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ANALOGICAL REASONING AS A MECHANISM IN KNOWLEDGE ACQUISITION: A DEVELOPMENTAL PERSPECTIVE

Stella Vosniadou
University of Illinois at Urbana-Champaign

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UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN
174 Children's Research Center
51 Gerty Drive
Champaign, Illinois 61820

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Abstract

Analogical reasoning involves the identification and transfer of an explanatory structure from a known system (the source) to a new and relatively unknown system (the target). Analogical reasoning can take place between two systems that belong to fundamentally different domains, or between two systems that belong to the same or similar domains. An analogy can be identified when the underlying structural similarity between two analogs is recognized. However, the productive use of an analogy, that is, the use of analogical reasoning to produce a new understanding of the explanatory structure of a target system, is often based on the recognition of some similarity in salient properties of the two systems, and not on similarity in their structure, because the explanatory structure of the target system is not known.

It seems that adults as well as children are capable of identifying the structural similarity between two analogs when the similar underlying structure is part of their representation of the source and target systems. They can also use the similarity in salient properties between two systems as a vehicle for discovering similarities in their explanatory structure. What develops is not so much the analogical mechanism itself but rather the conceptual system upon which this mechanism is based.

ANALOGICAL REASONING AS A MECHANISM IN KNOWLEDGE ACQUISITION: A DEVELOPMENTAL PERSPECTIVE

> Whether or not we talk of discovery or of invention, analogy's inevitable in human thought, because we come to new things in science with what equipment we have, which is how we have learned to think, and above all how we have learned to think about the relatedness of things. We cannot, coming into something new, deal with it except on the basis of the familiar and the old-fashioned. The conservation of scientific enquiry is not an arbitrary thing; it is the freight with which we operate; it is the only equipment we have. We cannot learn to be surprised or astonished at something unless we have a view of how it ought to be; and that view is almost certainly an analogy. (Oppenheimer, 1955, pp. 129-130.)

Interest in analogy has been generated to a large extent by a recognition of the role that analogy can play in the acquisition of new knowledge. While our models of learning have stressed the importance of prior knowledge in thinking, remembering and learning, they have remained mainly silent on the processes thereby which new knowledge is acquired. One mechanism which has been recognized by scientists, philosophers and psychologists alike as having the potential of bringing prior knowledge to bear on the acquisition of, sometimes, radically new information is analogy.

My purpose in this paper is to examine analogical reasoning, paying particular attention to the role it plays in knowledge acquisition. This question will be approached from a developmental point of view. I will discuss how analogical reasoning is used by adults as well as by children and I will speculate about how analogical reasoning may develop. The developmental questions are often ignored in our treatment of analogy. Yet, they are critical both in order to understand the psychological processes involved in analogical reasoning (see also Gentner, in press), and in terms of their implications for learning and instruction. For it is only if we understand how analogical reasoning develops with age and with the acquisition of expertise that we shall be able to influence its development.

The first section of this paper deals with the problem of "what" analogical reasoning is. It is argued that analogical reasoning involves the identification and transfer of structural information from a known system (the source) to a new and relatively unknown system (the target). Two different types of reasoning are discussed and some of the psychological processes involved in their identification are examined. It is concluded that the *productive* use of analogy, the use of analogy to produce *new* knowledge about the explanatory structure of the target system, is often based on the recognition of some similarity in salient properties of the two systems, and not on similarity in their structure, since the relevant structure of the target system is not known.

In the second section, a distinction is drawn between uses of analogical reasoning which require that the relevant structure is part of one's representation of the target and cases where analogical reasoning can produce this knowledge. With respect to the developmental question, the main thesis of this paper is that analogical reasoning is available to children. Like adults, children can identify the similarity in the structure between two analogs when this structure is part of their representation of the source and target systems. Moreover, it appears that children can use similarity in salient properties between two systems as a vehicle for discovering structural similarities between them, just like adults do. It is concluded that what develops is *not* the analogical mechanism itself but the conceptual system upon which this mechanism operates.

Analogical Reasoning: Definitional Issues

Mapping a Relational Structure

Two types of analogical reasoning. It is by now generally accepted that the process of reasoning by analogy involves transfer of structural information from a source to a target system. This transfer of knowledge is accomplished by mapping or matching processes which consist of finding the correspondences between the two systems.

In most cases, an analogy is said to exist between two structures (concepts, theories, systems, stories, etc.), which belong to fundamentally different or remote conceptual domains but which share a similar relational structure (hereafter "between-domain" analogies). For example, the analogy between the atom and the solar system is based on the similarity in the structure of the two systems. The particular properties involved (e.g., sun-nucleus, electrons-planets) are very different. Similarly, in the analogy between the "radiation problem" (Dunker, 1945) and the "fortress problem" (Gick & Holyoak, 1980, 1983; Holyoak & Thagard, in press), the particular properties involved (e.g., army and rays, fortress and tumor) are very different. However, the goals, resources, and constraints of the two problems (i.e., structural aspects) are similar, and hence can be transferred from one problem to the other.

In other cases, analogical reasoning involves items which belong to the same or at least very close conceptual domains, as in the case where "a styrofoam cup" is used as an example from which to reason analogically about a "ceramic mug" described by Kedar-Cabelli (1985) (hereafter "within-domain" analogies). The types of analogical reasoning described by Anderson and Thompson (in press) and Ross (in press) involve mainly within-domain analogies.

The distinction between within-domain and between-domain analogies is not a dichotomous one. Rather, it represents a continuum from comparisons involving items that are clear examples of the same concept to items that belong to different and remote domains. In that respect, the distinction between the two types of analogies is similar to the distinction between literal comparisons and metaphorical comparisons (Ortony, 1979; Vosniadou, 1987a). The important point for the purposes of this discussion is that analogical reasoning can be employed between items that belong anywhere in the continuum from literal similarity to nonliteral similarity.

Can within-domain comparisons be analogies? Some theories of analogy consider within-domain comparisons as literal similarities rather than as analogies. For example, Gentner (in press) believes that within-domain comparisons are not analogies because they involve items which are similar in many simple, descriptive, non-relational properties. Gentner draws a distinction between object attributes (descriptive properties of objects, roughly expressed as one-place predicates) and relations (roughly two-or-more place predicates) and argues that an analogy is defined by the presence of relational similarity and the absence of similarity in object attributes. According to this view, in an analogy only relational predicates are shared, while in literal similarity both relational predicates and object attributes are shared.

