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Analogy is a notoriously difficult term to define. Dejong (1989) calls it a "seductive name," a "fuzzy concept that means different things to different people," yet one that seems to be "a fundamental component of intelligence" (p. 346). Most researchers would agree that at the core of this fuzzy concept lies relational reasoning: analogies involve reasoning about relations, in particular about relational similarity, so that a correspondence is established between one set of relations and another.

Collins and Burstein (1989) have identified three types of correspondence that may compare "fundamentally different" kinds of entities: systems, concepts, and properties. System correspondences refer to analogies such as that between the solar system and an atom (Centner, 1983), in which the sun corresponds to the nucleus, the planets to the electrons, and the relations of attraction and centrifugal force that cause the planets to orbit the sun and the electrons to orbit the nucleus are common to both. Concept correspondences refer to decisions about the properties of two concepts, such as whether an is a y, and property correspondences compare a particular property of two concepts, such as whether a 3-inch disc is more like a quarter or a pizza. It is only system correspondences that require a correspondence to be established between both objects (the sun, electrons) and properties or relations (orbiting), and Collins and Burstein's analysis suggests that it is with system correspondences that research into analogical reasoning is mainly concerned.

This definition allows analogical reasoning to encompass problem solving (using the solution to a known problem to solve a structurally similar problem), relational mapping (e.g., recognizing the relational similarity between the solar system and an atom [Centner, 1983] and using one to understand the other), school procedures such as the use of Cuisenaire rods to represent the decimal number system, and even representation in general (a representational system requires that "some relations in the represented world are structurally preserved in the representing world"; Palmer, 1978, p. 267). Clearly, it is beyond the scope of this review to consider developmental research in all of these areas. Instead, we will focus here on research that has specifically set out to measure the development of analogical ability. In practice, it can be argued that this research has studied a subset of system mappings.

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Measuring Analogical Reasoning

Psychologists have measured the development of analogical reasoning in children in two ways. The traditional measure, taken from IQ tests, is the $a:b::c:d$ task, which seeks to capture the classical definition of analogy as "an equality of proportions ... involving at least 4 terms ... when the second is related to the first as the fourth is to the third" (Aristotle; *Metaphysics*, cited in Pellegrino, 1985, p. 198). An example would be *bicycle: handlebars::ship:ntdder*. More recently, psychologists have investigated children's ability to reason by analogy in problem-solving tasks. The analogy depends on a similarity of relational structure between a problem that has already been solved (the base) and a new problem (the target). A popular problem analogy is Duncker's "radiation problem"; the target problem is the destruction of a malignant tumor using strong rays but without destroying healthy body tissue, and the base problem is the destruction of an enemy fortress without sending a heavy army along mined approach roads (Gick & Holyoak, 1980, 1983). The analogous solution is to converge a number of weaker forces on the tumor/fortress.

How good are young children at reasoning by analogy? The answer seems to depend on the measure used. Younger children have been shown to perform very poorly in classical analogy tasks. Piaget (Piaget, Montangero, & Billeter, 1977) gives an example of a 3-year-old, Can, who has arranged four pictures into the analogical sequence *bird: feathers::dog:hair*. He is asked why the pairs of pictures go together. Can replies it is because "the dog eats the bird, those are the feathers!" (p. 118). This apparent ignorance of analogical relations contrasts sharply with the performance of 3-year-old Aaron (Brown, 1989, p. 393), who has just reasoned that the hawkmoth caterpillar (which can look like a poisonous snake to deter predators) and the porcupine fish (which can double its size and raise spikes to deter predators) have evolved analogous solutions to the problem of avoiding predation:

EXPERIMENTER: ... are they the same kind of stories?
AARON: Yes, they are the same ... Both of them have a mean guy that wants to eat them all up. . . . They both get mean and scary so they [the predators] run away!
EXPERIMENTER: They're pretty smart, huh?
AARON: Just like me!

Development

What do these two examples suggest about the development of analogical reasoning? To date, the discrepancy in performance in the two tasks has received little developmental analysis. Failure in classical analogy tasks has been attributed to the late developmental appearance of the ability to reason about "higher-order" relations, the relations linking the two halves of the analogy ($a:b$ and $c:d$). Success in problem analogies has been attributed to techniques that encourage children to focus on relational similarity, either through direct instruction or by the use of highly similar base and target problems. However, if analogical reasoning is common to both tasks, the discrepancy in performance is puzzling.

There are at least three alternative developmental possibilities in explaining performance in the two tasks. One is that analogical reasoning does not actually develop, at least beyond age 3. Analogical reasoning may be available from the very earliest stages yet assessed, and failures to demonstrate analogical reasoning, for example, in Piaget's tasks, may reflect task artifacts and the type of knowledge that the child is required to reason about. This developmental notion predicts that if children are presented with analogy tasks that they understand and are asked to reason about knowledge that is familiar, then they will display competent analogical ability.

Such a position would fit with knowledge-based theories of logical development, such as that of Keil (1989). Both Brown (1982, 1989) and Vosniadou (1989) have adopted a version of knowledge-based theory in explaining what develops in analogical reasoning. Brown (1989) links her explanation to constraints on learning, suggesting that the search for causal explanation is a powerful learning mechanism from very early in life, so that if there is relational similarity at the level of causal structure and children have the relevant domain knowledge, analogical transfer will be rapid. Vosniadou states that "what develops is not the analogical mechanism itself but the conceptual system upon which this mechanism operates" (p. 414).

A second possibility is that analogical reasoning does develop, and that apparent early competence is an artifact of the experimental task. Structural theories of development, such as that of Piaget, are representative of this kind of developmental explanation. Analogical reasoning may be a late-developing skill, consequent upon the development of earlier cognitive structures and the emergence of higher-order skills. To demonstrate true analogical ability, analogical reasoning tasks should include stringent crite-
ria such as the ability to resist false counter-suggestions that destroy the analogy. This explanation would predict that children in Brown's paradigm may not have been able to maintain analogical reasoning in the face of such criteria.

A third possibility is that both positions are true: children may be able to reason by analogy at an early age, but there may also be later qualitative developments in analogical reasoning. This position has been adopted with respect to logical development by Moshman (1990), who argues that despite impressive early logical competencies, there is still a role for development in explaining logical ability. For example, whereas young children may be able to successfully solve transitive inference tasks, only older children may be able to explicitly distinguish premises from conclusions and purposefully use inference to generate the latter from the former.

Two Types of Analogy?

There is an alternative and nondevelopmental explanation for the difference in the performance of 3-year-old Aaron and 5-year-old Can in the two tasks described above. The two kinds of analogy may require quite different kinds of reasoning. Collins and Burstein (1989) distinguish classical analogies and problem analogies by the number of elements that have to be mapped. They suggest that classical $a:b::c:d$ analogies involve four-element comparisons, requiring both within-group comparisons between the $a:b$ and $c:d$ terms, and between-group comparisons between the $a$-$b$ and $c$-$d$ terms. For example, in the analogy $\text{wolf:dog::tiger:cat}$, the within-group comparisons concern a "wildness" dimension, the between-group comparisons a "feline or canine class membership" dimension (p. 554). Piaget would call these lower-order and higher-order relations, respectively. By Collins and Burstein's analysis, problem analogies are only two-element comparisons, as there is a single source item (which can be a system, concept, or property) to be compared with a single target item. An example would be Gick and Holyoak's fortress-ray problem. This raises the possibility that problem analogies are simpler than classical analogies and so are solved earlier developmentally.

Holyoak (1984) notes that it is possible to describe an analogy between a base problem and a target problem in the classical format, that is, $\text{Problem}_R:\text{Solution}_R::\text{Problem}_T:\text{Solution}_T$. However, Holyoak's own view is also that the two kinds of analogy are different. They are functionally different: the task format in classical analogies makes it clear that analogical reasoning is required, and the goal is to solve the analogy, whereas in problem analogies the goal is to solve the problem and the skill lies in noticing that an analogy is required. They are also structurally different: the relations in classical analogies are frequently arbitrary, whereas those in problem analogies are causal. This second difference is more apparent than real, however, as classical analogies based on causal relations have been used developmentally, notably by Piaget. In fact, Holyoak himself notes that in spite of these differences, "I would expect to find a substantial positive relationship" between performance in the two tasks (p. 225).

