays a role in the mapping process: that children, at least by the age of eight, can use higher-order constraints to help keep the lower-order predicates straight. We found informal support for this claim in the self-corrections that the older children occasionally made. A child would begin to make an error, acting

out an event with the wrong character, and then stop herself with
a remark like "No, wait, it's the greedy one who got stuck in the
well, because he ate too much." These children, then, used
higher-order relations to check the correctness of lower-order
predicates during the mapping.

Discussion

In this research, we found effects of both systematicity and
transparency on the accuracy of children's analogical mappings.
These results have implications both for theories of analogical
processing and for accounts of the development of analogy and
metaphor. We begin by discussing the implications for theories
of analogy.

Systematicity in Analogical Mapping

The principle of systematicity is becoming increasingly
prominent in computational approaches to analogy (e.g., Burstein,
1983; Carbonell, 1983; Gentner, 1980, 1982, 1983; Gentner &
Gentner, 1983; Rumelhart & Norman, 1981; Winston, 1980, 1982).
Although accounts vary in detail, it is generally supposed that
the presence of some kind of common higher-order constraining
structure is an important determinant of the utility of an
analogy for learning and transfer. However, there has been
little evidence about how systematicity enters into the
analogical process. Is it simply a passive desideratum, which
the learner checks after interpreting an analogy to decide which
interpretation to choose and to determine how good the analogy

is? This limited view of systematicity is contradicted by the
present research. Our results show that systematicity enters
into the mapping process itself.

In this work we go beyond structure-mapping as a competence
theory--a theory of how people think an analogy should be
mapped--and consider its implications as a performance theory.
We ask what makes an analogy easy to process; and in particular
whether systematicity plays a role in making analogical mapping
easier. According to structure-mapping theory, once the base and
target domains have been accessed, the mapping process involves
setting up object-correspondences and carrying across predicates.
This suggests that at least two factors should enter into the
difficulty of the mapping process. The first is the transparency
of the object-correspondences: the more similar the
corresponding objects in base and target, the easier it should be
to keep the mapping straight, which here was manipulated by
varying the similarity among corresponding objects of base and
target. The second factor is the sturdiness of the predicate
structure that is to be mapped from base to target. This is
where systematicity enters in. The presence of constraining
higher-order relations that govern the lower-order predicates
both guides the on-line mapping of lower-order predicates and
provides the learner with checks on the correctness of the
mapping. Indeed, we saw children correct their enactments when

they remembered higher-order information that predicted a different event.

The theory predicts that both systematicity and transparency should facilitate analogical mapping.[5] Both these claims were verified for the eight-year-olds. We believe the same pattern of results will hold for adults. Preliminary results using an adult version of the same paradigm indicate that adults take longer to retell the story in the most difficult mapping condition--the cross-mapping case with a nonsystematic base story--than they do in the more natural conditions.

Developmental Implications and Further Questions

Two developmental questions were posed here:

1. Are there developmental differences in the effects of
   difficult object correspondences in analogical mapping?

2. Do children change in their ability to profit from
   systematic relational structure in dealing with those
   difficult correspondences?

One useful aspect of this methodology for studying development is that it allows an indirect measure of the child's ability to use systematicity. Research on development of metaphor has shown repeatedly that children do not articulate their interpretation of metaphors in the same manner as adults (Gardner, Kircher, Winner & Perkins, 1975; Gentner & Stuart, 1983; Reynolds & Ortony, 1980; Vosniadou & Ortony, 1983; Winner, Rosenstiel & Gardner, 1976). However, we cannot therefore infer that children

are intellectually unable to perform metaphorical and analogical transfer (cf. Brown & Campione, 1985; Carey, 1984; Winner, Engel & Gardner, 1980). There is some evidence that children can perform analogical mappings without necessarily being able to articulate all the predicates that they are mapping (Crisafi & Brown, 1983; Gardner, 1974; Gentner, 1977; Holyoak, Juin, & Billman, in press); see Vosniadou (1985) for a review of this issue. In the present methodology, children simply acted out stories with a new set of characters. Thus, although they were not required to verbalize the relational structure that they were carrying across, their ability to make the transfer was clear from the accuracy of their reenactment. Given that the child can act out the original story (which was in all cases true), we found:

1. children of both ages were affected by the transparency
   of the object mappings.

2. systematicity benefited the older children.