Gentner is primarily concerned about characterizing static similarity statements of the sort "The solar system is like an atom," rather than the process of reasoning by analogy. It is true that when it comes to characterizing such similarity statements the distinction between a within-domain and a between-domain comparison carries certain definitional implications. For instance, certain within-domain similarity statements (such as "Puppies are like kittens") *cannot* be considered analogies (although an analogy could be made out of some of these statements if the comparison were restricted to a particular relation between the two items being compared, as in "Puppies are to dogs like kittens are to cats"). Unlike similarity statements, however, the distinction between within-domain and between-domain comparisons does not have any definitional implications when it comes to characterizing the process of reasoning by analogy. Analogical reasoning can be employed between any two items that belong to the same fundamental category, if the reasoning involves transferring an explanatory structure from one item to the other.

In the system described by Kedar-Cabelli (1985), for example, an analogy exists between a ceramic mug and a styrofoam cup to the extent that the example of a ceramic mug can be used as a source from which to determine whether the target satisfies a given goal (e.g., that of drinking hot liquids). Very briefly, the analogy mechanism operates as follows:

1. The system retrieves a familiar source example (e.g., a ceramic mug) together with an explanation of how this source example satisfies some goal (e.g., of drinking hot liquids).

2. The system maps the explanation derived from the source onto the target and attempts to find out if this explanation is justified by the target example.

3. If the target example justifies the explanation, then it is concluded that it satisfies the goal (i.e., it can be used to drink hot liquids).

Although the base and target systems in this case share many similar simple properties, the reasoning process is analogical in nature because it rests on the mapping of an explanatory structure from the source onto the target system to determine if the target satisfies it. The reasoning process is one of mapping structural information.

Consider another example: Suppose we want to find out if there is a day/night cycle on the moon. If we do not know the answer to this question directly, one way to answer it is to reason by analogy to the earth. We know that there is a day/night cycle on the earth which is determined by the earth's rotation around its axis. If we know that there is an axis rotation of the moon (or assume there is on the basis of the other existing similarities between the moon and the earth), then we can come to the conclusion that there must also be a day/night cycle on the moon.

Thus, while the statement, "The earth is like the moon" can hardly be thought of as an analogy, the earth can nevertheless be used as a source from which to reason analogically about the moon. And, despite the many simple properties that the earth and the moon share (solid, spherical, suspended, rotating, etc.), it is only the *causal relation* between axis rotation and the existence of a day/night cycle that is mapped from the base to the target.

To conclude, we have argued that domain incongruence (belonging to different conceptual domains) is *not* a defining characteristic of analogy. The defining characteristic of analogy is similarity in underlying structure. Structural similarity can be found between items that belong to different conceptual domains as well as between items that belong to the same or similar domains. Domain incongruence is, however, a defining characteristic of nonliteral (i.e., metaphorical) similarity. (See Ortony, 1979; Tourangeau & Sternberg, 1982; Vosniadou, 1987a, for a more detailed discussion of this issue.) The items juxtaposed in a metaphor must belong to different conceptual domains. This can be shown by the fact that between-domain analogies can be turned into metaphors (e.g., "Atoms are Solar Systems," "Inflation is Disease," "Illiteracy is Prison," and the like), but within-domain analogies (e.g., "A puppy is to a dog like a kitten is to a cat") cannot. The statement "A puppy is a kitten" is just nonsense.[1]

Identifying Similarity in Relational Structure

The role of "surface" similarity. The definition of analogical reasoning which I have offered focuses on the mapping of an explanatory structure from a source to a target system, ignoring the question of whether these two systems are similar in "surface" (simple, descriptive, non-analogy-related) properties as well. Similarity in surface properties may be relevant, however, in determining how a source analog is accessed in the first place. It could be argued, for example, that within-domain analogs can be identified on the basis of their similarity in simple, descriptive (and therefore easily accessible) properties, which may not have anything to do with the analogy in the first place. Since between-domain analogs do not share similarity in such non-analogy related surface properties, they can be accessed only by noticing the similarity in their structure. This could be interpreted to mean that different psychological processes operate in accessing a between-domain analogy than a within-domain analogy. The argument I will advance in this paper is that while different psychological processes can operate in accessing a between-domain analogy from a within-domain analogy, access to a *productive* between-domain analogy (i.e., a between-domain analogy which provides new knowledge about the explanatory structure of the target system) must be based on the same psychological process as access to a within-domain analogy.

In support of the different psychological processes argument come the results of a number of experiments which show that surface similarity (i.e., non-analogy-related similarity in simple, descriptive properties of objects, like shape, color, size, names, profession, workplace of story characters, kinds of animals, etc.) is likely to be noticed more easily than similarity in underlying structure (e.g., Gentner & Landers, 1985; Holyoak & Koh, 1986; Vosniadou, Brown, & Bernstein, in preparation). The easy accessibility of surface similarity sometimes becomes the motivating force for selecting the wrong between-domain source analog (e.g., Ross, 1987).

These experiments have served an important purpose in showing that people are more sensitive to similarity in descriptive properties than similarity in structural aspects. They have erred only in allowing the inference that such a characteristic of the human reasoning system is an impediment to analogical reasoning. Contrary to common sense expectations, similarity in descriptive properties of objects is often analogy-related. As Medin and Ortony (in press) note, in our conceptual system, descriptive properties of objects are usually related to deeper, less easily accessible properties in a complex causal/relational network. In such a system, the easily accessible, descriptive properties which are analogy-related can become the vehicle for discovering the similarity in the underlying structure between two analogs. In fact, one of the reasons why people pay attention to "surface" similarities may be that such similarities can lead to the discovery of an analogy in a non-accidental way (see also Brown, in press, and Ross, in press). Being attentive to similarity in descriptive properties is thus one of the characteristics that an efficient analogy mechanism should have.

Accessing a productive between-domain analog. It could be objected here that the possibility of arriving at an analogy via similarity in the descriptive properties of two analogs can operate *only* in the case of within-domain analogical reasoning. The absence of descriptive properties in between-domain analogies necessitates that the identification of a between-domain analogy must be based on some recognition of the structural similarity between the source and target domains.

