THE CONCEPT OF SAME

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Is similar to is merely a blank to be filled.

Nelson Goodman

Development is away from the immediate, the subjective, the animal sense of similarity.

W. V. O. Quine

I. The Problem of Similarity

Similarity worries philosophers.

The philosopher Nelson Goodman (1972) doubted that the abstract concept of sameness has any meaning at all. We can think of a basketball as being the same as a football or different from a football. We can think of a set of objects that are all the same color as being *like* a set of objects that are all square. Sameness, according to Goodman, is too many things to be anything at all. Moreover, similarity is shifty; it does not stand still. Given a 1-ft, a 4-ft, a 6-ft, and a 15-ft object, we might judge the 1- and 4-ft objects to be similar because they are both small and the 6- and 15-foot objects to be similar because they are both big. But in another context (e.g., the possible heights of people), we might judge the 1- and 15-ft objects to be alike because they are both extreme. As Goodman argued, saying two objects are the same has no meaning at all unless you specify how they are the same. The concept of sameness thus seems superfluous and free of content.

The philosopher W. V. O. Quine (1977) believed similarity to have content, but he found that content insufficient to account for intelligence. According to Quine, perceptual similarity is an "animal sense" that presents a fixed picture of what the world looks like but is inflexible and not smart enough to account for the intelligent behavior of humans. A thought experiment (based on Carey, 1985) makes Quine's point. Imagine a mechanical monkey, a real monkey, and a real snake. The mechanical monkey and the real monkey look alike. Nonetheless, if we are told that the real monkey has a spleen and are asked which of the other two—the snake or the mechanical monkey—also has a spleen, we do not choose the object that looks like the real monkey. We abandon perceptual similarity for a more intellectual way of conceptualizing category membership. We pick the snake as like the real monkey in its internal structure.

Philosophers' worries have shaped the zeitgeist in psychology and made similarity unpopular (see Keil, 1989; Medin, Goldstone, & Gentner, 1992; Murphy & Medin, 1985, for discussion). Researchers on concepts and categories argue that similarity is overrated and has received far too much attention for what it contributes to cognition. Developmentalists argue that the important aspects of cognition require going beyond mere appearance to the conceptual structure of things (Gelman, 1988; Keil, 1989; Mandler & Bauer, 1988). One danger in letting the philosophers' worries set the research agenda, however, is that we may forget the psychology of similarity. People do perceive objects to be similar and different from each other; people do think about the appearance of things; people do talk about similarity. The processes that give rise to the experience of similarity and their developmental history are surely worthy of study. Indeed, an understanding of the developmental psychology of similarity may make the philosophical worries moot.

In this article, I argue that similarity is psychologically complex and composed of a diverse set of processes. The mutual interactions and developmental dependencies of these processes give rise to a creative system of perceptual comparison and a unitary concept of same that transcends specific perceptual details. These insights stem directly from research on the development of similarity (see Gentner & Rattermann, 1991; Smith, 1989b, for reviews) and an effort to build a connectionist model of developmental growth in similarity (Gasser & Smith, 1991). I begin with a discussion of four difficult problems for a psychological theory of similarity.

A. Four Psychological Problems

1. A Unitary Concept of Same

I take as my starting point the assumption that the concept of same does have some content; at least the human conceptual system confers a meaning on the word *same*. A cursory examination of the linguistic evidence from English reveals several devices that seem to have sameness as part of their meaning: *like, match, different, both, too,* numbers, and the plural form of nouns, as well as the word *same*. Surely, this variety of terms signals the importance of a concept of sameness in human cognition. A moment's reflection on our use of these terms suggests a single core meaning of *same* that transcends the specific perceptual properties of objects. We say:

(1) *This book is like that book.*
My dog is brown, too.
Our driveways are both concrete.
A whale looks like a fish but isn't one really.
Whales and dolphins are the same kind of animal.
They are the same flavor.
There are three flowers here.
There are three red ones.
These are the same color but those are the same size.

Each of these sentences makes an assertion about similarity. A likeness is imputed to exist. But the particular objects and the particular kinds of likeness differ from case to case. What is this concept of same? How does it describe the perceptual similarities of objects yet transcend particular perceptual properties?

2. *Perceptual Similarity Is Dynamic*

Those who study perceptual similarity agree on one fact: The perceptual similarity between any two objects varies considerably. Perceptual similarity varies with the attributes attended to (Nosofsky, 1984; Shepard, 1964). The dynamic nature of similarity is evident in the empirical research on perception and perceptual categorization and in formal theories of similarity (Goldstone, Medin, & Gentner, 1991; Nosofsky, 1984; Tversky, 1977). In these theories, similarity is some function of some weighted combination of features, attributes, and/or relations. The similarity of any two objects thus is not fixed but changes.

For example, in Smith's (1989a) model of perceptual classification, as in Nosofsky's (1984) and Shepard's (1987) mathematical models, similarity is calculated as an exponential decay function of the distance between stimuli in the psychological space. The similarity S_{ij} between any two objects O_i and O_j is defined in

(error, should read $S_{ij} = e^{-d_{ij}}$)

$$S_{ij} = e^{d_{ij}} \tag{1}$$

and distance d_{ij} is defined as the sum of the weighted dimensional differences in

$$d_{ij} = \sum_{k=1}^{N} W_k[O_{ik} - O_{jk}] \tag{2}$$

where $O_{ik} - O_{jk}$ is the difference between objects i and j on dimension k, N is the number of dimensions, W_k is the weight given dimension k, $0 < W_k < 1$, and the sum of the W_k is equal to 1.00. Weight represents the relative amount of attention given to a dimension.