3. systematicity had its greatest effect when the object
   mappings were most difficult.

The transparency of the object-mapping affects both younger and older children. Object similarity between base and target may well be important in determining the ease of analogical processing at all levels of development. The work of Ross (1984, 1986) and Reed (1985) suggests that even adults are greatly influenced by the degree of surface similarity between potential

analogs in learning and problem-solving tasks. In developmental

research on transfer tasks, the reliance of young children on

surface information is well-established (Keil & Batterman, 1984;

Kemler, 1983; Shepp, 1978; Smith & Kemler, 1977). Research by

DeLoache (1984) provides a particularly striking demonstration of

young children's reliance on surface similarity in transferring

knowledge. She tested children of 2 1/2 to 3 years of age in a

transfer-search task: an object is hidden in one space--for

example, a room--and the child must find a like object in a

similar space--for example, another room or a smaller scale model

of the original room. She finds that the children's performance

is extremely sensitive to surface similarity between the original

space and the search space. Our results are compatible with

DeLoache's findings in suggesting that transparency may be

developmentally among the earliest determinants of ease of

analogical mapping.

Systematicity, on the other hand, may make a somewhat later

developmental appearance. In our research, systematicity effects

were clearly present among the eight-year-olds, but not among the

younger children. However, our conclusions here must be

tentative; it is possible that with more sensitive methodology or

different materials we could find systematicity effects earlier

in development. Moreover, if indeed young children are deficient

in their ability to benefit from systematicity, there are at

least two different extreme interpretations, one based on

developmental increases in intellectual competence and other

based on acquisition of knowledge. The competence interpretation

is that younger children lack the processing ability to map whole

systems of relations. Their failure to use systematicity

reflects a developmental limitation in their basic competence.

The knowledge-based interpretation is that the younger children

had insufficient familiarity with the higher-order relations used

here. Thus even if they were intellectually able to use

systematicity in mapping, they were not in position to

demonstrate that ability. By this account, the difference

between younger and older children found here is a novice-expert

shift in the sense of Chi, Glaser and Reese (1982) or Larkin

(1983). From what we know so far, either account or a

combination could be correct.

To recapitulate, in this research we found that both younger

and older children did better when the object correspondences

were highly transparent. Only the older children benefited by

systematicity. In view of the centrality of systematicity in

analogical transfer, this developmental trend is important

whether it is a knowledge-based or a competence-based phenomenon.

The results of this study help us to delineate the subcomponents

of the mapping process and to chart their developmental course.

References

Asch, S. E., & Nerlove, H. (1960). The development of double

function terms in children: An exploratory investigation.

In B. Kaplan & S. Wapner (Eds.), Perspectives in

psychological theory. New York: International Universities

Press.

Bower, G. H., & Clark, M. C. (1969). Narrative stories as

mediators for serial learning. Psychonomic Science, 14,

181-182.

Bransford, J. D., & Johnson, M. K. (1972). Contextual

prerequisites for understanding: Some investigations of

comprehension and recall. Journal of Verbal Learning and

Verbal Behavior, 11, 717-726.

Brown, A. L., & Campione, J. C. (1985). Three faces of transfer:

Implications for early competence, individual differences,

and instruction. In M. Lamb, A. Brown, & B. Rogoff (Eds.),

Advances in developmental psychology (Vol. 3). Hillsdale,

NJ: Erlbaum.

Burstein, M. H. (1983). Concept formation by incremental

analogical reasoning and debugging. In Proceedings of the

International Machine Learning Workshop. Monticello, IL:

University of Illinois.

Buckley, S. (1979). Sun up to sun down. New York: McGraw-Hill.

Carbonell, J. G. (1983). Learning by analogy: Formulating and

generalizing plans from past experience. In R. S.

Michalski, J. Carbonell, & T. Mitchell (Eds.), Machine

learning. Palo Alto, CA: Tioga Publishing Company.

Clement, J. (1981). Analogy generation in scientific problem

solving. Proceedings of the Third Annual Meeting of the

Cognitive Science Society.

Clement, J. (1982). Spontaneous analogies in problem solving: The

progressive construction of mental models. Paper presented

at the AERA, New York.

Carey, S. (1984). Are children fundamentally different kinds of

thinkers and learners than adults? In S. F. Chipman, J. W.