Obviously, between-domain analogies can be accessed by recognizing the similarity in their underlying structure. The problem with this account of access is that it fails to explain how between-domain analogies can ever be used *productively*. As Hesse (1966) correctly observes, in order for an analogy to be used productively, that is, to lead to the discovery of new knowledge, it cannot be based on the recognition of the structural similarity between the two analogs. The reason is that understanding that two systems have the same structure presupposes that one has a theory not only about the source but also about the target system. If a theory about the target is not available, as must be the case for an analogy to be used productively, then one is *not* likely to understand that the two systems have a similar structure.

In such cases the access problem can be solved if we assume that the between-domain analogy is identified on the basis of some similarity in easily accessible properties of the two systems, just like in the case of many within-domain analogies. This argument rests on the presupposition that easily accessible similarity does not need to be similar in descriptive properties. Rather, it can be similarity in relational, abstract or conceptual properties for as long as these properties are salient with respect to people's underlying representations. This is why I shall use the term *salient* similarity to distinguish it from *surface* similarity (the differences between these two kinds of similarity will be discussed further in the next section). Such salient similarity can become the vehicle for discovering the presence of other less easily accessible similarities and eventually the crucial structural correspondences between the two systems.[2]

An access process of this sort can be traced in the discovery of a number of scientific analogies, like the analogy between elastic balls and the behavior of gasses which apparently suggested itself because of the similarity in the behavior of bouncing balls and balloons and the effects of pressure on a surface due to expanding gas. Another example is the analogy between light and particles made by Newton. This analogy appears to be based on the observation that light is reflected when it hits a surface the same way that particles bounce back when they hit a surface. Properties such as the behavior of particles and the behavior of light may appear to the layman to be remote and inaccessible. Yet to the physicist working in the context of a certain theory they appear to be as real and easily observable as it is to us the solid nature and spherical shape of the earth and the moon.

Surface Similarity vs. Salient Similarity

The access process for the productive use of between domain analogies which I have proposed requires some modification of currently accepted notions regarding easily accessible similarity. It has been assumed that what is easy to access is surface similarity and that surface similarity is either perceptual similarity (Rips, in press) or similarity in object attributes (Gentner, in press). In this section I shall argue that similarity which is easy to access (i.e, salient similarity) can be of a perceptual or conceptual nature, similarity in descriptive or relational properties. What matters is only the status that these properties have with respect to people's underlying representations.

Similarity in object attributes. In her work, Gentner has drawn a distinction between object attributes (simple, descriptive properties of objects) and relations (complex, relational properties of objects), and has argued that the latter are more difficult to access than the former. However, while descriptive properties of objects are often easy to access, this is not always the case. Take, for instance, the analogy between the earth and the moon discussed earlier. One may think that the similarity in object attributes like solid and spherical which the earth and the moon share should be easily accessible. Using the earth as a source analog from which to reason about the moon may thus be considered rather trivial. Yet, most children in our studies of knowledge acquisition in astronomy (Vosniadou, 1987b; Vosniadou & Brewer, 1987a), would never use the earth as a source analog from which to reason about the moon, although adults would. The reason is that until the end of the elementary school years many children do not really believe that the earth is a round sphere. Children's phenomenal experience that the earth is flat is so strong that information coming from adult sources regarding the shape of the earth is consistently misinterpreted. Furthermore, many children do not know that the moon is spherical either. Many believe that the moon is shaped like a crescent or that it is circular but flat, like a disc. It is apparent from the above, that the characterization of "spherical" as an object attribute of the earth and the moon carries no implications as to whether this is an easily accessible property of the objects in question or not.

The argument that descriptive properties of objects are more easily accessible than relational properties fails to take into consideration the status that this information has in people's underlying representations. Since similarity judgments can only be made with respect to people's underlying representations, it would be impossible to see similarity between analogs whose representations do not include these similar properties, or in which these properties are not salient. Just because a property is described as an object attribute does not necessarily mean that it is present in people's representation of that object or that it is an easily accessible property. Similarly, describing a property as relational does not imply that it is *not* included in people's representations or that it is not salient.

In fact, some developmental research indicates that relational properties of objects may be particularly salient even for young children. For instance, metaphor comprehension studies indicate that children find it easier to see similarity between moving objects belonging to different conceptual domains (like a ballerina dancing and a top spinning), than between stationary objects with similar object properties (like a curvy river and a curvy snake--see Dent, 1984; Calhoun, 1984). Our studies of children's knowledge about the sun and the moon also show that children are very sensitive to the movement of these objects across the sky.

Perceptual similarity. Defining easily accessible similarity as perceptual similarity is also problematic. As Smith (in press) argues the perception of similarity is not something static and well-defined, but something that changes with development (see also Piaget, 1969). What we perceive as similar at the time of birth is presumably determined by constraints on our perceptual apparatus. However, this "perceptual" similarity develops and changes with age and the acquisition of expertise. Moreover, going beyond what may be considered as perceptual, developments in people's representations of concepts allow them to have easy access to information which may not be of a perceptual nature at all.

The above observations suggest that easily accessible similarity does not have to be perceptual similarity or similarity in object attributes. Rather, both descriptive and relational properties of objects can be easy or difficult to access depending on how salient these properties are with respect to people's underlying representations.

Finally, it appears that what constitutes salient similarity may change in the process of knowledge acquisition. The results of a number of developmental and expert/novice studies show that older children's similarity judgments are different from those of younger children (e.g., Carey, 1985b; Keil, in press), or that experts categorize problems differently from novices (Chi, Feltovich, & Glasser, 1981). As Chi et al. (1981) have argued, there are fundamental differences in the representations of physics problems employed by experts and novices. Because of such differences, "experts are able to *see* the underlying similarities in a great number of problems, whereas novices *see* a variety of problems that they consider to be dissimilar because the surface features are different" (Chi et al., 1981, p. 130).

Conclusions

The analogy mechanism I have described can be characterized as a mechanism thereby which a problem about a target system (X) is solved by:

1. Retrieving a source system (Y) which is similar to X in some way.
2. Mapping a relational structure from Y to X.
3. Evaluating the applicability of this relational structure for X.

A distinction was made between the situation where X and Y represent examples of the same fundamental concept and the situation where X and Y belong to different conceptual domains. Although it is the latter type of analogy that has often been identified as the "true" case of analogical reasoning, it is important to notice that the same mapping process operates in both cases. In both cases a relational structure is mapped from the source to the target and its applicability is evaluated on the basis of what is known about the target concept.