The possibility that classical and problem analogies are measuring different skills should be kept in mind as we review current theories of analogical development and the evidence on which they are based. Three major theories have been identified for the purpose of this review: Piaget's structural theory, Stemberg's information-processing theory, and Centner's structure-mapping theory. Piaget's and Stemberg's theories are based on evidence from classical analogy-tasks, whereas Centner's relies on problem analogies. All three theories suggest a different view of what develops in analogical reasoning: Piaget offers a stage-based view, Stemberg appears to suggest that what develops is the efficiency of the different information-processing components involved in analogical reasoning, and Centner holds a position that attributes some developmental importance to structural change (the ability to reason about relational systems) while maintaining a role for the knowledge base of the child. Let us look at the theories.

Theories of Analogical Development

1. PIAGET: A STRUCTURAL STAGE MODEL OF ANALOGICAL REASONING

Piaget argues that reasoning by analogy is a developmentally sophisticated skill, being a perfect example of the development of formal operational structures. These cognitive structures emerge only in early adolescence. The prerequisites for analogical reasoning are a succession of abstractions made during the preoperational and concrete operational periods. These theoretical claims are based on a series of studies conducted with Montaner and Billeter (Piaget et al., 1977).

The Task

The task adopted by Piaget and his coworkers was an ingenious picture-based ver-
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ation of the classical $a:b::c:d$ analogy task, enabling even very young children (5 years and up) to be tested. The first stage in the task was to ask the children to sort sets of pictures into "pairs that go together." This first sort tested the ability to correctly relate the $a$ and $b$ terms and the $c$ and $d$ terms: these sets of relations were called "lower-order" relations to distinguish them from analogous "higher-order" relations.

The children were then asked to sort the pairs into "sets of four that go together." This second sort tested the ability to form analogies. The pictures were of objects and parts of objects, such as dog, hair; bird, feathers; ship, rudder; bicycle, handlebars; and vacuum cleaner, plug. The lower-order relations between these pairs seem to be mainly associative, while the higher-order relations are causal.

If children did not find pairing the pairs of pictures easy (the analogy task), hints were provided. For example, the pair bird:feathers ($a:b$) might be placed in front of the child, and the experimenter would say, "What helps the bird to keep warm?" "The feathers." The picture of the dog ($c$ term) was then placed underneath the bird, and the child was asked, "Which picture would go well here [indicating the space for $d$]? Try and choose what is to dog as feathers are to bird." If the child still could not choose correctly, three possible alternative pictures were offered from which a $d$ term had to be selected. So a generation task was succeeded by a multiple choice task.

If analogies were formed successfully, the ability to resist counter-suggestions was tested. Thus for the analogy bicycle:handlebars::ship:rudder, the child might be asked, "Would a bell also go with the bicycle? Then what would you have to choose for a ship?" (a siren), and so on. The ability to resist false counter-suggestions was theoretically important in demonstrating true analogical understanding.

The Stages

Based on children's performance in the picture-sorting task, Piaget was able to define three broad stages in the development of reasoning by analogy. These were:

Stage I (preoperational)—In stage I, responding was egocentric, and children used quite idiosyncratic relations to relate the $a$, $b$, $c$, and $d$ terms in an analogy. We have already seen an example of this in Can's cheery justification for relating bird:feathers::dog:hair: "The dog eats the bird, those are the feathers!" (Piaget et al., 1977, p. 118). Piaget noted that the properties used to pair the $a$ and $b$ terms and the $c$ and $d$ terms at this stage were so variable that they could not be inserted into a fixed framework of classes and subclasses. As the so-called lower-order relations could not be identified consistently, it was impossible to link pairs of terms analogically via the construction of higher-order or analogical relations.

Piaget identified two substages during stage I. In stage IA, children were completely unable to form even lower-order relations. Responses typical of a stage IA child can be illustrated by Cou (5-3). He would occasionally come up with the correct lower-order relations in the first pairing task (bicycle-handlebars), but would more often use egocentric relations such as ship-bird: "Because you can sometimes see birds at the lake"; or vacuum cleaner-ship: "Because it looks like a ship" (Piaget et al., 1977, p. 117). However, it should be noted that the "correctness" of the lower-order relations depends on the child choosing pairs of terms in the way intended by the experimenter. The association of bird with ship does not seem any less correct than the intended association of ship with rudder.

In stage IB, some children were able to form lower-order relations correctly, but they could not go on to build analogies. The already familiar Can (5-8) provides an illustration for this stage. He chose to pair bird:feathers ("otherwise it can't fly"), hoover:plug ("else one can't hoover"), and bicycle:handlebars ("so it can go"). However, he could not pair these pairs of pictures analogically, for example, choosing to combine car:petrol with bicycle:handlebars. His justification ("This is a car, this is a bicycle, both are for traveling on the road") does link the two halves of the analogy, but focuses only on the $a$ and $c$ terms (Piaget et al., 1977, p. 118).

Yet, paradoxically, Piaget does report occasional evidence for analogical reasoning in stage I children. The children who showed successful reasoning seemed to understand the causal relations necessary for constructing the higher-order or analogical relation. Cou (stage LA) was able to pair bicycle:handlebars and ship:rudder, explaining that they go together because "that's for steering" (Piaget et al., 1977, p. 117). As Cou knew about the steering mechanisms of bicycles and ships, he could construct the analogy. These signs of early competence are inconsistent with a strict interpretation of the stage model.
Stage II (concrete operational).—During the second stage in the development of analogical reasoning, children showed occasional success in analogy tasks. There were again two substages. In stage IIA, children could sometimes construct higher-order relations through a process of trial and error. However, they were unable to exclude false counter-suggestions for the d term that destroyed the analogy. In stage IIB, children became able to reject counter-suggestions, but still could not do so consistently.

A typical IIA performance is given by Mag (6-9). Mag was easily able to pair all the pictures in the first sorting task, and also formed analogies without difficulty. For example, when given the pair bird-leathers and asked to form an analogy, he immediately chose the pair dog:hair. His reason for doing so was that they were “two animals,” and he was able to explain that the relationship between feathers and hair was that “they are both what animals have on them” (Piaget et al., 1977, p. 120). He also correctly paired boat:rudder with bicycle:handlebars. However, for this analogy he was quite happy to accept the false counter-suggestion bicycle: pump as a replacement for handlebars, saying that pump could be used “to blow up the tires.” He agreed that both the pump and the handlebars would go with the boat.

Piaget argued that the increasing stability of the lower-order relations used by the children during stages I and II was controlled by the development of the same ability that enabled the growing recognition of higher-order relations. This was the ability to construct classes. The construction of classes was completely absent from stage I, but in stage II enabled the children both to consolidate elementary relations between terms and to consider their extension and their common qualities. This enabled the application of class-type relations to pairs of terms, and so the onset of the ability to form analogies.

Mag seemed to understand all the higher-order relations used in the analogies and was also able to consider the extension and common qualities of classes, as shown by his explanation that feathers and hair are related by being “what animals have on them.” It was only his willingness to accept false counter-suggestions that prevented him from being attributed with full analogical understanding. However, this willingness to accept false counter-suggestions may not be a good test of analogical understanding. Children’s unwillingness to contradict adult experimenters has been documented in a variety of paradigms (e.g., Donaldson, Grieve, & Pratt, 1983). Mag’s acceptance of the pair bicycle: pump may thus reflect social-situational or linguistic features of the experimental set-up rather than shaky analogical understanding.

Stage III (formal operational).—Entry into stage III marks the emergence of full analogical ability, identified by the ability to extract and use higher-order relations. Children at this stage were also able to imagine alternative permissible relations without difficulty, and understood that analogies could be expressed as mathematical proportions, using “= ” (e.g., plug/hoover – petrol pump/car).

It is clear that Piaget’s theory of the development of analogical reasoning in children closely mirrors his more general theory of cognitive development. The same three stages are evident, and in spite of the fact that the major hurdles preventing analogical understanding seem to be passed during the concrete operational period, it is claimed that “true” analogical reasoning does not emerge until formal operations. This claim seems theoretically rather than empirically motivated. Recent evidence that children can understand the extension and common qualities of classes even before the period of concrete operations (Gelman & Baillargeon, 1983) further weakens the basis for this stage model.