Segal, & R. Glaser (Eds.), Thinking and learning skills:

Current research and open questions (Vol. 2). Hillsdale,

NJ: Erlbaum.

Chi, M. T. H., Glaser, R., & Reese, E. (1982). Expertise in

problem solving. In R. Sternberg (Ed.), Advances in the

psychology of human intelligence (Vol. 1). Hillsdale, NJ:

Erlbaum.

Collins, A. M., & Gentner, D. (in press). How people construct

mental models. In D. Holland & N. Quinn (Eds.), Cultural

models in language and thought. Cambridge, England:

Cambridge University Press.

Crisafi, M., & Brown, A. L. (1983). Flexible use of an

inferential reasoning rule by very young children. Paper

presented at the Biennial Meeting of the Society for

Research in Child Development, Detroit, Michigan.

DeLoache, J. S. (1984). Oh where, oh where: Memory-based

searching by very young children. In C. Sophian (Ed.),

Origins of cognitive skills (pp. 57-80). Hillsdale, NJ:

Erlbaum.

Dent, C. H. (1984). The developmental importance of motion

information in perceiving and describing metaphoric

similarity. Child Development, 55, 1607-1613.

Forbus, K., & Gentner, D. (1986). Learning physical domains:

Towards a theoretical framework. In R. M. Michalski,

J. Carbonell & T. Mitchell (Eds.), Machine learning: An

artificial intelligence approach, Vol. II. Morgan Kaufmann.

Gardner, H. (1974). Metaphors and modalities: How children

project polar adjectives onto diverse domains. Child

Development, 45, 84-91.

Gardner, H., Kircher, M., Winner, E., & Perkins, D. (1975).

Children's metaphoric productions and preferences. Journal

of Child Language, 2, 1-17.

Gentner, D. (1977). Children's performance on a spatial analogies

task. Child Development, 48, 1034-1039.

Gentner, D. (1980). Metaphor as structure-mapping. Paper

presented at the meeting of the American Psychology

Association, Montreal.

Gentner, D. (1982). Are scientific analogies metaphors? In D.

Miall (Ed.), Metaphor: Problems and perspectives. Brighton,

England: Harvester Press Ltd.

Gentner, D. (1983). Structure-mapping: A theoretical framework

for analogy. Cognitive Science, 7(2).

Gentner, D. (1986). Structure-mapping in the development of

metaphor. Manuscript submitted for publication.

Gentner, D., & Block, M. J. (1983, October). Analogical

development and the novice-expert shift (Tech. Rep. No.

5478). Cambridge, MA: Bolt, Beranek and Newman.

Gentner, D., & Gentner, D. R. (1983). Flowing waters or teeming

crowds: Mental models of electricity. In D. Gentner & A. L.

Stevens (Eds.), Mental models. Hillsdale, NJ: Erlbaum.

Gentner, D. & Landers, R. (1985). Analogical remindings: A good

match is hard to find. In Proceedings of the International

Conference on Systems, Man and Cybernetics. Tucson,

Arizona.

Gentner, D., & Stuart, P. (1983). Metaphor as structure-mapping:

What develops (Tech. Rep. No. 5479). Cambridge, MA: Bolt,

Beranek and Newman.

Holyoak, K. J., Juin, E. N., & Billman, D. O. (in press).
Development of analogical problem-solving skill. Child
Development.

Inhelder, B., & Piaget, J. (1958). The growth of logical thinking
from childhood to adolescence. New York: Basic Books.

Keil, F. & Batterman, N. A. (1984). A characteristic of defining
shift in the development of word meaning. Journal of Verbal
Learning and Verbal Behavior, 23, 221-236.

Kemler, D. G. (1983). Holistic and analytical modes in perceptual
and cognitive development. In T. J. Tighe & B. E. Shepp
(Eds.), Perception, cognition and development: Interactional
analysis. Hillsdale, NJ: Erlbaum.

Kempton, W. (in press). Two theories used for home heat control.
In D. Holland and N. Quinn (Eds.), Cultural models in
language and thought. Cambridge, England: Cambridge
University Press.

Kogan, N. (1975). Metaphoric thinking in children: Developmental
and individual-difference aspects. Paper presented at the
Biennial Meeting of the Society for Research in Child
Development, Denver, Colorado.

Larkin, J. H. (1983). Problem representations in physics. In D.
Gentner & A. L. Stevens (Eds.), Mental models. Hillsdale,
NJ: Erlbaum.