While in many instances a between-domain analogy can be identified on the basis of the structural similarity between the analogs, the productive use of a between-domain analogy (i.e., its use for the purpose of acquiring new knowledge about the explanatory structure of the target system) requires an access mechanism similar to the one used to access a within-domain analogy. In both cases, access to a productive analog must be based on similarity in some salient, easily accessible, properties of the two systems.

Using Analogical Reasoning

In this section I will try to show how an analogy mechanism like the one described above is used, and particularly, how it is used to acquire new knowledge. Examples will be drawn from research describing adults' and children's abilities to reason analogically, and emphasis will be placed on how analogical reasoning develops with age and expertise. Finally, a distinction will be drawn between two cases where analogical reasoning can be used. The first is the situation where the employment of analogical reasoning requires that the underlying structure shared between two analogs is present in the subject's representation of both the source and target systems at the time when the analogy problem is solved. The other is the situation where the relational structure needs to be present only in one's representation of the source. Analogical reasoning can contribute most to the acquisition of new knowledge in this latter case. Instructional uses of analogy, where the source analog is given, and cases where similarity in explanatory structure is discovered on the basis of similarity in the salient properties of two systems are some instances where analogical reasoning can lead to the acquisition of new knowledge.

The Ability to Identify Similarity in Relational Structure

In most experimental investigations of analogical reasoning (e.g., the solution of four-term verbal or pictorial analogies, the comprehension of analogies, the transfer of a solution from story A to story B), the application of analogical reasoning is based on the identification of the structural similarity of the two systems in the absence of any known similarity in easily accessible properties between them.

Take, for example, the situation where story A is followed by an analogous story B, and where A contains some information which can be used to solve a problem about B (e.g., Brown, Kane, & Echols, 1986; Gentner, in press; Gick & Holyoak, 1980; 1983; Holyoak, Junn, & Billman, 1984; Ross, 1987; Vosniadou, Brown, & Bernstein, in preparation). In these situations one must identify the similarity in the structure between the two stories and, on the basis of this similarity, transfer the problem solution from story A to story B.

The results of a number of experiments employing this paradigm have shown that often the similarity in the structure of two analogs is not identified, with the corresponding result that story A is not used as a source analog for story B. However, in order to identify this structural similarity, the relevant structure must be present in the subject's representation of stories A and B at the time when the analogy problem needs to be solved. It has now become apparent that analogous stories (problems, concepts, etc.) are not always represented at a level at which the underlying structural similarity is preserved, and as a result analogical reasoning cannot be applied to them.

Sometimes these appropriate representations are not achieved because of lack of relevant knowledge. This is often the case with children. At other times, the relevant relational structure could be inferred from what exists in the knowledge base, but it is not.[3] This creates the problem of "inert" knowledge discussed by Bransford (in press) and Brown (in press). In general, it appears that when familiarity with the target and source domains is high then the likelihood of achieving an appropriate representation of the source and target system is increased (thus the observed differences in analogical reasoning between adults and children and experts and novices, e.g., Novick, 1985). When familiarity with the source and target domains is not very high but appropriate representations could be achieved by inference to what is already known, then certain experimental manipulations (e.g., presenting *two* instead of *one* source analogs, giving subjects various hints indicating that the two systems are similar, increasing the similarity in some descriptive properties of the two analogs, etc.), can bring about appropriate representations and thus facilitate analogical reasoning.

It becomes apparent from the above discussion that failure to reason by analogy in the cases where an appropriate representation has not been achieved carries few implications with respect to the ability to reason analogically per se (i.e., to identify and map a relational structure). The problem in such cases may lie not in the analogical mechanism itself (the "analogy engine" as Gentner, in press, calls it), but in the representational structures on which this mechanism operates.

Lack of concern for children's knowledge about the source and target systems is a common problem in developmental research on analogical reasoning. When this problem is corrected, the possibility of discovering that children can reason analogically increases. There is now considerable evidence which suggests that when children represent the target concepts at the appropriate level of generality, they can solve four-term analogy problems (Gentner, 1977), understand relational metaphors (Vosniadou, Ortony, Reynolds & Wilson, 1983), and solve a problem subsequent to listening to a story in which an analogous problem is solved (Brown, Kane, & Echols, 1986).

The shift from attributes to relations. Recently, Gentner (1987; Gentner & Toupin, 1986) has advanced the argument that although children do not lack the fundamental competence to make relational mappings, they do not have the propensity to do so. According to Gentner, "there is a developmental shift from attributional focus to relational focus in production, choice and rating of analogy interpretations" (Gentner, in press). This could be due either to lack of knowledge or to lack of some cognitive ability to observe relational similarity systematically.

Gentner (in press) cites the results of two experiments (Gentner, 1987; Gentner & Toupin, 1986) to support the attribute to relations shift hypothesis. In Gentner (1987), children and adults were asked to interpret figurative comparisons of the sort "Clouds are like a sponge." Results showed that the children produced mainly attributional interpretations (e.g., "both are round and fluffy"), while adults produced mainly relational interpretations (e.g., "both can hold water and later give it back").

As I have argued elsewhere (Vosniadou, 1987a), there is a confounding of relational interpretation with lack of necessary knowledge in this experiment. In other words, the information that clouds are round and fluffy is usually part of children's knowledge about clouds, but the information that clouds hold water may not be. This criticism applies in general to the materials used. Consider, for example, the statement "plant stems are like drinking straws." Again, it is highly debatable whether one should expect a 5-year-old to know that plant stems have liquids running through them, whereas the knowledge that plant stems are relatively tall and thin is readily available. In order to test the hypothesis that children do not have the propensity to map relational information one must first ensure that this information is part of children's knowledge base.

In the second experiment (Gentner & Toupin, 1986), children were asked to act out a story plot twice using different story characters. One of the variables manipulated was the degree to which the target objects resembled the source objects. Results showed a strong effect of the transparency of the character correspondences on transfer accuracy. Transfer accuracy was nearly perfect when highly similar characters were used and lower when the characters were quite different. Gentner (in press) concludes that these results provide "a striking demonstration of young children's reliance on surface similarities in transferring knowledge." However, reliance on surface similarity is not a developmental phenomenon. Surface similarity enhances analogical access and mapping not only in children but also in adults (Gentner & Landers, 1985; Ross, in press).