The important point is that similarity depends on the weights. How similar two objects are depends on what dimensions are attended to. The three stimuli in Fig. 1 provide an example. Are the two birds perceptually more similar or are the crow and bat perceptually more similar? No single answer to this question is possible. With dimension weights that emphasize overall shape and color, the crow is perceptually more similar to the bat, but with dimension weights that emphasize head and feet, the crow and flamingo might be perceptually more similar. In his treatment of similarity, Nosofsky (1986) illustrated the instability of perceptual similarity by drawing similarity spaces in which the relative similarity of stimuli is represented by their distance in that space. This manner of representation is used in Fig. 2 to show how the perceived similarity of the bat, crow, and flamingo will change with changes in the attention weights. The top

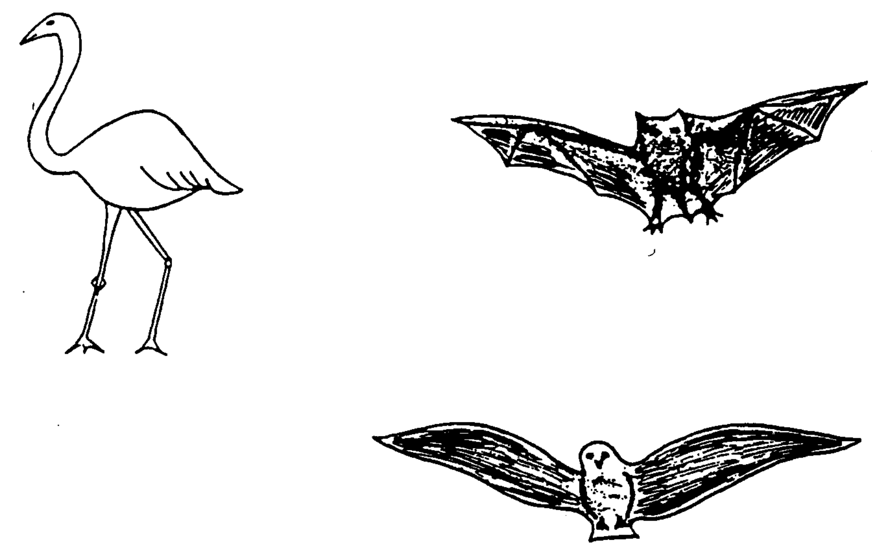

Fig. 1. *Renditions of three stimuli similar to those used by Gelman and Markman (1985).*

figure shows a stretching of similarities along the shape and color axis when those dimensions are attended to, and the bottom figure shows a stretching of similarities along the head and feet axis when those dimensions are attended to. Thus, it seems, similarity changes with changes in attention to dimensions and features. But what are the features and dimensions?

3. *No Single Definition of Features and Dimensions*

What properties of objects are relevant for similarity? There is no consensus; indeed, there is no consensual vocabulary with which to talk about features, attributes, and dimensions. The difficulties in the psychological definition of features and dimensions arise because there are several sets of well-documented findings that point in decidedly different directions.

1. Neurophysiological and empirical evidence indicates a definite set of features that are independently processed and subsequently conjoined to form the temporally and spatially whole objects we perceive (Treisman & Gelade, 1980). One relevant finding implicating separate features is that of illusory conjunctions. Subjects who are shown a *P* and a *Q* very briefly so that processing time is limited sometimes report seeing an object that corresponds to an incorrect conjunction of separate features of *P* and *Q*. For example, they might report seeing an *R*. The extant developmental evidence suggests little change in the features that are independently processed at the preperceptual level and little change in the

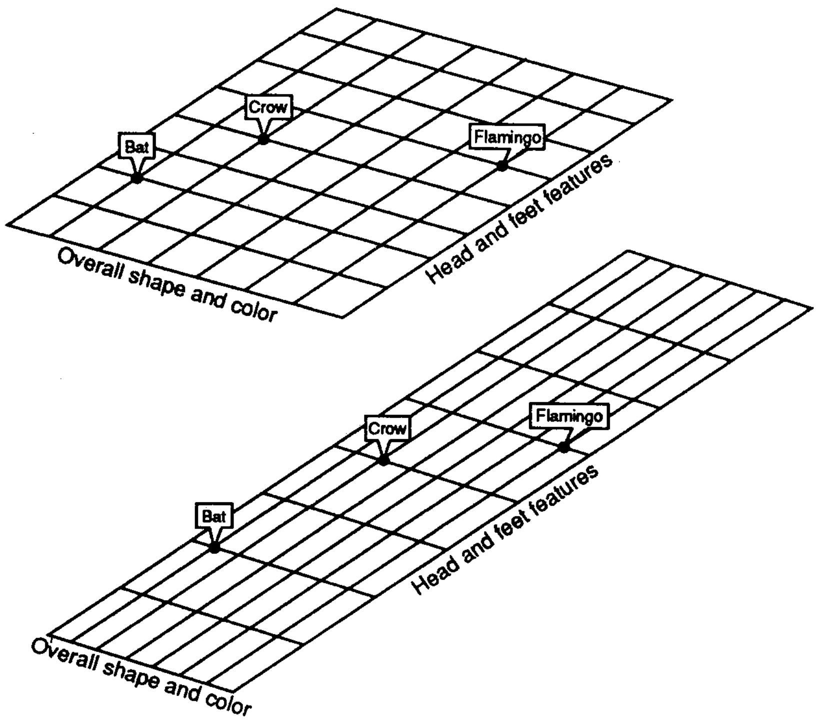

Fig. 2. Similarity of the bat, crow, and flamingo under two different sets of attention weights. Similarity is represented by distance in the multidimensional space.

processes through which features are combined to form perceived wholes (see Aslin & Smith, 1988, for a review, and for more specific evidence from Treisman-like tasks used with children, see Thompson & Massaro, 1989).

2. Languages employ a small set of words, the dimensional adjectives, to talk about the properties across which objects vary (Bierwisch & Lang, 1987; Miller & Johnson-Laird, 1976). Although languages differ considerably in the specific nature of their dimensional objectives, the world's languages consistently (perhaps even universally) include words for certain object attributes such as size, color, location, shape, and texture. The attributes picked out by languages to label in single words are reasonable candidates for the independent properties across which similarity is computed. These *named* perceptual properties do not, however, correspond in a perfect one-to-one fashion with the features that are independently processed at the preperceptual level.