Mandler, G. (1967). Organization and memory. In K. W. Spence &
J. T. Spence (Eds.), Psychology of learning and motivation,
Vol. 1. New York: Academic Press.

Reed, S. K. (1985). A structure-mapping model for word problems.
Paper presented at the meeting of the Psychonomic Society,
Boston.

Reed, S. K., Ernst, G. W., & Banerji, R. (1974). The role of
analogy in transfer between similar problem states.
Cognitive Psychology, 66, 436-450.

Reynolds, R. E., & Ortony, A. (1980). Some issues in the
measurement of children's comprehension of metaphorical
language. Child Development, 51, 1110-1119.

Ross, B. H. (1984). Remindings and their effects in learning a
cognitive skill. Cognitive Psychology, 16, 371-416.

Ross, B. H. (1986). This is like that: Object correspondences and
remindings and the separation of similarity effects on the
access and use of earlier problems. Manuscript submitted
for publication.

Rumelhart, D. E., & Norman, D. A. (1981). Analogical processes in
learning. In J. R. Anderson (Ed.), Cognitive skills and
their acquisition. Hillsdale, NJ: Erlbaum.

Shepp, B. E. (1978). From perceived similarity to dimensional
structure: A new hypothesis about perceptual development.
In E. Rosch & B. B. Lloyd (Eds.), Cognition and
categorization. Hillsdale, NJ: Erlbaum.

Smith, L. B. & Kemler, D. G. (1977). Developmental trends in free

　　classification: Evidence for a new conceptualization of

　　perceptual development. Journal of Experimental Child

　　Psychology, 24, 279-298.

VanLehn, K. & Brown, J. S. (1980). Planning nets: A

　　representation for formalizing analogies and semantic models

　　of procedural skills. In R. E. Snow, P. A. Federico & W. E.

　　Montague (Eds.), Aptitude, learning and instruction:

　　Cognitive process analyses. Hillsdale, NJ: Erlbaum.

Vosniadou, S. (1985). On the development of metaphoric

　　competence. Unpublished manuscript.

Vosniadou, S., & Ortony, A. (1983). The emergence of the literal-

　　metaphorical-anomalous distinction in young children. Child

　　Development, 55, 14-161.

Vosniadou, S. & Ortony, A. (in press). Testing the metaphoric

　　competence of the young child: Paraphrase versus enactment.

　　Human Development.

Winner, E. (1979). New names for old things: The emergence of

　　metaphoric language. Journal of Child Language, 6, 469-491.

Winner, E., Engel, M., & Gardner, H. (1980). Misunderstanding

　　metaphor: What's the problem? Journal of Experimental Child

　　Psychology, 30, 22-32.

Winner, E., Rosenstiel, A., & Gardner, H. (1976). The development

　　of metaphoric understanding. Developmental Psychology, 12,

　　289-297.

Winston, P. H. (1980). Learning and reasoning by analogy.

　　Communications of the ACM, 23(12).

Winston, P. H. (1982). Learning new principles from precedents

　　and exercises. Artificial Intelligence, 19, 321-350.

Footnotes

[1] Besides analogy, other kinds of similarity can be characterized by the distribution of relational and attributional predicates that are mapped. In _analogy_, only relational predicates are mapped. In _literal_ _similarity_, both relational predicates and object-attributes are mapped. In _mere-appearance_ matches, it is chiefly object-attributes that are mapped.

[2] The _order_ of a relation is determined by the order of its arguments. A first-order relation is one that takes objects as its arguments. A second-order relation has at least one first-order relation among its arguments. An nth order relation has at least one (n - 1)th order argument.

[3] A relational chain can also provide support--particularly in cases where little or nothing is known about the target domain--if it merely generates no contradictions in the target.

[4] It should be noted that there was no significant Age X Systematicity interaction in the overall analysis of variance. Therefore it is possible that systematicity benefited both groups, but that only in the older group did the effects reach significance.

[5] Note that, although both systematicity and transparency are postulated to make analogical mapping easier, only systematicity enters into the perceived soundness of an analogy. Indeed, if the object similarity becomes too high, the comparison becomes a literal similarity match instead of an analogy.