The Ability to Map a Relational Structure

It could be argued that in an analogy comprehension task like Gentner's (1987), the relational structure does not need to be included in the subject's knowledge of the source. In an analogy comprehension task the source analog is given *explicitly* and does not need to be identified (as in four-term verbal analogies, or even in the case where two analogous stories or problems are provided). All that needs to be done in this case is map the relevant relational structure from the source to the target. In other words, the children in Gentner's (1987) experiment could infer that plant stems have liquids running through them by transferring this information from the source to the target.

I can think of two responses to this argument. First, similarity statements of the sort "X is like Y" are ambiguous with respect to whether they should be interpreted as comparisons (in which case the *existing* representations of X and Y are compared) or as invitations to transfer information from the more familiar Y to the less familiar X. Second, even in the case where a mapping is considered, the mapping may fail for lack of adequate knowledge about which properties of the source could be safely mapped onto the target. Consider again the statement "plant stems are like drinking straws." It is possible that there is so much discrepancy between what children think about plant stems and the possibility that they have liquids running through them, that the mapping of the relevant property of "drinking straws" is not even considered. A similar mapping difficulty could be experienced by adults, as in the situation where a physics-naive individual is faced with statements such as "Heat is like water," "Particles are like light," and "Electrons are like a spinning top." Mapping an underlying structure may not necessarily require the presence of this structure in one's current representation of the target, but it certainly requires that enough is known about the target domain to make such a mapping from the source feasible.

This argument holds even when the information to be mapped is a simple, descriptive property, rather than structural information. The case of transfer failure discussed earlier regarding children's understanding of the statement "the earth is round like a ball," is a good example. The reason why children have problems with this statement is that their knowledge of the earth is shape (i.e., that the earth is flat) incompatible with the information that the earth is round. When children (or adults) try to make sense of such similarity statements, they often end up with gross misconceptions. For example, many children interpret the "earth is round like a ball" statement to mean that the earth is circular but flat, like a disc; others believe that people live inside. Finally, some children think that there are two earths; a round one which is a planet up in the sky, and a flat one on which the people live (Vosniadou & Brewer, 1987a, 1987b)!

If the mapping operation were obstructed by difficulties in mapping *relations* as opposed to *object attributes* the children in our experiments should not have any difficulty understanding that the "earth is round like a ball." The mapping operation is obstructed because the knowledge of the target concept contradicts the information which needs to be mapped from the source. When what is known about the target is consistent with the direction and nature of the required mapping, then the mapping can take place regardless of whether what is mapped is a descriptive property, a relational property, or an underlying structure.

Studies of analogy comprehension in our lab (Vosniadou & Ortony, 1983; Vosniadou & Schommer, in press) show that children readily map a structure from a source analog to a target domain when this structure is available in their knowledge of the source and is also consistent with what they already know about the target domain. In these studies children read texts introducing them to relatively unfamiliar concepts (e.g., an infection) using an explanatory analogy from a more familiar domain (e.g., war). Children are asked to recall the texts, to describe the information contained in them to another child, and to answer various inferential questions about them. Results show that kindergarten and second grade children are perfectly capable of mapping the relevant structural information from the source to the target. In other words, they are capable of understanding that in an infection, bacteria germs attack the body just like in a war, enemy soldiers attack a country.

Most revealing in this experiment are children's inferences. Children often go beyond the information given to make correct or incorrect inferences about the target domain based on their knowledge of the source. If children did not have the propensity to make relational mappings, we should expect most of these inferences to involve the transfer of descriptive properties. Contrary to this prediction, our results show that descriptive properties are rarely transferred but relational properties often are. Children do not infer, for example, that white blood cells look like people, wear uniforms or carry guns when they are told that white blood cells are like soldiers. On the contrary, they often say that white blood cells can die from an infection, that they feel sorry when they hurt the germs, that they think that the germs are bad, etc. While many of these mappings are clearly inappropriate, they do demonstrate children's propensity to transfer relational information from the source when this information does not contradict what is already known about the target concept.

In fact, if there is something children could be accused of, it should not be the lack of relational transfer, but overgeneralization and inappropriate transfer caused by lack of relevant constraints in their immature knowledge base. The phenomenon of overgeneralization and inappropriate transfer, common also to adults when using analogies in unfamiliar domains (Halasz & Moran, 1982; Spiro, Feltovich, Coulson, & Anderson, in press), is particularly characteristic of the thought of the preschool child, as Chukovsky's (1968) often hilarious examples amply demonstrate.

Finally, the claim that children may have the capacity to make relational mappings but not the propensity to do so is difficult to accept because the perceptual information for events, for linguistic structure, and for coordinated action that young children use to make sense of the world around them is primarily relational. Brown (in press) reviews much of the relevant literature on cognitive development and makes a persuasive argument for the claim that young children can not only transfer their knowledge on "deeper bases than mere appearance matches," but also for the primacy of relational information. The view that infants come predisposed to seek causal explanations and to uncover potential mechanisms is also a point discussed by Keil (in press).

In ending, it appears that both children and adults can see the similarity in the structure between two systems, concepts, or stories which are not similar in descriptive properties if their current representations of these systems already include the relative structures. Both children and adults can also map a structure from a source to a target system if their knowledge of the target is not inconsistent with such a mapping.[4] What develops is not the ability to engage in analogical reasoning per se, but, rather, the conceptual system upon which analogical reasoning must operate.

The Ability to Access a Productive Analogy

So far I have emphasized the importance of prior knowledge in analogical access and mapping. Obviously, it is not possible to identify the structural similarity in two systems if the relevant structure is not already present in one's representation of these systems. Instructional uses of analogy can augment and modify one's knowledge about the target system but in these cases the source analog is given, not discovered. How can an analogy be discovered and also lead to the acquisition of new knowledge, particularly knowledge about the explanatory structure of a system?

As was argued before, accessing a *productive* analogy cannot be based on the identification of the similarity in the structure of two systems. Rather, it must be based on some similarity in easily accessible properties between the two systems. Once access to a possible analogy has been achieved, the structure of the source can then be mapped onto the target to solve a problem, answer a generative question, provide a missing explanatory framework, or restructure the target concept. In the pages that follow some of these productive uses of analogical reasoning will be explored.