3. Perceptual similarity depends on more than a simple count of shared and unshared perceptual features or attributes; it depends on emergent Gestalt properties (e.g., Palmer, 1989; Pomerantz, Pristach, & Carson, 1989). The relations

between features—not just the features themselves—matter in the perceived similarity of objects (Goldstone et al., 1991; Markman & Gentner, 1990).

4. The dimensions and features relevant for similarity also depend on perceptual learning and the manner of perceptual learning (Gibson, 1969). One pertinent study was conducted by Freyd (1983), who taught adults to recognize new letter-like characters by having them watch a character being drawn by one of two methods. Figure 3 illustrates a character and the two drawing methods. Although the drawing methods differed, the characters drawn by each method during training were identical. After training with one drawing method, subjects were presented static representations and asked whether or not they were instances of the modeled character. Some of these test characters were "sloppily" drawn versions of the modeled character. Freyd found that subjects were reliably faster at recognizing static characters distorted in a manner consistent with the drawing method they observed during training than they were at recognizing equally distorted characters that were inconsistent with the observed drawing method. For example, subjects who observed drawing method 1 during training recognized test item 1 more rapidly than test item 2 and subjects who watched drawing method 2 during training recognized test item 2 more rapidly than test item 1. These results indicate that the features of letters and the perceived similarity of letters do not depend only on the perceptual properties of the letters themselves. Rather, the context in which the letter categories were learned matters.

5. Finally, people invent new features and new forms of similarity with which to compare objects. For example, depending on the task at hand, we might invent the feature "older than my father" or "less than 100 pounds" or "on my desk." The number of such possible features is perhaps infinite, but people systemat-

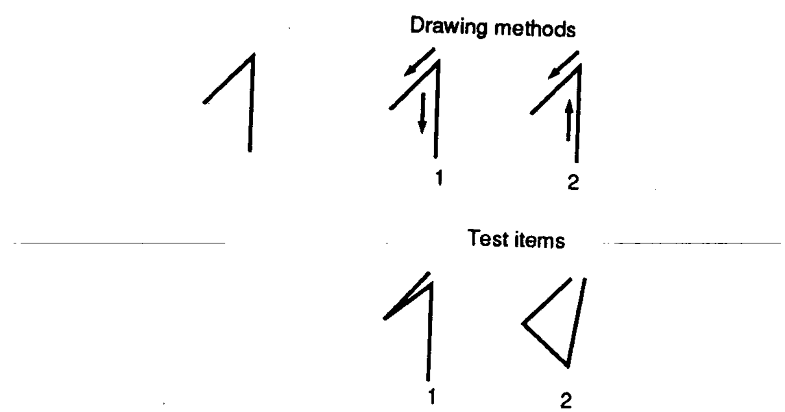

Fig. 3. Illustration of a stimulus used by Freyd (1983), its production by two possible drawing methods, and two possible test items.

ically use them nonetheless in making category and similarity judgments (Barsalou, 1987; Murphy & Medin, 1985). Indeed, the creative discovery of new dimensions of similarity is the hallmark of both poetry and science itself.

Clearly, these facts are problematic for a theory in which perceptual similarity moves about through the weighting of features and dimensions. What are the psychologically relevant features and dimensions for the perception of similarity? The ones that are independent at preperceptual stages of processing? The ones we talk about? The ones that emerge in the relations between perhaps more basic sensory features? What is the role of learning? How do we create novel features and dimensions to fit the task at hand?

4. *The Mechanism of Selective Attention*

Even if we solved the feature problem generally or merely locally for a specific stimulus set and task, we would still need to solve the problem of the mechanism of weight changes. This problem has been thought about mostly in the context of the role of similarity in categories and concepts (Murphy & Medin, 1985). The features that are relevant for membership in a category appear to be category specific. For example, color is a more relevant property in determining whether some object is a member of the category of citrus fruits called *oranges* than it is in determining whether some object is a member of the category called *balls*. To determine whether an object is an orange, color is weighted heavily. To determine whether an object is a ball, color is not weighted at all. These facts are troublesome; they suggest that one has to know the potential category to know which features are relevant. Yet clearly one uses the perceptual properties of an object to determine the potential categories of which it is a member. Thus, perceptual similarity and category membership are interdependent.

The problem of changing attention weights is not just a problem for complex categories such as oranges and balls. A mechanism for shifting attention weights in task-relevant ways is also a problem for knowing that some object is red or knowing that two objects are the same size. To explain it all, a theory of similarity needs some mechanism that knows to emphasize and deemphasize color in the classification of oranges versus balls and a mechanism that knows to emphasize and deemphasize color in judging the colors of things versus the sizes of things. Are the mechanisms involved in judging balls and oranges at all like the mechanisms involved in perceiving red and big? If not, how do they differ?

B. WHAT IS SIMILARITY?

These four problems—a unitary meaning of *same*, the dynamic nature of perceptual similarity, the multiple levels and kinds of candidate features and dimensions, and the mechanisms through which aspects of perceptual information differentially contribute to judgments of sameness—show that whatever the psychological nature of similarity, it is not simple. The philosophers have good reasons to worry. Psychology, however, requires neither worry nor the dismissal of similarity as too difficult a problem. Psychology requires an open-minded respect for the data and an explanation of the mechanisms that cause perceptual similarity to be what it is.

I propose that similarity is a complex and diverse set of processes that in their mutual interactions yield both a system of perceptual comparison that is inherently creative and a unitary concept of same that transcends specific perceptual features. I suggest that there exist multiple kinds of sameness judgments. Furthermore, I propose that these different kinds of sameness judgments involve independent yet overlapping processes. The creative power of similarity—the ability to impute and discover new forms of similarity—emerges in the operation of these overlapping processes.