Evidence for Piaget’s Theory

In spite of this theoretical problem, experimental evidence apparently consistent with Piaget’s model is not difficult to find. A large number of studies seem to support the claim that children are unable to reason by analogy until the formal operational period. The developmental milestone is usually identified as the ability to reason about higher-order relations. This term is never satisfactorily defined, but usually implies that children have the ability to recognize that the relations linking the α and β terms and the γ and δ terms are similar. This recognition is measured in most experiments by the ability to solve a:b::c:d analogies correctly, and additionally in some by the ability to verbalize this relational similarity.

Lunzer (1965) gave boys aged from 9 to 17 years verbal and numerical classical analogies to solve of different levels of difficulty. Examples of the verbal analogies are “Black is to white as hard is to steel/stone/solid/soft/blue” (level A, easy), and “Leather is to soft/shoe/hide as hard/clay/house is to brick” (level D, hard). Numerical analogies included 3:1, 9:7, 10:8, 4:7, 5:125, 4:64, 2:8,
Lunzer found that the 9-year-olds could only solve about 30% of the verbal analogies, even considering only the easiest verbal problems. Performance only rose above 50% after the age of 11-12 years. For the numerical analogies, the performance of the youngest boys was even worse, rising from 12% correct at age 9 to 50% correct by ages 11-12. Lunzer concluded from these results that "even the easiest verbal analogies of this form are beyond children at the concrete level of reasoning" (p. 40). He followed Piaget in concluding that the main barrier to analogical reasoning concerned the "apprehension of second-order [higher-order] relations" (p. 41).

Lunzer's study seems to support the notion that analogical competence is found only after the stage of formal operations has been entered, as this was when children began to solve most of the analogies. However, the problems that Lunzer used also tested the possession of other skills, such as mathematical skills, which are separate from the ability to reason analogically. This makes interpretation awkward, as a child who does not know about (for example) cubing numbers will be unable to extract this relation from a series of numbers such as 5:125, 4:64, etc. and use it to solve the analogy. Without a control task to measure understanding of the relations necessary to solve the analogies, it cannot be assumed that failure in Lunzer's tasks is evidence for an inability to reason by analogy.

Levinson and Carpenter (1974) made the interesting point that two different types of analogy are given to young children in standardized testing situations: "quasi-analogies" and "true" analogies. In quasi-analogies, in which children often do very well, the higher-order relations in the analogy are specified for the child (e.g., "A bird uses air, a fish uses ?"). In true analogies, the higher-order relation between the $a:b$ term and the $c:d$ term is left to the child to work out ($Bird:air::fish:$ ?). Levinson and Carpenter argued that younger children's apparent success in solving some of the analogies included on standard intelligence tests occurred because these tests used quasi-analogies rather than true analogies. They then set out to test this claim experimentally. Their prediction was that children under 12 years of age should be able to solve quasi-analogies but not true analogies, whereas children over 12 years of age should be able to solve both kinds of problem.

Levinson and Carpenter tested their hypothesis by giving children aged 9, 12, and 15 years verbal analogies to solve, which were either quasi-analogies or true analogies. The same items were used for each type of analogy, and vocabulary level was controlled at 3 years below the subjects' chronological age. Word association was also controlled, so that the $d$ term used was a very low associate of the term, association being around 0.08. Consistent with their predictions, they found that the 9-year-olds performed significantly better with the quasi-analogies than with the true analogies, whereas the 12- and 15-year-olds were equally good at solving both. The 9-year-olds also performed significantly more poorly than the 12- and 15-year-olds overall.

Levinson and Carpenter argued that the 9-year-olds showed an emerging ability to reason by analogy, but that the difference in performance with quasi-analogies and true analogies still indicated a developmental difference of some kind compared to the older children. However, their data are clearly inconsistent with Piaget's claim that children cannot solve analogies before the period of formal operations. Their finding that the 9-year-olds could solve true verbal analogies 50% of the time even when word association and vocabulary level were controlled is very striking. There was also a transfer effect: children who received the true analogies after the quasi-analogies solved more of these analogies at all ages. This transfer effect is evidence that performance with the true analogies is at least partially dependent on knowledge of the relations necessary to solve the analogies correctly. When children had learned about the relations in the quasi-analogy task, they were able to solve more analogies in the more difficult "true analogy" format.

Gallagher and Wright (1977) followed Lunzer in using a multiple choice task to study the development of analogical reasoning. They were critical of Piaget's use of pictures to form classical $a:b::c:d$ analogies, arguing that pictures forced the children to attend to "observables," a factor that might impede analogical solution. Instead they gave children written word problems to solve, also asking them to provide a written explanation for their choice of answer. An example of a word problem would be "automobile is related to gas as sailboat is to (travel/wind/sails/rudder)." A plausible counter-suggestion was included as one of the distractors (e.g., "sails").
Gallagher and Wright found that improvement in analogical solution was strongly related to age, with the older children solving more analogies than the younger children. They then calculated the percentage of "symmetrical responses" given in the written explanations of the children's answers. A symmetrical response was one based on a comparison between both halves of the analogy, and was intended as an index of the ability to reason about higher-order relations. In contrast, a response based only on the relations in the second (c:d) half of the analogy ("asymmetrical") was taken as evidence for an inability to appreciate higher-order relations. An example of a symmetrical response is "an automobile gets its energy from gas and a sailboat from wind. They both need something to make them go." An explanation such as "you need a rudder for the boat" would be scored as asymmetrical.

Gallagher and Wright found that the number of symmetrical responses increased with age, and that the percentage of symmetrical responses was a significant predictor of analogical performance even when IQ was partialed out in a multiple regression analysis. They took this as evidence that symmetrical responding was a reliable index of the ability to use higher-order relations. Another possibility is that "symmetrical responding" provides an index of children's knowledge of the relations required to solve the analogies. Older children know more of these relations, and so can solve more analogies. As Gallagher and Wright did not control for age in their regression analysis, the relation between symmetrical responding and analogical performance could simply be due to both skills being related to age.

In a related paper (Gallagher & Wright, 1979), they considered the possibility that the relations used in different analogical problems could affect performance. They identified two types of analogy among the problems used in their first study: concrete, in which solution was based on directly "observable" features; and abstract, in which solution was based on "higher-order rules." A concrete item would be picture is related to frame as yard is to (swings/tree/children/fence). An abstract item would be food is related to body as rain is to (wateri/storm/coat/ground).

Children aged from 9 to 12 years were given 10 items of each type of analogy, and were asked for written explanations of their answers as before. Gallagher and Wright found that abstract items were significantly more difficult than concrete items. Children of all ages studied were able to solve most of the concrete items, but performance on abstract items improved with age. The percentage of symmetrical explanations also improved with age. Gallagher and Wright concluded that a shift in performance on abstract items occurred at around 12 years of age, when higher-order relations were understood (more symmetrical responses given), their results thus providing support for Piaget's model.

Curiously, Gallagher and Wright do not accept successful performance with the concrete analogies as evidence for analogical ability. They explain the younger children's success with concrete items by arguing that these analogies can be solved by association, a lower-level form of reasoning that does not require an understanding of higher-order relations. As we shall see when considering componential theories of analogical reasoning, the idea that younger children's success in analogy tasks is due to associative reasoning is a popular one. However, in the concrete analogy picture is related to frame as yard is to (swings/tree/children/fence), the response tree also seems to be a plausible associate for yard. Without independent evidence for the associative claim (such as associative norms for the different answer options), the successful performance of the younger children is not easily dismissed.

Most of the evidence usually cited in support of Piaget's position is therefore open to alternative interpretations. The failure of younger children to reason by analogy in the a:b::c:d task has a number of possible causes, but it is particularly noteworthy that control tasks checking that the children possessed the relational knowledge required to reason by analogy were omitted from all the above studies. Hence all the studies purporting to support Piaget's theory may in fact provide evidence for a knowledge-based view of what develops in reasoning by analogy.

Recent Studies Testing Piaget's Theory: Is a Knowledge-based Explanation of Failure Warranted?