Transferring a structure from a within-domain example. The evidence that adults engage in analogical reasoning based on surface similarity to a within-domain example is abundant (e.g., see Anderson & Thompson, in press; and Ross, in press). This is particularly the case when people reason in unfamiliar domains where they lack general rules. Universal novices, as they are, children lack general rules and powerful domain-free problem-solving heuristics. As a result, they should be likely to use similarity-based analogical reasoning to solve problems and deal with everyday situations. Is there any evidence that children employ this kind of analogical reasoning?

According to Piaget (1962), reasoning on the basis of similarity to particular examples is the main form of reasoning for young children (2- to 7-year-olds). Here is an example of the kind of reasoning Piaget observed in his daughter Jacqueline at the age of 2 years and 10 months.

> Obs 111(6) at 2:10(8). J. had a temperature and wanted oranges. It was too early in the season for oranges to be in the shops and we tried to explain to her that they were not yet ripe. 'They are still green. We can't eat them. They haven't yet got their lovely yellow color.' J. seemed to accept this, but a moment later, as she was drinking her camomile tea, she said, *Camomile isn't green, it's yellow already. . . . Give me some oranges*. (Piaget, 1962, p. 231)

In this example the child uses the camomile as a base from which to reason about oranges. The reasoning is clear. The child takes camomile as the source from which to reason about oranges, possibly based on some easily accessible similarity between them (e.g., that they can both be yellow). The child then maps the explanatory structure of the "when you make camomile tea" to solve the problem of "when you can eat oranges" (see Table 1). Based on the similarities in this relational structure the child arrives at the inference that "if camomile has turned yellow, then oranges must have turned yellow too." And if oranges are yellow, it means that they are ripe and ready to eat, since there is a particular causal relationship between "yellowness" and "ripeness."

[Insert Table 1 about here.]

According to Piaget (1962), this type of reasoning based on similarity to particular "images" is characteristic of the preconceptual child and is inferior to both deductive reasoning and analogical reasoning proper which depend on a stable conceptual system and which develop at the stage of concrete operations. We now know that this view is not correct. Developmental research has shown that children are capable of forming consistent and stable classes from an early age and that they can reason deductively when the necessary knowledge is available (Carey, 1985a; Gelman & Baillargeon, 1983; Rosch, Mervis, Gay, Boyes-Braem, & Johnson, 1976; Smith, 1979; Sugarman, 1979). Alternatively, unlike Piaget's claims (1962), adults often reason on the basis of similarity to particular cases as the work of Tversky and Kahneman (1982), Rumelhart and Norman (1981), and Rumelhart (in press) can easily testify. In fact, the type of reasoning just described is similar to the kind of analogical reasoning described by Anderson and Thompson (in press), Ross (in press), Kedar-Cabelli (1985) and Carbonell (1983).

The analogical type of reasoning based on similarity discussed here is different from the probabilistic type of reasoning based on similarity identified by Carey (1985b). In her experiments, Carey asked children to decide whether certain animals had unknown properties like "spleens." Children below 10 answered this question by identifying the known spleen owner most similar to the object being probed, and by deciding whether that object had a spleen or not on the basis of its similarity to the retrieved exemplar. In the absence of a known causal relation between the existence of spleens and a particular property or properties of the base, the children in Carey's (1985b) experiments determined the probability that the target had the property in question (e.g., a spleen) on the basis of the number of shared similar properties between it and the source exemplar. This type of similarity-based probabilistic reasoning is similar to the reasoning discussed by Brooks (1978) and Smith and Osherson (in press). It differs from the similarity-based analogical reasoning discussed here, which involves the mapping of an explanatory structure. It appears that when there is no explanatory structure to be mapped, children (and adults) resort to similarity matches and apply some probabilistic reasoning on them.

Transferring an explanatory structure from a different domain. Adults often borrow an explanatory framework from a familiar domain in order to reason about a target system where an appropriate explanatory framework is missing. Presumably this is done on the basis of some similarity in easily accessible properties of the two systems. It has been shown, for instance, that people borrow a "sand and grain" model to reason about the behavior of molecules in water (Collins & Gentner, in press), or describe the workings of a home thermostat in terms of an analogy to a car accelerator (Kempton, in press). Our investigations of knowledge acquisition in the domain of observational astronomy (Vosniadou, 1987b; Vosniadou & Brewer, 1987a) have shown that not only adults but children are also capable of transferring an explanatory framework from a familiar to an unfamiliar domain. One such example is the use of people as a source analog from which to reason about the movement of the sun and the moon.

Preschool children have certain observational knowledge of the sun and the moon, but this knowledge cannot provide an explanatory framework for answering questions like "Where is the sun during the night?" "Where is the moon during the day?" "How does this happen?" "Why does the sun move?", etc. In order to answer such "generative" questions, children need to borrow an explanatory framework from a different domain. Very young children (2-3 year-olds) usually transfer an explanatory framework from the domain of people. The reason seems to be the sun's and moon's appearance of self-initiated movement. Because self-initiated movement is a characteristic of animate rather than inanimate objects, children feel compelled to explain it in ways appropriate to an animate object. They thus provide psychological explanations of the sun's movement (e.g., the sun hides behind the mountain, the sun went home to sleep, the sun plays with the moon, etc.), and attribute to the sun (and moon) certain human-like qualities related to the ability to move independently (i.e., intentionality, playfulness, fatigue, etc.).

It could be objected here that rather than thinking analogically, young children may simply fail to make a distinction between animate and inanimate objects. They thus attribute to the sun all the qualities that an animate object should have (e.g., see Piaget, 1962). This view is not consistent with research showing that children can observe the animate/inanimate distinction from very early on, (Carey, 1985a; Gelman, Spelke, & Meck, 1983). It also does not agree with our findings that children attribute to the sun *only* those human qualities which are associated with self-initiated movement, and no more. For example, the same children who say that the sun hides or sleeps to explain the day/night cycle, do *not* think that the sun can eat or drink, that it can read newspapers, or that it knows what people do during the day. Finally, additional evidence for the analogical nature of children's thinking comes from the fact that some children borrow an explanatory framework from the domain of inanimate objects rather than the domain of animate objects. These children explain the sun's or the moon's movement to have been caused by the push of the clouds or by the push of the air.