II. Kinds of Sameness

A. IMPLICIT VERSUS EXPLICIT JUDGMENTS OF SAMENESS

Much intelligent behavior is based on specific similarities. For example, if an organism has acted to avoid danger (or secure food) in the context of a specific pattern of sensory activation, then patterns of sensory activation that have sufficient overlap with the original experience will yield a similar response. The generalization of previous experience requires the computation of specific similarities among present and past perceptual experience. This is one important sense of sameness. If we train a dog to salivate to red, it will salivate also to orange but not to blue. If we teach a girl to call her collie *dog*, she will call labradors *dog*, and perhaps goats *dog*, but she will not call a motor scooter *dog*. This is the sense of sameness that underlies the everyday actions of biological organisms; however, this kind of sameness involves only the implicit use of similarity for some other end (e.g., naming or categorizing an object). An organism that generalizes a particular response from one object to the next need not possess a concept of same. An organism that names dogs *dog* and red things *red* need not possess, or even be able to learn, the meaning of the word *same*.

We can see that "response generalization," the simplest form of categorization, does not entail a concept of same by trying to build a device that can learn category names. Figure 4 illustrates a pattern recognition device that can categorize dogs as *dogs* and label attributes such as blue and red. The device consists of three levels. The first is the sensory processing of the object; the second is the perceived object; the third is the category labels. To label a dog as *dog* or a dog as *red* (if it is red), changes in attention weights between the levels must occur so that dog-relevant features access the category label *dog* and color features access the term *red*. If we have a device that can do this shifting of weights, we will have a device that names objects and labels perceptual attributes.

But the device will not have a concept of same. This device will only know when it "sees" certain patterns of activation (the ones associated with *dog*, perhaps) to give the associated response (*dog*). The device thus might know *dog* and *red* in this limited sense. But it has no way of making a sameness judgment; when it is classifying one dog as *dog* and a second dog as *dog*, it has no way of knowing that it is doing the same thing. (See Karmiloff-Smith, 1986, for a lucid discussion of what it means to "have" a concept.) Similarity is implied but it is implied to us, the theorists, looking down from the outside. The device itself knows only one-place predicates; *same* as it is used by people is a two-place predicate. The device in Fig. 4, then, is not enough to explain the psychological nature of similarity.

People use the word *same* to make a variety of sameness judgments between objects. We use the word *same* to talk about the relation that holds between two dogs, two pigs, two red objects, two big things. What kind of device can compare objects? A device is needed that transcends the particular properties that make a dog a dog and a pig a pig. A device that can do this is illustrated in Fig. 5. This device takes two perceptual objects as inputs and subtracts them. For any two perceptual events to be judged the same, the difference between their patterns of activation must be close to zero. This device implements a two-place relation. I call this device an *explicit sameness* device because the comparison is explicitly part of the machinery. (Explicit in this context does not mean that the machinery is consciously aware of what it is doing.) Our use of the word *same* suggests that we have an explicit sameness device. Moreover, because we use the single word *same* to talk about same thing, same color, and same size, a plausible

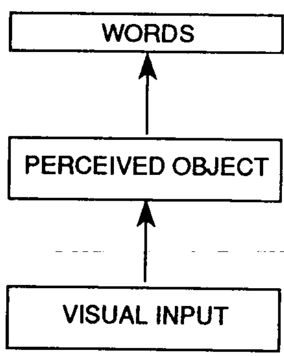

Fig. 4. Illustration of a simple device that could recognize and label individual objects and individual attributes.

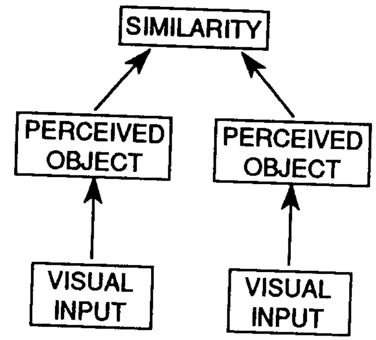

Fig. 5. Illustration of a device that embodies the concept of same *by comparing two objects and judging their similarity to each other.*

assumption is that we have a single mechanism for all these sameness judgments. If a single device underlies all explicit sameness judgments, then it must have some way of altering the attention weights so that sometimes the explicit similarity is calculated relative to the features pertinent for determining category membership (same thing) and sometimes relative to the features pertinent for determining color or size for same color versus same size judgments.

B. UNLABELED VERSUS LABELED SIMILARITY

By the previous definitions, *dog* and *same thing* are, respectively, implicit and explicit similarity judgments; *red* and *same color* are also, respectively, implicit and explicit similarity judgments. But in the first case the similarity judgments concern categories. In the second, they concern a perceptual property of the object that may or may not be relevant to category membership. Nonetheless, the implicit similarity judgments that yield *dog* and *red* could both derive from a single device such as the one in Fig. 4. The two judgments would differ only in the weights used to calculate similarity. For example, naming a dog might involve a more complicated and broader set of features than naming the property red. The explicit similarity judgments of same thing and same color could also involve a single device, the one shown in Fig. 5. Again, however, different features and dimensions would be emphasized in the two judgments.

This proposal, although reasonable, does not capture the different roles of categories and attributes in human sameness judgments. Categories are an unlabeled form of similarity. Category names label categories, not kinds of similarity. Dimensional terms, in contrast, label kinds of perceptual similarities. Calling an object *dog* does not directly specify the perceptual properties across which dogs are similar, but calling an object *red* does precisely specify the relevant perceptual property. Categorization is an inarticulate means of communicating about similarity in that the particular kind of similarity involved is unlabeled. Dimensional adjectives, in contrast, are articulate about the similarity imputed; the particular kind of similarity is labeled.

Labeling different kinds of attributes as *red* or *square* or different kinds of sameness as a *same in color* or *same in shape* requires either a set of multiple implicit and explicit similarity devices, one for each psychological dimension, or a set of single implicit and explicit devices and a mechanism for selectively attending to individual attributes and dimension.

C. THE SAMENESS OF RELATIONS

The scheme used to partition kinds of similarity thus far is a neat two by two. A judgment of sameness can be implicit—one object is not explicitly related to another but a similarity to previously perceived objects is implied. The implied similarity can be indefinite in being about membership in some category or it can be definite in being about a specific property. A judgment of sameness can also be explicit—two specific objects are stated to be the same. This explicit sameness judgment can be based on the inarticulate similarity of category membership or it can be about dimensional kinds of sameness.