Table 1

Sample Story, in Systematic and Nonsystematic Versions

(Systematic Version Includes Indented Material)

> Setting a: There once was a very jealous cat who was
> friends with a walrus. The cat often said to the walrus,
> "Don't ever play with anyone else but me."

One day the cat went away on a trip and the walrus had no one to play with. But then a seagull came to visit the walrus. He brought a wagon along and said, "Would you like to play with me and my wagon?" The walrus said, "Yes." The seagull and the walrus had a great time pulling each other around in the seagull's wagon.

When the cat came back and found the walrus playing with someone else he got very angry. He shouted, "I'll never play with you again!"

The cat was so angry that he jumped into the seagull's wagon. But the wagon began to roll faster down a steep hill. The cat was very scared.

The seagull jumped up and chased after the wagon so the cat wouldn't crash. The seagull stopped the runaway wagon and saved the cat's life.

> Moral b: In the end, the cat realized that being jealous
> only got him into trouble. It is better to have two friends
> instead of one.

a. _Setting_, Nonsystematic Version: There once was a very strong cat who was friends with a walrus.

b. _Moral_ is omitted in nonsystematic version.

Table 2

Characters Used in the Stories, Showing the Three Mapping

Conditions for each Story

| Story	Test	S/S	D/S	S/D
1	seal	walrus	lion	cat
	penguin	seagull	giraffe	walrus
	dog	cat	camel	seagull
2	goose	swan	giraffe	raccoon
	panda	raccoon	camel	monkey
	chimp	monkey	lion	swan
3	hare	rabbit	camel	bear
	beaver	bear	giraffe	porcupine
	mole	porcupine	lion	rabbit
4	bull	cow	shark	cricket
	mule	camel	elephant	cow
	ant	cricket	lion	camel
5	moose	elk	shark	medicine man
	hog	pig	elephant	elk
	warrior	medicine man	lion	pig
6	dragon	dinosaur	lion	unicorn
	horse	unicorn	shark	eel
	snake	eel	elephant	dinosaur
7	hunter	cowboy	ostrich	fly
	pony	zebra	turtle	cowboy
	spider	fly	giraffe	zebra
8	gorilla	orangutan	giraffe	lizard
	steer	buffalo	turtle	orangutan
	alligator	lizard	ostrich	buffalo
9	eagle	vulture	turtle	bobcat
	hippo	rhino	giraffe	vulture
	tiger	bobcat	ostrich	rhino

Figure Captions

Figure 1. Partial depiction of the analogy between solar system and hydrogen atom, showing a person's presumed initial knowledge of the solar system and the mapping of that knowledge to the atom.