The type of analogical reasoning just discussed is not qualitatively different from the kind of analogical reasoning employed by adults when they borrow an explanatory framework from a different domain, such as the one found in the work of Collins and his colleagues (e.g., Collins & Gentner, in press; Collins & Stevens, 1984).

Restructuring the Knowledge Base

One of the most significant roles that analogy can play in knowledge acquisition is as a vehicle for theory change. Analogies have often been cited as mechanisms for theory change in science. This is particularly the case when dissatisfaction with an existing theory is high and its replacement with a new theory is actively sought.

It is sometimes difficult to determine whether it is the analogy itself that caused the restructuring or whether some restructuring of the knowledge base occurred independently and made it possible for the analogy to be accessed in the first place. One such case is found in Rutherford's planetary analogy of the atom. The accepted model of the atom before the time of Rutherford was known as the "plum pudding" model. As the name suggests, according to the "plum pudding" model, the atom consisted of a positively charged sphere (the "pudding") in which the negatively charged electrons (the "plums") were embedded (see Figure 1A). Rutherford's experiments showed that instead of being spread throughout the atom, the positive charge is concentrated in a very small region, or nucleus, at the center of the atom (see Figure 1B). Once one starts thinking of the positive charge of the atom as concentrated in a small mass in the center of the atom and the electrons being in the periphery, the similarity of the atom to the planetary system becomes quite salient. Once accessed, however, the adoption of the planetary analogy suggested possibilities about the structure of the atom which might not have been thought otherwise, thus further aiding the process of theory change.

[Insert Figure 1 about here.]

In other cases, access to an analogy which can lead to restructuring may be more fortuitous. Sometimes the perceived similarity in the formal equations used to describe two systems can become the vehicle for accessing a scientific analogy. In physics, identical equations can be used to describe fundamentally dissimilar systems. Scientists sometimes come across such similarities accidentally and it often requires quite a lot of courage to draw the implications of these similarities to their logical conclusions. One such example is that of DeBroglie's theory of matter-waves. DeBroglie noticed that Bohr's equations describing the orbits of electrons in an atom were the same equations used to describe the waves of a violin string. Taking this analogy seriously, he proposed a wave theory of matter which revolutionized atomic physics and became the foundation of quantum mechanics. Other examples include the well known similarity in the formal description of electromagnetism and hydraulics as well as that between a spinning top and the behavior of an electron (spin).

It is possible that children use analogical reasoning to restructure their knowledge base in ways similar to those of adults. We know that the spontaneous restructuring of the knowledge base does occur in children (Carey, 1985b; Chi, 1987; Keil, in press; Vosniadou, 1987b). But we still do not know how such restructurings occur and the role that analogical reasoning may play in them. This is an interesting area for future research.

Conclusions

The ability to identify within-domain or between-domain analogies and to use them to solve problems about an unfamiliar target system is present both in adults and in children. It appears that both adults and children are capable of seeing the structural similarity between two systems when the relevant structure is part of their representation of these systems. They also seem to be capable of using the similarity in salient properties between two systems to discover a productive analog. Both adults and children are knowledgeable about the network of causal relationships that exist between "surface" and "deep" properties of a system (such as the relationship between "yellowness" and "ripeness," or the relationship between "self-initiated movement" and "intentionality"), and capable of using the similarity in some of these properties as a vehicle for discovering an analogy. What develops does not seem to be the ability to engage in analogical reasoning per se, but the content and organization of the knowledge base on which analogical reasoning is applied. The richer and more tightly structured one's representation of a system is, the easier it becomes to see the structural similarities between it and other systems and the greater the possibility of identifying productive analogs. The developments of the knowledge base make it possible to access more and more remote analogs, to see the structural relationships between superficially unrelated systems, and to map increasingly complex structures. Thus, although critically limited by the information included in the knowledge base, analogical reasoning can act as a mechanism for enriching, modifying, and radically restructuring the knowledge base itself.

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Footnotes

[1]It could be argued that there is a way of turning some seemingly within-category comparisons into metaphors. For example, the statement "Chicago is the New York of the Midwest" appears to be metaphorical, although it juxtaposes two items (Chicago and New York) that do not belong to different conventional categories (both are cities). What is really juxtaposed in this metaphor, however, is *not* "Chicago vs. New York" but "cities of the Midwest vs. Cities of the East." This becomes evident if we consider that the statement "Chicago is New York" is unacceptable. In order to make a metaphor, the speaker must provide information to the listener about the relevant category which is being violated--in this case "Chicago as a city of the Midwest" versus "New York as a city of the East."

[2]The access process for the discovery of *productive* between domains analogies will be described in greater detail in future work. It is based on the assumption that in people's conceptual representations easily accessible properties (which can be either descriptive or relational in nature) are linked to less accessible ones in complex, causal, explanatory networks, such that the identification of similarity in one property can lead to the discovery of similarity in other properties and eventually in the discovery of structural correspondences between the two systems.

[3]See Michalski (in press) and Barsalou (in press) on what aspects of people's conceptual knowledge may be profitable to represent at the "base" level of conceptual representations and which at the "inferential" level.

[4]I do not mean to argue here that instructional analogies cannot be helpful in restructuring the knowledge base (see Vosniadou & Brewer, 1987). I think they can, but they cannot do the job of restructuring on their own. Additional help is required by a teacher who understands the discrepancies between the two inconsistent representations of the same concept and guides the student through the restructuring.

Table 1

REASONING ABOUT "ORANGES" ON THE BASIS OF THEIR SIMILARITY TO "CAMOMILE"