This scheme does not exhaust our uses of the concept of *same*. We make analogies: Increasing size is like increasing loudness; a mansion is to a bungalow like a yacht is to a dinghy. Kotovsky and Gentner (1990) used a triad task to investigate analogical reasoning. They asked subjects to choose which of two figures is most similar to a standard, the top figure in Fig. 6. Adults readily select

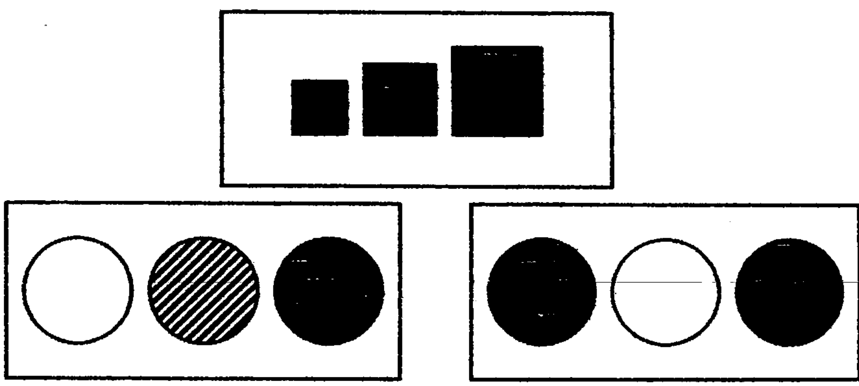

Fig. 6. Triad task used by Kotovsky and Gentner (1990).

the left figure as more similar to the standard. No specific object or attribute similarity is involved here; the shapes, shadings, and sizes of the objects in the two figures are different. What is the same between the figures is the relation of "increase from left to right"—the top figure increases in size, the one on the left in darkness. Goldstone et al. (1991) have shown that adults systematically shift from using properties of individual objects to using relations as the basis for similarity judgments when such relations are present. Thus, a complete theory of same requires a sameness device in which relations as well as objects can be compared and judged to be "same" or "different."

Indeed, a complete theory of similarity requires an explanation of how sameness judgments may be made of sameness judgments themselves. The recursiveness of same was made clear by Premack (1976, 1978) in his consideration of just how abstract a concept of same could be demonstrated in chimpanzees. To understand Premack's problem, we must first consider the simpler case: matching to sample. Matching to sample is like Gentner's analogy problem in that the organism must discover the sameness of a relation among diverse individual objects. Specifically, in the matching-to-sample task, the organism must find the two objects in a set of three that are the same. Experimentally, this task might be accomplished by training the animal to select out the two objects that are the same (or, alternatively, the one that is odd). If an organism can learn this response with a diverse set of objects, then we can conclude the animal has a "concept of same"—an explicit similarity device like that illustrated in Fig. 5 that takes diverse inputs, computes the difference between them, and responds same if the calculated difference between the two inputs approaches zero. This concept of same has been demonstrated in various animal species (although some of the demonstrations are controversial, e.g., Oden, Thompson & Premack, 1988; D'Amato, Salmon, & Columbo, 1985; Santiago & Wright, 1984).

Premack's problem takes this matching to sample (or simple analogy) a level higher. The input to the system is two cards, each containing two pictures. Table I shows the required responses. Given the joint presentation of the first two cards, the correct response is "same"; given the joint presentation of the next two cards, the correct response is again "same"; the next two cards when jointly presented require the response "different"; and the final two cards when jointly presented also require the response "different." What is the rule? The objects in card 1 of set 1 are the same and the objects in card 2 of set 1 are the same; "same" and "same" are the same relation so the response is "same." The objects in card 1 of set 2 are different from each other, and the objects in card 2 of set 2 are different from each other; "different" and "different" are the same relation so the response is "same." In contrast, sets 3 and 4 each have one "same" card and one "different" card, so the response to the pair of cards in each case is "different."

TABLE I

Examples of the Kinds of Trials That Make Up Premack's Problem

Presentation	Cards	Correct response
Set 1		Same
Card 1	X—X	
Card 2	Y—Y	
Set 2		Same
Card 1	X—Y	
Card 2	O—R	
Set 3		Different
Card 1	X—X	
Card 2	O—R	
Set 4		Different
Card 1	X—Y	
Card 2	O—O	

This problem is learnable by adult humans, older children, and chimpanzees with language. What kind of a mechanism could achieve this? The mechanism required is one that takes *the output* of a sameness device as its input.

D. SUMMARY

Is there a unitary concept of same, an explicit similarity device that makes same thing, same dimension, same relation, same sameness judgments? The fact that we use a single word for all these forms of sameness suggests such a device. But this device would require some mechanism of selective attention such that sometimes similarity is judged across the properties relevant for category membership, sometimes across a particular dimension, and sometimes across relations. Are the mechanisms of selective attention the same for all these unlabeled and labeled forms of explicit similarity? A mechanism of selective attention is also required for implicit similarity judgments, for judgments that an object is a dog or is red. Are the mechanisms of attention in implicit and explicit similarity judgments the same?

III. The Development of a Concept of Same

Two comprehensive reviews of the development of similarity have been published (Gentner & Rattermann, 1991; Smith, 1989b; see also Smith & Heise, in press). Smith saw the data as fitting a trend from holistic similarity to dimensionally differentiated similarity. She specifically proposed that dimensions of sameness were *constructed* with development. Gentner and Rattermann saw the data as fitting a trend from object-based similarity to relational similarity. Early in development, children tend to compare individual objects, first holistically and later in terms of individual attributes. With development, relational similarity is added to object-based similarity. Gentner and Rattermann, like Premack, suggested that learning the words by which we talk about sameness—and the labels for particular dimensions of similarity—might be critical for the development of relational similarity.

Neither of the two extant reviews of the development of similarity included a distinction between implicit and explicit forms of similarity nor between labeled and unlabeled forms of similarity. Given these two comprehensive reviews, I highlight here the major findings only as they are related to the present distinction between kinds of similarity.