Figure 2. More detailed depictions of a person's representations of the solar system.
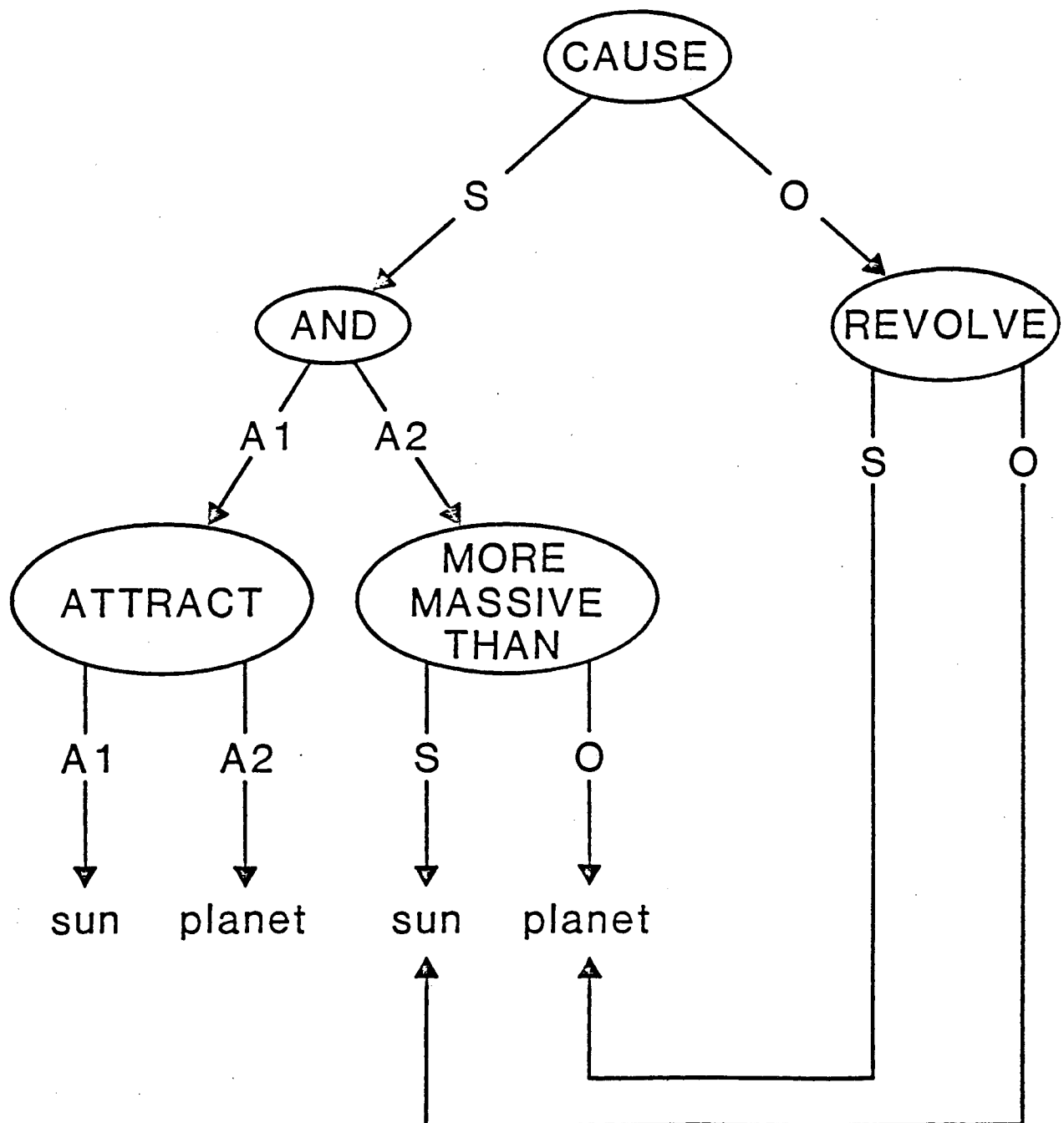
- a. Systematic representation

- b. Nonsystematic representation

Figure 3. Results: Proportion of statements in the target stories correctly enacted under different conditions for four-to-six-year-olds (top graph) and eight-to-ten-year-olds (bottom graph).