If young children are failing in Piaget's and similar tasks because they lack knowledge of the relations required to solve the analogies rather than because they are unable to reason about higher-order relations, a clear prediction emerges: children should be able to solve classical analogies if the analogies are based on relations that are already part of their knowledge structures. Recent studies
have tested this prediction in a number of ways. We recently provided a test by designing analogies based on physical causal relations such as cutting and melting (Coswami & Brown, 1989). Understanding of these relations is known to develop between the ages of 3 and 4 years (Bullock, Gelman, & Baillargeon, 1982; Das Gupta & Bryant, 1989).

Following Piaget, we designed a pictorial version of the $a:b::c:d$ task, but unlike Piaget we always used a multiple choice format. Our pictures were arranged in a horizontal sequence rather than in a $2 \times 2$ matrix, and children were provided with a choice of five possible $d$ responses to complete each $a:b::c:?$ sequence. These distractors were chosen to be indicative of different solution strategies.

The analogies were constructed using pictures of familiar objects that had undergone a causal change, such as playdoh:cut playdoh::apple:cut apple; or car:wet car::hair:wet hair. The higher-order relation was one of causal identity, following Piaget. The distractors included a "mere appearance" match that looked physically similar to the term (e.g., apple:banana, hair:beard), an incorrect object with the correct causal transformation (e.g., cut apple-cut bread, wet hair-umbrella), and the correct object with a nonanalogical causal transformation (e.g., cut apple-bruised apple, wet hair-cut hair).

In our first experiment (Goswami & Brown, 1989), children were simply asked to "choose the picture to finish the pattern. Try and work out how the pattern goes." They thus had to deduce that analogical matching was required. The children named all the pictures prior to the task to ensure that they understood them. Three-, 4-, and 6-year-olds were tested.

Following the Induction task, the children were given the analogies a second time, now with feedback after each problem. After completing each analogy, children were told whether their answers were correct or incorrect, and the analogical basis for each solution was explained. A causal reasoning control condition was included in the experiment to check that the children knew the causal relations on which the analogies were based.

The 4- and 6-year-olds proved to be highly successful in the analogy task, with over 90% succeeding in solving at least of the analogies successfully ($p < .01$, using the Binomial expansion) in the Explanation (feedback) condition. The 3-year-olds were less successful, but even here 50% succeeded in solving a significant number of analogies in the Explanation condition. Conditional analyses showed that successful performance in the Analogy task was significantly related to knowledge of the causal relation on which a given analogy was based, measured by the control task. This is strong evidence for the relational knowledge hypothesis: even 3-year-olds are able to reason by analogy if they have knowledge of the relations necessary for solving the analogies. The ability to reason by analogy is not a formal operational skill.

To examine the solution strategies that led to incorrect performance, an analysis of the errors was carried out. This analysis showed that the most frequent incorrect choice was the distractor picture of the correct object with an inappropriate causal transformation (e.g., a bruised apple for the analogy playdoh:cut playdoh::apple:cut apple). This error could either reflect faulty causal knowledge or the use of similarity matching based on appearance. The actual "mere appearance" match (a ball in the case of the apple) was not chosen very frequently. It is also possible to argue that similarity cues might be supporting analogical reasoning to some extent, as the same object was depicted in the $a$ and $d$ terms of each analogy (e.g., apple:cut apple), in contrast to Piaget. However, this support cue cannot completely explain children's success in the Analogy task, as a similarity explanation would predict roughly equal selection of both the Analogy and Wrong Causal Transformation responses, which was not found.

To clarify the basis for correct solutions, the study was repeated using the same physical causal relations but with new picture items in which the $a$ and $d$ terms did not depict the same objects as the $a$ and $d$ terms. For the wetting analogy, for example, the new sequence was instant coffee granules: mug of coffee::soap powder-soapy water (Appearance Differs analogies). The original analogies were also administered as a comparison (Appearance Same analogies). If similarity is supporting analogical performance to some extent, then children should perform significantly more poorly with the former analogies than the latter.

Interestingly, this did not occur: all the children performed as well with the new (Appearance Differs) analogies as with the old (Appearance Same) analogies. So successful performance in Experiment 1 was due to the correct extraction and application of the
causal relations: the children were truly reasoning by analogy. To distinguish between errors due to faulty causal knowledge and to mere appearance matching, a new distractor item was included: an identity match for the term. This provides the best possible mere appearance match, yet the most frequent error was again the correct object with the wrong causal transformation, even though this now frequently shared few surface features with the term (it was a glass of Kool-aid for the new wetting analogy). So even the children who did not solve the analogies successfully were focusing on causal relations in our analogy task.

The ability of even 3-year-old children to solve analogies based on physical causal relations shows that Piaget's claim that children are unable to reason by analogy until the formal operational period is wrong. When children understand the relations on which classical analogies are based, they find reasoning by analogy straightforward. A number of other studies have provided evidence for this claim by using perceptual analogies based on geometrical shapes. Children as young as 4 years of age are able to solve analogies such as large red circle:small red circle:large blue square:small blue square (Alexander, Willson, White, & Fuqua, 1987), using the relations of color, shape, and size; or half circle:half rectangle:quarter circle:quarter rectangle (Goswami, 1989), using the relation of proportion. Hence, a knowledge-based account of the development of classical analogue reasoning seems at least plausible. We will return to the issue of what develops in the discussion.

2. COMPOXENTIAL THEORIES OF ANALOGICAL REASONING

A rather different approach to studying the development of analogue reasoning in the analogical reasoning paradigm has been taken by information-processing theorists, notably Sternberg (Stemberg & Nigro, 1980) and Goldman and her co-workers (Goldman, Pellegrino, Parseghian, & Sallis, 1982). These authors have attempted to identify the different component skills underlying reasoning by analogy in the classical paradigm. While information processing is really a methodology rather than a theory, this work does ask a developmental question, namely, whether developmental differences in analogical ability arise from differences in the execution of these various component skills. Stemberg's componential theory of analogue reasoning, originally devised for adults (Stemberg, 1977) but later applied to children (Stemberg & Downing, 1982; Stemberg & Nigro, 1980; Stemberg & Rifkin, 1979), will be discussed first. Componential work based solely on adult subjects (e.g., Alderton, Goldman, & Pellegrino, 1985; Grudin, 1980) will not be discussed.

The Components

Stemberg suggested that six different components were involved in analogical reasoning. The first was encoding the terms of the analogy, so that the subject could establish the semantic extensions of the terms. The second was inferring the relation between the a and b terms, which was followed by mapping or discovering the relation between the a and d terms. A relation analogous to this one then had to be applied to the b term to generate a solution for the analogy. The goodness of match of this candidate d term had to be justified, and a response made.

Evidence for the Componential Theory

Stemberg and Rifkin (1979) decided to test the componential theory of analogue reasoning developmentally by asking children aged 8, 10, and 12 years to solve analogies based on schematic figures. These figures were of two kinds: those based on "separable" attributes (composed of little men who varied in the kind of hat they wore, the pattern of their suits, their footwear, and their garment color), and those based on "integral" attributes ("people piece" analogies: figures who varied in their sex, height, weight, and garment color).

In each experimental session, children were given 12 analogies to solve, these being either integral or separable. Three sessions were devoted to each kind of analogy, and the children were given 64 sec to complete each block of 16 problems. Developmental differences were expected to arise from five different sources: the availability of the different component skills, children's ability to combine the different components, the number of repetitions of individual components, children's consistency in adopting different solution strategies, and the ability to carry out the different components as fast and as accurately as possible. It is notable that only the first of these relates uniquely to reasoning by analogy. The others would apply to the components underlying any cognitive task.

In each analogy item, the children were shown the schematic figures for the a, b, and terms and were then given a choice of two possible figures for the d term. An example of a separable item would be a man with boots, a
Evidence that younger children succeed in analogy tasks by using associative reasoning has been presented by many authors (Achenbach, 1970, 1971; Gentile, Tedeschi; and Berman, 1978). Stemberg and Rifkin argued that this development took place serially rather than in parallel. However, this did not seem to matter developmentally in their task: relational difficulty did not interact with age. Item format did interact with age: the 9- and 12-year-old children showed no increase in response time as the number of inferences required by the analogy form increased, whereas the older children took longer to solve the more complex analogies (types II and III). Furthermore, inference difficulty was correlated with speed of response for the two older groups, whereas the degree of association between the correct d term and the c term was correlated with speed of response for the 9- and 12-year-olds. Stemberg and Rifkin argued from this that the younger children "rely heavily on association in analogy solution . . . association is used, at least to some extent, as a substitute for full reasoning by analogy" (p. 34). In contrast, "older children appear to rely almost exclu-
sively on reasoning processes in analogy solution."