A. IMPLICIT UNLABELED SIMILARITY: NAMING

The evidence suggests that the implicit similarity involved in naming objects with basic category names is not fixed but evolves in the course of children's lexical acquisition. Perhaps the most elegant documentation of the natural growth of attention to category-specific properties is Mervis's (1987) study of her son Ari's acquisition of the word *duck* from 10½ to 24 months. The first ducks that Ari heard named (and did so on a regular basis) were a real mallard and a toy mallard. At first, Ari generalized *duck* to novel objects that had similar shape, size, and amount of textural detail to the exemplar ducks. He called porcelain grebes, ostriches, swans, and real geese *duck*. He did not apply the word *duck* to stylized ducks (Disney's Donald and yellow rubber bathtub ducks), songbirds, and owls. With development, as Ari heard more and more ducks so named and more nonducks named by something other than *duck*, he began to emphasize specific duck properties such as head shape and bill—the same kinds of properties that are emphasized in the stylized ducks that are toys, soap dishes, and cartoon characters and that distinguish ducks from geese and ostriches. In the course of language learning, Ari learned to attend in a category-specific way to some properties more than others. The similarity among objects was changing for Ari as he learned the properties that mattered for being called *duck* in his language.

Other evidence suggests that when children learn words, their implicit similarity judgments change generally as well as in category-specific ways. In particular, the act of naming itself acquires the ability to organize attention. In one study, Landau, Smith, and Jones (1988) found that the presence of a novel count noun causes young children to attend to shape. In their study, 24- and 36-month-old children were presented novel wooden objects; the experimenter labeled one exemplar object with a count noun, "This is a dax," and then asked which other objects were also "a dax." Children generalized the novel name only to new objects that were the same shape as the exemplar. The children ignored quite dramatic differences in material substance and size. In a control condition, the children were shown the exemplar, but it was not named by the experimenter; instead, the children were asked only whether individual test objects were "like" the exemplar (thus, an explicit similarity task). In this no-name condition, children did not attend selectively to shape but attended to all dimensions. The results strongly indicate that the implicit similarity task of naming recruited attention to shape.

Landau et al. suggested that the shape bias is learned as children learn names for categories of concrete things. Jones, Smith, and Gershkoff-Stowe (1992) attained longitudinal data from four 17- to 24-month-olds that support this view. They found that the shape bias in the context of a novel word emerged in all four children several weeks after the increase in rate of word acquisitions known as the name explosion. The shape bias, then, may depend on learning enough names for things that the imperfect but apparently sufficient relation between what a thing is called and its shape could yield a generalized attentional bias for shape in the context of naming.

Other attentional biases emerge over other patterns of regularity between words and attending. Jones, Smith, and Landau (1991) found that a novel word in the context of objects with eyes directed 36-month-old children's attention to shape and texture. Without eyes, a novel word resulted in selective attention to shape alone. In this experiment, the only difference between the eye and no-eye conditions was whether every object had a pair of eyes. This one constant difference in stimulus properties, however, made a large difference in what objects children thought similar enough to the exemplar to have the same name. Importantly, the presence of eyes mattered only in naming objects. Children attended indiscriminately to all the dimensions in the no-word similarity judgment task regardless of whether the objects had eyes or not. Apparently, objects with eyes, the context of naming, and attention to shape and texture covary sufficiently to affect the implicit similarity judgment of naming. Results obtained by Soja, Carey, and Spelke (1991) suggest that by the time children are 24 months old, their implicit similarity judgments also reflect a regularity between naming, object rigidity, and shape and between naming, nonrigidity, and texture.

All these results are consistent with the idea that learning object names educates implicit similarity, and, as a result, the act of naming itself becomes a potent organizer of the features and dimensions emphasized in the internal calculation of similarity.

B. IMPLICIT LABELED SIMILARITY: ATTRIBUTE TERMS

Learning to label a property of an object—to call the color red *red*—is an implicit similarity task. A measure of similarity must be calculated between the candidate property and the representations in memory of the properties previously called red. In this way, learning *red* should be like learning *duck*. But it is not. In contrast to the ease with which children acquire names for concrete things, children acquire the words to talk about perceptual properties slowly and with some difficulty (e.g., MacNamara, 1982; see also, Bornstein, 1985). At first glance, the reason is not clear. The set of dimensional adjectives in English is small and restricted. Moreover, although the common category names for concrete objects appear to be organized by complex and category-dependent features that must be learned, attribute terms like *red* and *bumpy* refer to fairly circumscribed and (from the adult point of view) distinct components of perceptual experience.

Young children's difficulty in learning dimensional adjectives has sometimes been attributed to their general inability to attend selectively (Smith, 1989b). This attribution makes sense. In a wide variety of nonword tasks—speeded selective attention tasks, discriminative learning tasks, and perceptual classification tasks—children below the age of 5 years have been repeatedly shown to have difficulty selectively attending to variation on a single dimension (see Kemler, 1983, for review). For example, if young children are asked to push one button for red things and another for blue things, they respond slowly and make many errors when the objects vary in shape or size as well as the relevant dimension of color; older children's and adults' performances, in contrast, are not disrupted by irrelevant variation. The evidence on the shape bias in the context of novel count nouns, however, raises questions about whether these selective attention difficulties play the limiting role in children's learning of dimensional adjectives. Quite young children selectively attend to shape when interpreting novel count nouns, so why do they not learn to attend selectively to other properties when learning the names of these properties?

Several researchers have directly compared the attention-recruiting properties of novel adjectives versus novel count nouns. Smith, Jones, and Landau (1992) presented 36-month-old children with novel objects and labeled the exemplar with a novel word in an adjectival context, for example, the exemplar was called "a dax one," or with a novel word in a count noun context, for example, the exemplar was called "a dax." Across stimuli that varied in the inherent salience of individual dimensions, they found that the novel adjective sometimes increased the children's attention to shape (relative to the no-word condition) and sometimes increased their attention to another dimension such as surface pattern or coloring. A novel count noun, however, always directed attention to shape. Results obtained by other investigators (e.g., Au, 1990; Au & Laframboise, 1990; Gelman & Markman, 1985) also suggest that novel adjectives are more variable in their attention-recruiting powers than are novel count nouns.