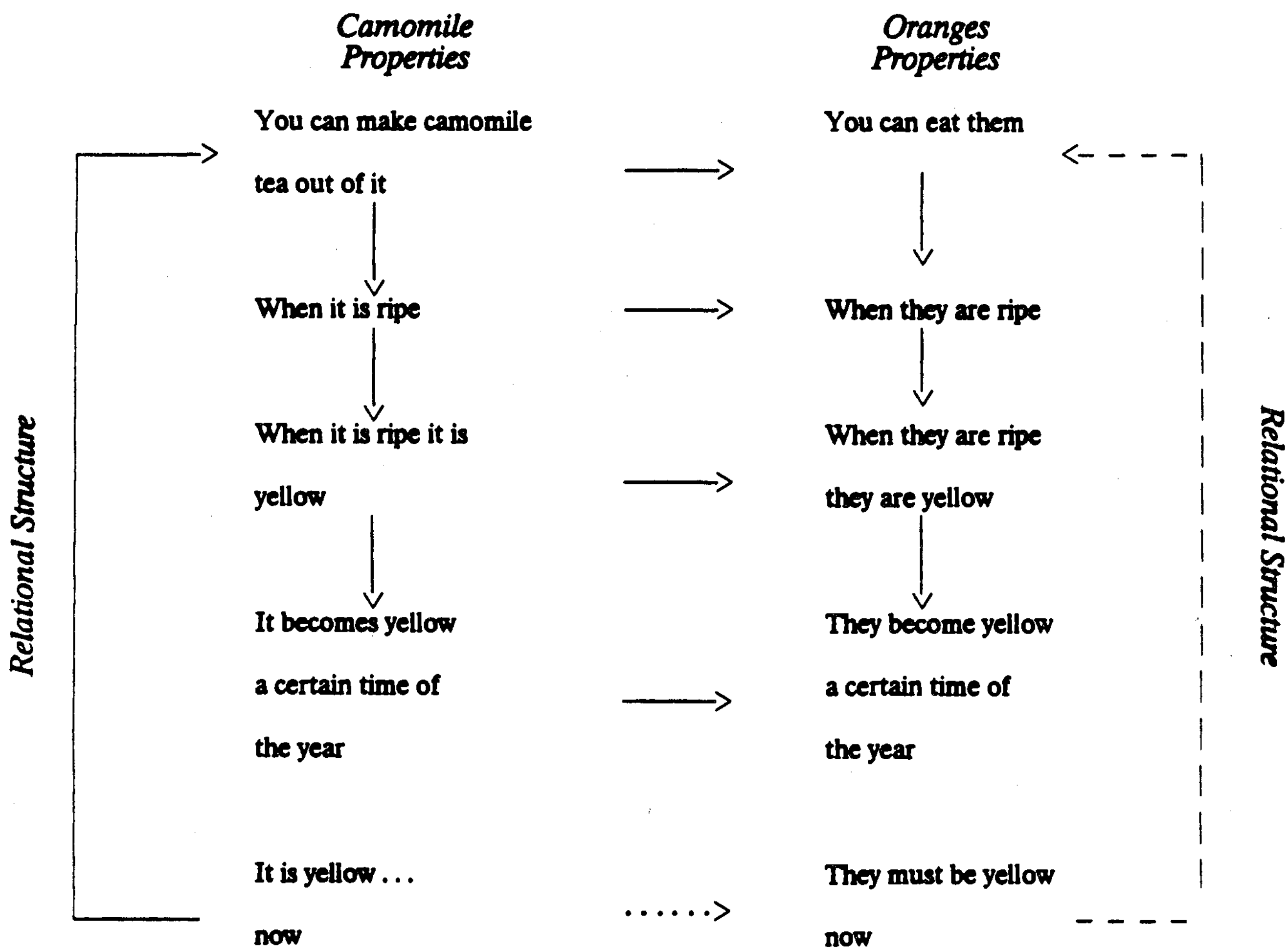

Figure Caption

Figure 1. Models of the Atom.

A: Thompson's "plum pudding" model of the atom

B: Rutherford's "planetary" model of the atom

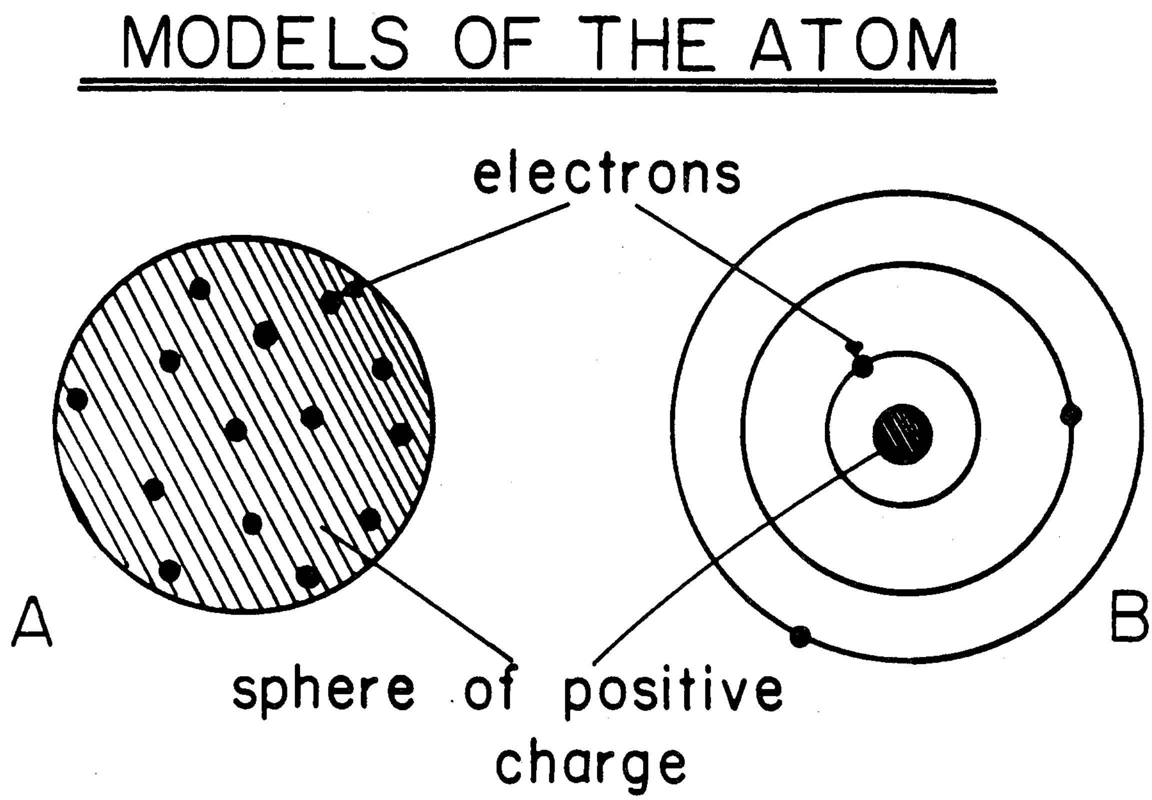

Figure 1