Developmentally, therefore, Sternberg and Nigro are tending toward a structural explanation of analogical development, with reasoning at first being associative and later analogical. However, they do not fully commit themselves to a stage model: "two levels of performance appeared in the solution of verbal analogies. In a first level, whose occurrence coincides roughly with concrete operations, solution is primarily but not exclusively associative: Association affects but does not wholly control analogy solution. Reasoning in this stage is incomplete rather than absent.... In a second level, whose occurrence coincides roughly with the ages associated with formal operations, children and adults fully relate the first half of the analogy to the second half" (p. 36). Thus Piagetian stages are implicated, but partial analogical competence is granted to the younger children.

Goldman and her co-workers (Goldman et al., 1982) hypothesized that relational inference might be an important source of developmental differences in analogical reasoning. They suggested that the difficulty in inferring a relation for younger children might indicate a general lack of attention to the α and b terms in the analogy. They thus used a version of Steinberg’s componential theory to try and study in more detail the source of developmental differences in reasoning by analogy. The components that they identified were inferring the relation between α and b, applying the inferred relation to c, recognizing the correct d term, and the amount of distraction that occurred from alternative d responses.

Goldman et al. gave 8- and 10-year-old children verbal analogies to solve of the kind used by Stemberg, but in two different tasks: generation, in which a d term had to be generated from the stem a:b::c: ?, and forced-choice (given 2 weeks later), in which the same analogies were presented with five alternative solutions. They found that the 10-year-olds were significantly better in both tasks than the 8-year-olds. The older children were also more likely to select the correct solution for an analogy item in the forced-choice task after having generated an incorrect response in the generation task (recognition) and were less likely to be distracted by incorrect responses. These factors also differentiated skilled and less skilled responders in both groups. Closers analyses of the behavior of the less skilled responders showed that these children were more likely to choose distractors that were highly associated with the term.

Inference ability could not be measured independently of application in this study, but the combined inference application measure was significantly higher for the older children. This suggests that the younger children may have had a poorer understanding of the relations on which the analogies were based. In a second experiment, Goldman et al. measured inference ability independently by asking children how the α and b terms went together. They found that inference ability was significantly related to analogical performance, but less strongly than the recognition and distraction measures. They concluded that while relational inference is a source of developmental change, recognition and distraction measures were more predictive of individual differences.

Goldman et al. concluded that their results were "supportive of the notion that a significant aspect of age and skill differences is the ability (and/or attempt) to coordinate sets of relations relative to the constraints of the analogy task" (p. 557). They suggested that younger children’s understanding of the constraints on analogical solutions was weaker and was easily disrupted. This weaker understanding meant that "different models of analogy solution are necessary; to characterize the development of analogical reasoning" (p. 558). In a related article, Goldman and Pellegrino (1984) suggested that mature analogical reasoning involved higher-order relations: "an understanding of the parallelism and directional constraints on solution. Developmentally earlier models [of analogical reasoning] involve some type of associative processing component, although the precise understanding of its characteristics is presently lacking" (p. 177).

Again, this explanation does not commit the authors to a structural view of development, even though analogical reasoning is held to change with age. Goldman et al. allow young children some analogical competence (although it is not clear whether this includes the ability to reason about higher-order relations), but suggest that this competence is dependent to some extent on an associative understanding of analogy. It should also be noted that neither Stemberg nor Goldman included a control task to test for knowledge of the relations used in their analogies (which may be independent of inferential ability), so a knowledge-based view of the developmental differences that they found cannot be
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ruled out Associative responding could occur whenever children do not have the relational knowledge required to solve the analogies, as Goldman et al. (1982) acknowledge.

Both information-processing accounts thus agree that associative strategies will predominate in younger children's analogical responding. This associative hypothesis can be tested in two ways. One is to provide strong associates in an analogy task after having ensured that children fully understand the relations involved in the analogies. The other is to challenge children about the appropriateness of their analogical solutions.

Studies Testing the Associative Hypothesis

In a recent study (Goswami & Brown, in press), we set out to test the associative claim by designing analogies that pitted associative relations against higher-order structure. If young children can use the higher-order structure of an analogy to identify the correct solution term, then they should be able to override any tendencies to respond associatively in analogy tasks as long as they are familiar with the relations on which the analogies are based. This is a strong test of the associative hypothesis, as the only way to identify the correct solution term is to use higher-order relations.

We designed a version of the classical $a:b::c:d$ analogy task in which the key distractors were based on thematic relations. Thematic relations are known to be highly attractive to young children, and play an important role in their knowledge structures from a very early age (e.g., Markman & Hutchinson, 1984; Nelson, 1977; Smiley & Brown, 1979). In some sorting tasks, young children prefer to relate objects thematically (associatively) rather than categorically, for example, choosing to pair dogs with bones rather than with other animals, or bees with honey rather than with other insects. We were interested in whether young children would erroneously select these high associates in an analogy task.

The analogies were again given in a pictorial multiple choice task and were based on familiar relations such as "lives in." An example of an analogy would be bird:nest::dog: doghouse, with the distractor bone as the strong thematic associate for dog. Additional distractors were a "mere appearance" match choice (e.g., another dog), and a category match (e.g., a cat). Performance in the Analogy task was contrasted with performance in a Thematic Control condition, in which the term was presented in isolation with the four distractors used in the Analogy task. Our prediction was that the Analogy response (e.g., doghouse) should be chosen significantly more frequently in the Analogy condition, in which the higher-order structure of the problem signifies the correct response, than in this Control task.

Four-, 5-, and 9-year-olds were tested, and all age groups showed an ability to utilize higher-order structure: the Analogy response was chosen significantly more frequently in the Analogy task than in the Control task. So even 4-year-old children do not display a simpler associative understanding of analogy if they understand the relations on which the analogy is based, in spite of the inclusion of high associate (Thematic) distractors which were the wrong response to the analogy. This result with 4-year-olds was replicated in a second study using the same analogies (Experiment 2).

To test Goldman and Pellegrino's (1984) claim that younger children only have a weak understanding of the constraints on analogy solution, the children were also asked whether there could be "another right answer" in both the Analogy and Control trials. If younger children's understanding of analogical constraints is easily disrupted, they should be willing to allow more than one correct answer to the Analogy sequences as well as in the Control trials. However, 4-year-olds denied that there could be anodier correct answer on a majority of the Analogy trials (60%), compared to a minority of the Control trials (18%). It is clear that with familiar relations, younger children have few difficulties in distinguishing between analogical and associative constraints: in the Control task, reasoning by association was recognized as being appropriate, whereas in the Analogy task it was not.

A second feature of these experiments was to ask children to predict the correct solution to the analogy before laying out the different distractor pictures. This led to a very interesting result: the younger children tended to produce verbal associates to the term in the prediction phase, but then changed to the analogical response once they saw the pictures, even though they were not informed that their prediction was wrong. For example, in the second study, the 4-year-olds predicted the Analogy response on only 35% of occasions, but actually chose the Analogy picture on 66% of the trials. Over 60% of incorrect predictions were verbal associates of the term. Verbal questioning about analogy items clearly encourages associative respond-
ing, thus grossly underestimating the analogical ability of younger children.

In terms of what develops, therefore, it can be argued that children do not necessarily move from associative strategies to analogical ones with increasing age. Even 4-year-olds can distinguish associative from analogical constraints. The reliance in the information-processing work on verbal analogies, and the use of relations that were difficult for the younger subjects, resulted in too much emphasis being given to the role of associative reasoning in the solutions of younger children. More recent work building on componential theory has shown that the component processes can be used successfully to solve geometric analogies even by 4-year-olds (Alexander et al., 1989). These authors also found that training in the component processes, including mapping, improved analogical solutions.