These facts are not surprising if the attention-recruiting powers of a syntactic frame accrue from the regularity with which the frame and the act of attending to a particular dimension are paired. Although shape may be neither necessary nor sufficient for what any individual thing is called, it may nonetheless be the single dimension that is generally associated with the act of naming an object. The act of naming a property, in contrast, the adjectival syntactic frame, is associated with a variety of distinct dimensions of variation. Sometimes adjectives refer to properties of color, sometimes shape, and so on.

The "mapping" of count nouns to shape in early word learning and the "mapping" of adjectives to other particular properties may also differ in the precision of selective attention required. As Medin and Ortony (1989) suggested, imperfect selective attention is probably not harmful for learning basic-level categories. Dogs, for example, may be critically alike in shape but if the child does not attend exclusively to shape but attends (a bit) to color and size as well as shape, the proper category assignment is likely to be obtained, perhaps even more likely than with exclusive attention to shape. In contrast, naming perceptual properties requires near-perfect selective attention. All that matters for calling an object *red* is that it is red; attention to an object's shape and size is surely detrimental to the determination of its color. Perhaps, then, children's difficulty in learning to label perceptual properties stems from the need to learn to shift attention in very precise ways to a *number* of individual dimensions. Also, children's easy acquisition of the shape bias may stem from ease of learning to attend imprecisely to a single dimension.

C. EXPLICIT SIMILARITY

When do children show evidence of a two-place sameness relation? They do so at least by the end of the second year. One piece of unambiguous evidence is children's early productive use of the plural (Bowerman, 1982; Brown, 1973). The fact that children say *dogs* in referring to more than one dog or *foots* for feet shows the existence of a comparison process that is independent of the specific perceptual properties of the objects. The formation of a productive rule of the sort "when two objects are the same, use the plural" requires a sameness judgment that is independent of the specific features that make an object a dog, a chair, or big. Evidence from a variety of other tasks, including object banging (Forman, 1982), iterative naming, and classification (Sugarman, 1983), also shows a two-place same relation in very young children.

With development, these early sameness judgments become supplemented in two ways: (1) by the addition of sameness judgments along attributes and dimensions and (2) by the addition of sameness judgments as they apply to relations.

1. *Sameness Judgments along Attributes and Dimensions*

Many of the tasks that have been traditionally used to study the development of selective attention—speeded same–different judgments, discriminative learning, perceptual classification—require the explicit comparison of objects along a single dimension (see Kemler, 1983). In these tasks, the child must look at two objects and judge their likeness on a single dimension, and the evidence suggests that young children have difficulty doing so. The similarity judgment tasks that have served as control tasks in the studies of shape bias are also explicit similarity tasks: Children are asked whether individual objects are "like" the exemplar. These tasks have revealed little evidence of systematic attention to individual dimensions. Although such typical selective attention tasks suggest that selective attention to dimensions is difficult for young children, these typically used tasks do not provide precise information about the growth of different kinds of sameness.

One researcher (Smith, 1984) who did systematically examine different sameness relations found a developmental progression from 2 to 4 years of age in children's ability to make "same thing," "same attribute," and "same-on-a-dimension" judgments. The experimental task was a follow-the-leader game in which each participant (Experimenter 1, Experimenter 2, Child) was given a set of three objects. The child watched first one experimenter and then a second experimenter select two objects by a particular rule from their own sets. The question was whether the child would imitate the rule underlying the experimenters' selections. Sample trials are listed in Table II. On "same thing" trials, the first experimenter might select two large yellow cups and the second experimenter might select two small red houses. The child would demonstrate use of the concept "same thing" if he or she selected the purple boots. Even 2-year-olds

TABLE II
Three Trial Types Used by Smith (1984)

Participant	Trial type: Same thing	Same attribute	Same dimension
E_1	Large yellow cup	Small red car	Small red house
	Large yellow cup	Large red car	Large red house
	Medium blue cow	Small white car	Small white house
E_2	Small red house	Medium red car	Medium blue house
	Small red house	Large red car	Large blue house
	Large white daisy	Large blue car	Large green house
$Child_3$	Medium purple boot	Small red car	Small yellow house
	Medium purple boot	Medium red car	Medium yellow house
	Small pink chair	Small green car	Small pink house

performed this task well. Very young children, then, appear to possess a unitary same device like that in Fig. 5 such that the same "sameness" judgment is invoked by two yellow cups, two red houses, and two purple boots.

On the "same attribute" trials, the experimenters selected objects that shared an attribute but differed on the other dimensions (e.g., each would select red objects). The rule here is to choose two objects that possess a particular attribute. Only half the 2-year-olds but all the 4-year-olds succeeded in this task. Apparently, sameness judgments that require selective attention to specific attributes are more difficult than ones based on overall similarity.

Finally, on "same dimension" trials, the rule governing the selected choices was sameness on a particular dimension. For example, if the dimension were color, the first experimenter might select two red objects and the second experimenter might select two blue objects. A correct choice by the child might consist of selecting two yellow objects. At issue is the dimensional kind of similarity. In this task, none of the 2-year-olds, some of the 3-year-olds, and all of the 4-year-olds imitated choice by dimensional sameness. The errors on the dimension trials were telling. Children virtually always chose objects that shared an attribute, but the youngest children did not preserve the dimension of match. Thus, if the experimenters chose by same color, the 2-year-olds were equally likely to choose two objects that were same in color or same in size. Apparently, the children recognized that the task was about "sameness" but they did not have "sameness" differentiated into dimensional kinds. In several related tasks and experiments, Smith (1984) found that children's comprehension of the words for different kinds of sameness (*same thing, same color, two reds*) developed in close temporal proximity to the ability to make the different kind of same judgments in the follow-the-leader task.