AGE 4-6

AGE 8-10
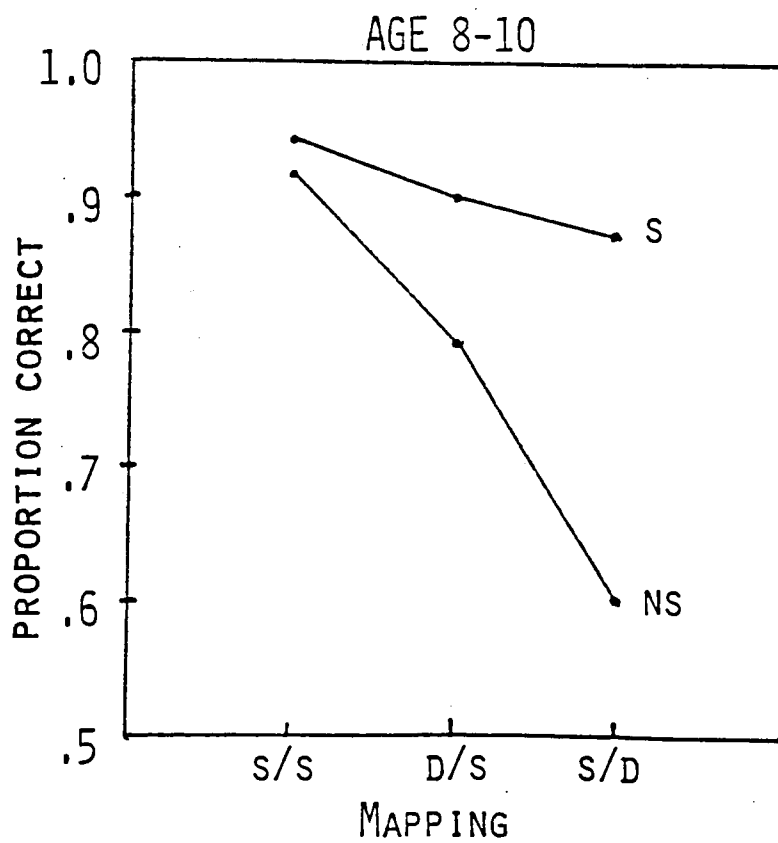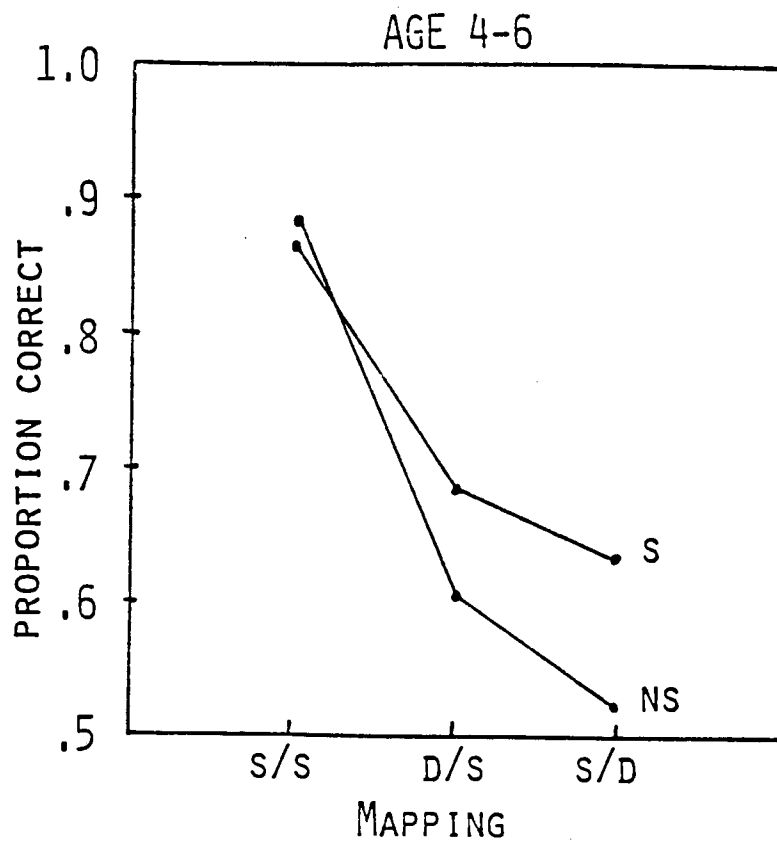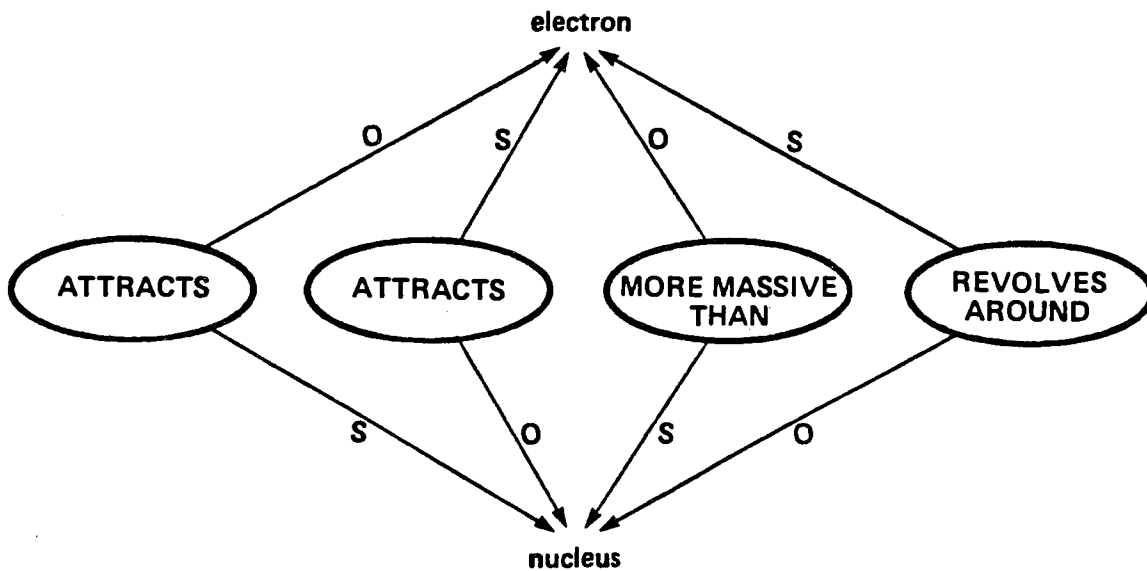