3. CENTNER: THE STRUCTURE-MAPPING THEORY OF ANALOGY AND THE RELATIONAL SHIFT

Centner’s (1988,1989) structure-mapping theory of analogical reasoning is based on children’s solution of problem analogies rather than classical analogies. However, her theory is similar to those already discussed in that she also identifies the ability to reason about relational similarity as the focus of developmental change. Centner’s theory contrasts the role of “surface” (attribute-based) and relational similarity in the development of reasoning by analogy. She postulates a “relational shift” in this development, children moving from a reliance on surface features to a reliance on relations in their analogical solution strategies.

Structure-Mapping

Centner argues that in solving an analogy, people map knowledge from one domain, the base, to another domain, the target, in a way that preserves the relational structure of the base by putting objects in the target into a 1:1 relational correspondence with objects in the base. The key to successful analogizing is to notice relational commonalities between base and target domains independently of the objects in which those relations are embedded. For example, in the analogy between the solar system and the atom mentioned earlier, the relational correspondence between the planets and the sun is mapped to the electrons and the nucleus: the electrons are thus understood to revolve around the nucleus in a similar fashion to the planets revolving around the sun.

Structure-mapping holds that people will seek to maximize the relational similarity between the base and the target by mapping systems of predicates linked by higher-order relations such as cause in preference to lower-order relations (bigger than) or isolated predicates (red). This constraint is called systematicity. The ability to use systematicity may be late-developing. Centner suggests that younger children and novices do not show the same relational focus as adults in analogy and metaphor tasks: instead, they focus on object similarities (attribute or “mere appearance” matching) when solving analogies and interpreting metaphors. This “relational shift” is not necessarily a structural change, however. Centner has argued that it may either reflect a genuine competence deficit or be determined by increasing domain knowledge.

Evidence for the Relational Shift

The evidence for the relational shift comes from two studies. The first examined children’s ability to use analogy in a story mapping task (Centner & Toupin, 1986). The second examined children’s ability to interpret relational metaphors (Centner, 1988).

Centner and Toupin wanted to find out when children become able developmentally to utilize systematicity. They designed a story mapping task in which the analogical step was to transfer a story plot from one set of toy characters to another. Systematicity was manipulated by providing an explicit causal structure for some of the stories, which had a moral at the end, such as “in the end, the cat realized that being jealous only got him into trouble.” Centner and Toupin’s hypothesis was that the use of systematicity should make analogical mapping easier. They predicted that children who could use relational structure would perform better in stories with a moral than in stories without a moral.

To test the role of surface similarity in analogical solution, the animal characters used in the base and target stories were either similar in appearance (e.g., chipmunk-squirrel, robin-bluebird) or different (e.g., chipmunk-elephant, robin-shark). The children listened to one story (the base) and then acted it out with one set of animal characters to another. Systematicity was manipulated by providing an explicit causal structure for some of the stories, which had a moral at the end, such as “in the end, the cat realized that being jealous only got him into trouble.” Centner and Toupin’s hypothesis was that the use of systematicity should make analogical mapping easier. They predicted that children who could use relational structure would perform better in stories with a moral than in stories without a moral.

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(elephant, shark, and cricket). In a third cross-mapping condition, similar characters assumed conflicting roles (e.g., chipmunk, robin, horse; zebra, squirrel, bluebird).

Children aged 4 to 6 years and 8 to 10 years took part in the study. Centner and Toupin found that only the older children benefited from systematization in the mapping task: the 4-6-year-old children did not show superior transfer when a moral was provided. However, surface similarity strongly affected performance for both age groups. Transfer was better when the animals in the base and target stories were similar in appearance than when they were different, and was worst of all in the cross-mapping condition. Centner and Toupin concluded that systematization may make a later developmental appearance than surface similarity as a basis for performance in analogy tasks, either via a competence deficit or because the younger children lacked knowledge of the higher-order relations used in their study. In order to benefit from systematization in the story mapping task, children had to understand quite sophisticated emotions and motivations (jealousy and greed) and predict their likely effects on behavior. It would have been simple to test the knowledge-based explanation by including a control task to establish that the 4-6-year-olds understood these relations.

In a later study of metaphorical understanding, Centner (1988) obtained more evidence for the relational shift. She compared children's and adults' ability to understand three kinds of metaphor: relational metaphors, which required relational or analogical reasoning (A cloud is like a sponge); attribute metaphors, which required reasoning about surface or attribute similarities (Soap-suds are like whipped cream); and double metaphors, which shared both common attributes and common relations (Plant stems are like drinking straws). The relational shift hypothesis would predict a developmental increase in the ability to interpret metaphors based on shared relational structure. Furthermore, younger children should interpret double metaphors in terms of similar attributes, whereas older children should give primarily relational interpretations.

Three different age groups were tested: 5-6-year-olds, 9-10-year-olds, and college students. The subjects were asked to rephrase the different kinds of metaphors as similes (e.g., t is like y). Both of Centner's predictions were supported by the results. A second study in which children were asked to choose between attributional and relational interpretations of the metaphors rather than being asked to produce interpretations themselves replicated these effects. Centner argued that she had found evidence for a developmental relational shift in metaphor interpretation, which could arise either from an increase in cognitive competence with age or from increasing domain knowledge.

Again, it would have been simple to test the domain knowledge view by including an independent test of children's knowledge of the relations used in the double metaphors. These metaphors required quite sophisticated knowledge about the physical world: children who do not know that plants get water from the soil through their stems may quite logically decide that plants are like drinking straws because "both are tall and skinny." In fact, Centner herself (Centner, 1977) has shown that when relations that younger children do understand are the higher-order relations in a metaphor task (spatial relations involving body parts: "If a tree had a knee, where would it be?"); children as young as 4 years can interpret metaphors relationally. Vosniadou (1987) has also demonstrated considerable success in metaphor tasks by very young children.

We turn now to recent evidence using analogy tasks that supports the view that the domain knowledge interpretation of the relational shift is the correct one.

Studies Testing Centner's Theory: Do Younger Children Lack a Relational Focus in Analogy Solutions?

Two kinds of study can be identified that are relevant to Centner's question. The first examines the degree to which the analogical solutions of younger children depend on surface similarity. The second examines the conditions under which younger children display a relational focus.

The Role of Surface Similarity

In a landmark study, Holyoak, Junn, and Billman (1984) asked children aged from 4 to 6 years and 11 to 12 years to solve a problem involving the transfer of some small rubber balls from one bowl on a table to another bowl further away, placed out of the children's reach. On the table was a selection of materials that could be used to help solve the problem, such as a large sheet of heavy paper, an aluminum cane, a long hollow tube, scissors, string, and so on. The children had to devise, as many ways as possible of transferring the balls from the filled to the empty bowl without leaving their seat. Performance on the problem presented alone was com-
pared with performance after hearing a story that contained an analogous problem and its solution.

Two story analogues were used. In both stories, a genie wanted to transfer some precious jewels from one bottle to another. In one story, he solved the problem by using his "magic staff" to pull the new bottle over to the side of the old bottle. In the other story, the genie commanded his magic carpet to roll itself into a tube, and used it to roll his jewels from one bottle to the other. Analogous solutions in the rubber balls problem would be using the aluminum cane to pull the far bowl nearer (the cane solution), and rolling up the paper into a tube so that the balls could be rolled through it (the paper solution). Children were tested individually in three conditions: magic staff story, magic carpet story, and no-story control.

Children in the two experimental conditions were not told that the story could help them until they became stuck on the rubber balls problem. At this point a hint to use the story was given, the experimenter asking what the genie did, and asking if the children could do something similar. Holyoak et al. found that all the preschoolers were able to devise the cane solution to the rubber balls problem by applying the magic staff analogy. Half of them did so without needing a hint, whereas in the control condition only one child (out of 10) thought of this solution. In the magic carpet condition, only three of the preschool children rolled up the sheet of paper into a tube to produce a fully analogous solution, all without receiving a hint, compared with one of the preschoolers in the control condition. For the older children, everyone given the magic carpet story produced an analogous solution for the rubber balls problem by rolling up the sheet of paper. Thus significantly more analogies were made by the older subjects in this condition.

Preschool children were apparently only able to use analogy in the magic staff condition. Holyoak et al. pointed out that surface similarity cues were stronger in this condition: the magic staff and the cane were perceptually and functionally more similar than the magic carpet and the piece of paper. So younger children may only be able to use analogy when surface similarity acts as a support cue.

This possibility was investigated in a study by Brown, Kane, and Echols (1986). They tested three variants of the apparently difficult rolling solution in a similar story-mapping paradigm: children listened to a story and were then required to solve a problem about transferring precious items by rolling a flat object into a tube. Three scenarios were used: the genie story, a story about an Easter bunny moving eggs, and a story about a farmer moving cherries. The genie story was always the base for the analogy. Performance was measured in three conditions: explicit goal structure, in which the protagonist, goal, obstacle, and solution were highlighted for the child; recall, in which the child had to recount the genie story before solving the transfer tasks; and control, in which it was left to the child to figure out the similarity between the stories. The first two conditions were expected to facilitate a focus on relational similarity. Four- and 5-year-old children acted out the genie story with toy characters and then received the transfer problems.

Brown et al. found that when the children had to notice the analogy for themselves (the control condition), performance was around the same disappointing level as that found by Holyoak et al. (approximately 30% transfer). However, when the similarity structure of the problems was highlighted for the children in the explicit goal structure condition, performance leapt to 70% transfer, with the recall condition intermediate between the two.

Brown et al. concluded that when the perceptual similarity between analogies was low, as for the rolling relation, children only showed analogical transfer when the underlying relational similarity between the base and target problems was made explicit in some way. Another way of highlighting relational similarity is to tell children that the problems are similar. Studies by Crisafi and Brown (1986) and by Brown, Kane, and Long (1989) have shown that setting up a "learning set" to look for analogy promotes analogical transfer in children as young as 2 and 3 years.

Crisafi and Brown (1986) presented 2- and 3-year-olds with a very simple transfer task that involved getting candy from different kinds of machine (gumball machine, truck, and automated box) by inserting a token. They showed that children who received hints that the solutions were similar, or who were required to tell a Kermit puppet the rule for solving the problems in between trials, performed much more successfully at transfer test than a control group who were not told that the problems were similar. Crisafi and Brown argued that they had shown that even very young children can demonstrate success-
fill analogical transfer if task similarity is emphasized.

Brown et al. (1989) examined performance in the rolling paradigm used by Brown et al. (1986). Children were first given the genie problem to try and solve unaided, and if they were unsuccessful the problem was put aside and they were told that they would work on an easier problem that would help them to solve the genie’s problem. The bunny or farmer problem was then presented and solved with the experimenter’s help, and subsequently the genie problem was reintroduced. Children were told that now that they knew how the bunny/farmer solved the problem, they could help the genie. Almost half of the 7-year-olds tested solved the analogy, compared to 20% success for a control group who did not receive the instructional hints. When a third analogous problem was then presented for solution (farmer/bunny), 98% of the children in the hint condition were successful, compared to 39% in the control group. If children are looking out for analogies, they can clearly focus on relational similarities even in the absence of surface similarity cues. This goes against a competence deficit explanation of the relational shift.

The Role of Domain Knowledge

Recent studies by Brown (1989) and by Brown and Kane (1988) have used problem analogies based on relations that are extremely well understood by young children, such as certain causal relations, to examine analogical understanding. Brown and her colleagues have shown that under these circumstances, spontaneous analogical transfer in young children is easy to demonstrate.

The causal relations used by Brown and Kane (1988) were simple forms of physical causality, such as using a tool to move an object into reach, or stacking objects to stand on to reach something high up. Analogy was again examined using a story mapping task. Problem and solution were common across different story scenarios (e.g., stacking tires in a toy garage, or stacking bales of hay on a toy farm), and the measure of analogy was the transfer of a common solution to different problem types.

Brown and Kane found that 4- and 5-year-old children transferred the analogous solutions very successfully without any hints after one experience of an analogous problem. Three-year-olds took slightly longer to spontaneously use analogy, needing two prior experiences to enable transfer. However, the important result was that analogical transfer occurred in the absence of surface similarity cues or hints. Brown and Kane call this a “learning to learn” effect, with children rapidly learning that transfer of the demonstrated solution was what was required.

Similar spontaneous transfer was found in children as young as 20 months by Brown (1989), in a paradigm involving active experience of the kind of physical causality mechanisms used in the story-mapping task. Children were presented with different attractive objects placed just out of reach, and were given a set of tools with which to try and reach the objects. Only some of the tools were useful for the task (e.g., a toy cane vs. a floppy wand). Brown showed that these young children quickly learned which tools would enable them to reach the objects, and transferred this knowledge to different problems involving analogous sets of tools of a physically dissimilar appearance (e.g., a rake instead of a cane). These very young children were focusing on relations in the absence of prior domain knowledge (at least, about this particular class of tools). What they did understand, however, was the causal mechanisms that the tools could be used to exploit, such as the relation of push-collide.

In a recent set of studies using animal defense mechanisms as a basis for analogy, Brown and Kane (1988) demonstrated analogical reasoning in 3-year-olds for whom the analogical relations were completely unfamiliar. Brown and Kane taught the children about three types of defense mechanism: mimicry (the hawkmoth caterpillar, which mimics a poisonous snake, and the crested rat, which can mimic a skunk), changing color (the arctic fox and the chameleon), and changing shape (the stick insect, which can look like a leaf or twig, and the pipe fish, which can look like a reed). Children listened to stories about these animals that included details of habitat, eating preferences, etc., and were then asked transfer questions about defense, such as, “How could the hawkmoth caterpillar stop the big bird that wants to eat him?”

Brown and Kane found that 90% of 3-olds demonstrated analogical transfer by the third problem set without requiring any hints. The analogical relation “disguise yourself to avoid being eaten” was being extracted from the story sets in spite of the difference in the actual mechanisms and in the appearance of the animal protagonists. This is striking evidence for a relational focus in children as young as 3 years when they have been taught
the required domain knowledge. The relational shift documented by Centner thus seems likely to be a function of children's knowledge rather than a competence deficit in analogical ability.

What Develops?

At least three alternative possible answers to the question of what develops in analogical reasoning were outlined at the beginning of this review. Let us consider each of these in light of the evidence.

The Structural View

This view of what develops holds that analogical reasoning is a late-developing skill, consequent upon earlier logical development. The main developmental hurdle identified by Piaget and the information-processing theorists was the ability to reason about higher-order relations, termed *systematicity* in Centner's theory. While only Piaget can be said to hold a firmly structural view of what develops in analogical reasoning, the notion that there is some kind of change with development toward a relational focus is common to all the theories discussed here.

Recent studies have clearly shown that a strong structural view of what develops is not justified by the evidence. Children as young as 3 and 4 years of age can solve classical analogies if they understand the relations on which these are based (e.g., Alexander et al., 1987; Goswami, 1989; Goswami & Brown, 1989). Furthermore, they are able to use higher-order structure to distinguish between alternative distractors in classical tasks, and can defend their analogical solutions against associative 'solutions (Goswami & Brown, in press). Hence Piaget's strong criterion for demonstrating analogical competence (the ability to reject counter-suggestions) has been to some extent fulfilled.

The Knowledge-based View

From the studies reviewed in this article, a strong case can be made for a knowledge-based view of what develops. Recent studies in both the classical paradigm and the problem-solving paradigm (e.g., Brown & Kane, 1989) have demonstrated highly competent analogical reasoning in young children as long as they have the knowledge base relevant to the relations used in the analogies. Three-year-olds can even reason analogically to solve similar problems when the knowledge base is provided as part of the learning task (Brown, 1989). Such studies suggest that analogical reasoning is available very early developmentally, with Brown's work showing that 20-month-olds can use analogies.

One objection to a knowledge-based view can still be made. In many of the problem analogies that did not provide surface similarity support cues, most of the children who did not receive hints or instructions to reflect on the underlying relational structure of the problems did not show analogical reasoning, even though the performance of the Experimental groups suggested that the knowledge required to reason about the analogical relations was present. For example, 70% of the children in Brown et al.'s (1986) study showed no analogical transfer between the genie rolling up his carpet and the Easter bunny rolling up his blanket (Control condition).