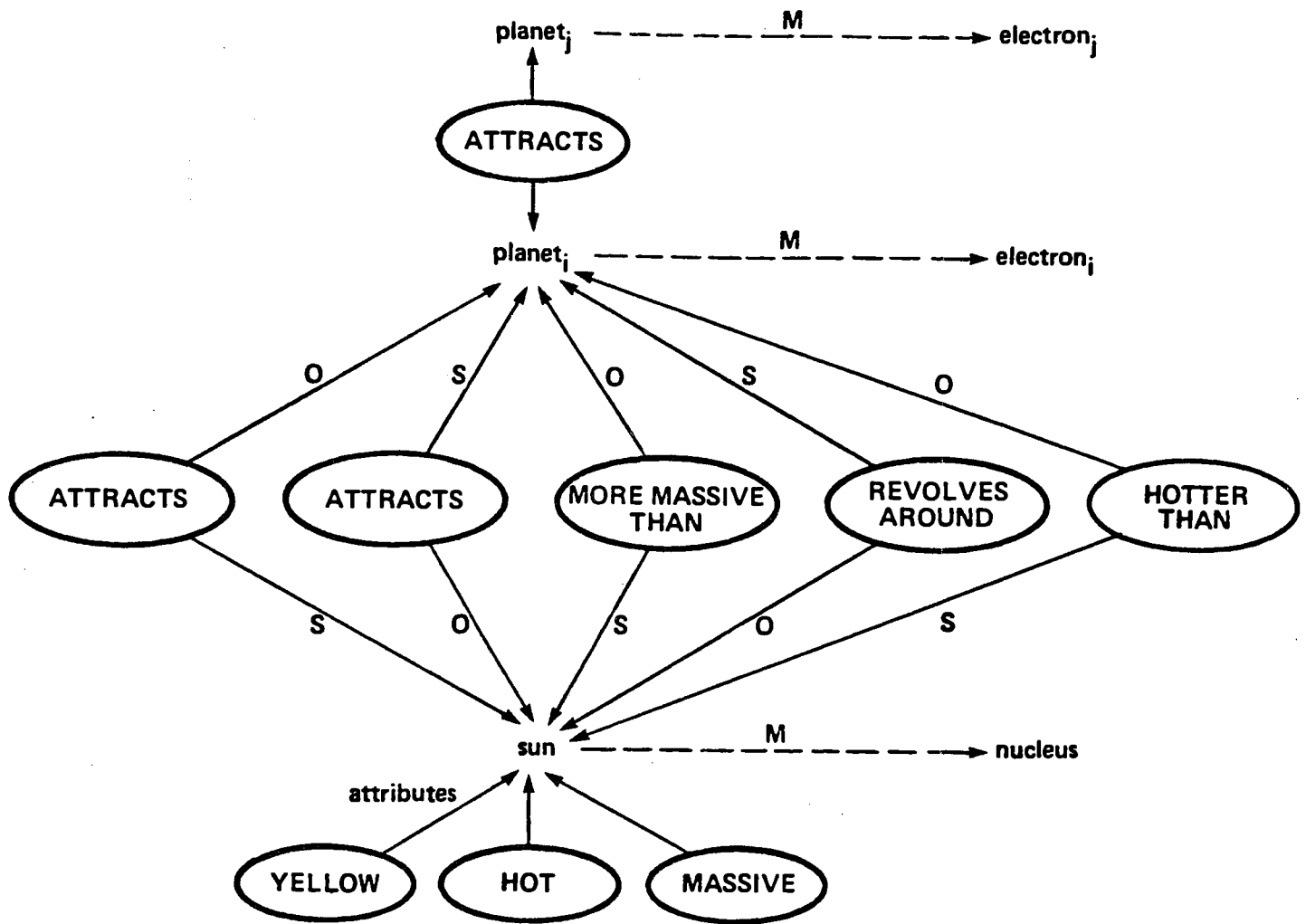
Systematic Partial Representation
of Solar System

Non-Systematic Partial Representation of Solar System