If possession of the relevant domain knowledge is held to be sufficient for successful analogical reasoning, this poor performance is difficult to explain. Vosniadou's (1989) view that what develops is the conceptual system itself is unsatisfactory, since children in the experimental conditions clearly possessed the conceptual system required for the task—instructions to recall the goal structure of the stories or simply to recall the stories prior to solving the analogous problems was associated with a huge improvement in performance. Brown's view that constraints on learning in the shape of a quest for causal mechanism can account for many of the failures to display analogical transfer explains much of the data. However, this view cannot account for the younger children's failure to show transfer in her simple problem paradigms in the absence of any support cues such as surface similarity, hints, or task instructions, as she herself has noted (1989, p. 405). Brown suggests that general factors such as learning strategies and metaconceptual competence may also play a role in development, and it is to these that we now turn.

Early Competence with Developmental Change

The third developmental possibility outlined earlier was that children are genuinely able to reason by analogy from early in development, but that there are later changes in the nature of analogical reasoning. The evidence reviewed above provides ample documentation of early analogical competence in both the classical and problem analogy paradigms, as long as children have an understanding of the relations used in the analogies. What then might be the nature of later developmental
change? An obvious conclusion from the literature would be that children become able to solve analogies without the benefit of hints or surface similarity. However, work with adults shows that this is not necessarily so. Adults also benefit from the provision of hints or surface similarity in analogy tasks (e.g., Holyoak & Koh, 1987), and frequently perform very poorly without them (Gick & Holyoak, 1983).

A more appealing notion is that children become able to reflect on their own knowledge with development and to explicitly seek out relational similarity in analogy tasks. While metacognitive explanations of development are not new (e.g., Flavell & Wellman, 1977), they may still be useful. For example, the degree of successful performance in Brown's analogy tasks depended on whether the children were explicitly required to reflect on their own knowledge. Many authors have suggested that the ability to consciously or strategically employ such reflection develops with age. Moshman's (1990) concept of metalogical understanding provides a useful framework. He argues that the logical competence of young children largely involves the application of unconscious inference schemata. After 5 or 6 years of age, children become capable of purposive application of inference schemata (via "metalogical strategies" such as seeking counter-examples), and of conceptualizing the nature of logic ("metalogical understanding").

Applied to analogical development, this framework would grant the young child the ability to solve analogies (by "unconscious" application of higher-order relations), but would predict that 4- and 5-year-olds would not be able to consciously apply analogical reasoning to particular tasks or to conceptualize the nature of analogy. Neither of these predictions has been supported by current work. Children seem to have an implicit understanding of the nature of analogy, as demonstrated by their understanding of the constraints on analogical solutions (Goswami & Brown, in press). They also show a "learning to learn" effect in the use of analogies to solve problems (Brown & Kane, 1988), but this has not been shown to be independent of the paradigm in which it is induced. There is no strong evidence at present that young children are able to purposefully apply analogical reasoning strategies or to conceptualize the nature of analogy, but there is also no direct evidence against this. Neither is there evidence that these abilities distinguish older from younger children in analogy tasks.

Earlier attempts to gauge conscious analogical understanding used measures of whether children were able to verbalize the basis for analogy solution (Gallagher & Wright, 1977, 1979; Levinson & Carpenter, 1974). These studies consistently found greater success for older children. However, this approach does not help us to identify the onset of metalogical ability, as metalogical theory would not claim that the hallmark of conscious understanding is the ability to verbalize knowledge. Piaget's criteria for the attainment of formal operations (e.g., hypothesis generation, the use of counter-examples to disprove hypotheses) are highly reminiscent of "metalogical" skills, and may provide useful indices of metalogical ability. However, the metalogical account differs from Piaget's in that the ability to reason about higher-order relations is granted to the child. What develops by this account would be the ability to purposefully use higher-order structure in problem-solving tasks regardless of task content.

At present there is insufficient evidence to strongly support the metacognitive view of what develops. However, the strong version of the structural view can confidently be rejected. The knowledge-based view can explain much of the data, but without a clearer definition of what is meant by "knowledge" or the "conceptual system" (does it perhaps include some metacognitive skills?), the developmental import of this view is difficult to assess. One claim can be made, however. Problem analogies do not seem to be developmentally simpler than classical analogies. The two kinds of task do not seem to be measuring widely different skills. Bodi requires a focus on relational similarity, and both can be solved by very young children.

**Conclusion**

The evidence discussed in this review does not support the idea that the ability to reason about relational similarity is either late-developing or dependent on the presence of support cues such as surface similarity or hints to focus on relations. Instead, young children can reason analogically in both classical and problem analogy tasks as long as they have knowledge of the relations used in the analogies. Analogical development might thus consist of a metacognitive understanding of analogy rather than development of the ability to reason about higher-order relations per se.

Given that children are able to reason about relational similarity from at least 3 years
of age, how might this analogical ability be useful in learning and development? Halford (1987, in press) has recently proposed that analogical reasoning may lie at the core of development, as children may represent the world around them by mental models that are structurally similar to the real world. Development is thought to consist of assigning elements of one structure to elements of another in a way that preserves corresponding relations in increasingly complex ways. He describes this as a structure-mapping theory of cognitive development, and assumes that classical analogical reasoning is present in children by at least age 4. The idea that mental models of the world are at the core of representation and that analogical reasoning is an essential tool for developing increasingly sophisticated mental models of the world shares obvious similarities with Palmer’s view of representation. He has argued that representation requires the structural preservation of relations in the represented world in the representing world (Palmer, 1978). More recently, Palmer (1989) has suggested that analogies are like representations, as both are model systems. Halford’s work incorporates this idea into a developmental theory.

To find evidence that analogies help in learning, we must turn to classroom learning tasks. Experimental work in reading acquisition has shown that young children can use analogies as an aid to both decoding and comprehension. Five- and 6-year-old children taught to read a word like beak can use the relation between the spelling and sound of this word as a basis for analogies about the pronunciations of new words like peak and bean (Goswami, 1986, 1988a). Similar analogies based on sound-spelling relations can be found in spelling development (Goswami, 1988b). Work in language acquisition has also demonstrated the use of analogy (e.g., in morphological development: MacWhinney, 1976).

In reading comprehension tasks, children of a wide range of ages have been found to use analogies to help them in understanding difficult text. Hayes and Tierney (1982) demonstrated that California students found it easier to understand passages describing the game of cricket if baseball analogies were used in the text, and Vosniadou and Ortony (1983) found that 6- and 8-year-olds were helped to understand passages about topics like infection if analogies such as invasion by an enemy were provided. Brown, Campione, Reeve, Ferrara, and Palinscar (in press) have shown that even children experiencing difficulties in reading comprehension use analogies, and that practice greatly improves this ability.

Bean, Singer, and Cowan (1985) have also noted a role for analogy in improving comprehension in science teaching. They note the use of a “biscuit” analogy in teaching students about the relations between molecules, atoms, and substance, whereby biscuit crumbs provide an analogy for molecules in being the smallest part of the biscuit still having the same properties as the biscuit itself (Simons, 1984). Bean et al. suggest the development of analogical study guides in science teaching, using analogies such as a factory for a cell (so that the cell walls are analogous to factory walls, the cell membrane to security guards, and so on). While the use of analogies in mathematics learning awaits direct study, Gholson, Emard, Morgan, and Kamhi (1987) have demonstrated that 8- and 11-year-olds can benefit from analogies when attempting to solve a version of the “missionaries and cannibals” problem (the “farmer’s dilemma”) in which a specific sequence of moves is required for solution.

However, it is important to realize that the use of analogies may not always be beneficial. Halford and Boulton-Lewis (1989) have pointed out that analogies may have limitations in mathematics teaching, as poor analogues may generate incorrect information. Limitations in the value of analogies in teaching medical concepts to medical students have been demonstrated by Spiro, Feltovich, Coulson, and Anderson (1989), who found that a frequently used analogy between pressure in the cardiovascular system and household plumbing led to many misconceptions about the nature of blood pressure. Negative transfer in analogical problem solving by 6-year-olds has been found by Chen and Daehler (1989). Children given misleading base stories in a problem analogy task were hindered in successfully solving the target problem compared to controls given neutral stories.

Analogies thus seem to play a central role in learning and development from an early age, and can be employed creatively in classroom teaching. Far from being unable to reason by analogy until late in development, young children seem to adopt a relational focus in certain kinds of reasoning task spontaneously and without effort. However, it is clear that analogies may not always be beneficial. Future research needs to dis-
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tinguish the factors that determine when analogies are useful and when they are used.

References