The evidence thus suggests an early concept of same, one with a singular meaning that is applied to diverse perceptual comparisons so long as they are the same. With development, sameness becomes differentiated—dimensionalized—such that same and different are same and different in particular specifiable ways.

2. *The Sameness of Relations*

Children's ability to imitate choices of objects by the relation that holds between the objects suggests more than just a concept of same. Children have some additional ability that takes as input the outputs of the sameness device and relates them. It is helpful to consider the kind of mechanism needed to accomplish this task: The child sees the first experimenter take two yellow cups; the sameness detector (as in Fig. 5) "fires." The child sees the second experimenter take the two red houses; the sameness detector "fires" again. But for the child then to take the two purple boots and make the sameness detector "fire" again, he or she must notice that the sameness detector did the same thing in response to each experimenter's choices. To imitate the experimenters' choices, the child has to relate the two relations of sameness and know that they were the same.

Gentner (1988) and Gentner and Rattermann (1991) have proposed a relational shift, a transition from similarity based on comparing objects to similarity based on comparing relations. In terms of the mechanism in Fig. 5, the issue is precisely whether objects (one-place predicates) or relations (two-place predicates) are input to the sameness detector. Gentner and Rattermann suggested that the ability to input relations as opposed to objects (or their properties) develops. They suggested, however, that no single monolithic shift occurs from object similarity to relational similarity. Rather, they suggested that the development of relations is domain specific, because the ability emerges as the natural consequence of expertise in particular domains. The evidence from the imitation task reviewed in Section III,C suggests that children have a process that relates the relation of overall sameness by the time they are 2 years old. Other evidence (Gentner & Rattermann, 1991) suggests, however, that it will not be until these children are 5 years of age or older that they will be able to relate a relation such as same color to another relation such as same size.

D. SUMMARY

The developmental data suggest the following:

1. Children learn what features to attend to in making category judgments.
2. Learning object names causes increased attention to shape in the context of count nouns.
3. Learning names for properties of objects is hard.
4. Precise selective attention to individual properties and dimensions develops slowly.
5. Very young children make explicit sameness judgments.
6. Explicit sameness judgments develop in a particular order: from unlabeled (same thing) to labeled (same color) to relational (same kind of relation) similarity.

IV. A Connectionist Model of the Development of Similarity

How are the various achievements in the development of similarity related to each other? One way to try to answer this question is to build a model that develops the various forms of similarity and shows the same developmental pathway that children do. This is the current research enterprise of Gasser and

Smith (1990, 1991). They have developed a network through which they can simulate the development of similarity in children. They call their model the Network for Implicit and Explicit Comparison and, following the convention for most computer simulation models, I refer to it by its acronym, NIEC. The central idea of NIEC is that implicit and explicit similarity judgments are separate processes, but separate processes that mutually influence and constrain each other. In NIEC, implicit and explicit similarity judgments result from the same internal representations and selective attention develops in response to the joint demands of implicit and explicit similarity tasks as engendered by language learning.

The model makes three contributions to the psychological understanding of *same:*

1. NIEC provides a mechanism for context-dependent shifts in attention weights—the shifts that are necessary to explain how we attend to the features relevant to oranges when classifying oranges and to the features relevant to balls when classifying balls and the shifts that are necessary to explain how we can describe the same individual object as *red* and *big* and *dog* and how we describe pairs of objects as the same color, the same size, and the same thing.
2. NIEC provides a mechanism for shifting weights that can yield both unlabeled and labeled similarity.
3. NIEC shows how the features across which we explicitly compare objects, the ones we talk about, need not map coherently onto the distributed feature sets that enter into the implicit similarity judgments involved in naming and categorizing objects.

A. RATIONALE FOR A CONNECTIONIST APPROACH

Gasser and Smith's model is a connectionist model. Connectionist modeling is sometimes called "brain-style" modeling (Rumelhart, 1989), because like the brain the connectionist network is made of many units that, like neurons, only fire or not fire. The knowledge in a connectionist network is in the strength of connections between the units. This aspect of connectionist models differs from traditional models based on serial computers in which one unit equals one concept. A model in which one unit represents one concept (as in a single node for *dog*) is said to have *localist* representations. A model in which concepts and knowledge reside in no single specified place is said to have *distributed* representations. Connectionist models like the brain have distributed representations. For example, in NIEC, the concept of *dog* is not in any one place; indeed, individual units and individual connections are (for the most part) meaningless. Rather, knowledge resides in patterns of connection strengths between the many individual units. Connectionist models are also like the brain in that they are based on the assumption of a high degree of connectivity between units. For any given unit, there are *fan in connections,* connections from other units that go to one single unit, and *fan out connections,* connections from a single unit that go to many other units. The number of fan in and fan out connections in the brain is astoundingly high, averaging as many as 100,000 fan ins and fan outs from a single neuron in some parts of the brain.

Finally, connectionist models are like the brain in that they are plastic; they modify themselves by changing the strengths of connections between units. Thus, in modeling children's acquisition of words such as *big, red,* and *dog,* Gasser and Smith did not write a program that specified how to understand these words nor did they write a program or decision tree specifying how the device should selectively attend. Rather, they specified a large number of units with a particular pattern of connections, set the strengths of the connections between the units randomly, then put the network in an environment in which it might learn to attend selectively by learning to call red things *red,* big things *big* and dogs *dogs.*

The reason Gasser and Smith chose this form of theorizing is precisely because connectionist models learn. These models allow one to model the mechanisms of developmental change itself. Traditional developmental models do not model development in the sense of providing a mechanism for change. Neither of the two most detailed current models of the development of similarity, Smith's (1989a) model of the development of perceptual classification or Gentner's (1989) model of the development of analogical reasoning, provide a mechanism for developmental change. Each model offers a unified account of very young children's performances and adult performances. Smith's model is made to fit both immature and mature classifications by altering a few parameters such as the attention weights. Gentner modeled developmental differences by running the model in different modes (a literal similarity mode versus an analogy mode). In both cases, the adjustments to parameters or the mode of operation are accomplished by the theorist, not the theory. Developmental growth occurs outside the model. The computational and mathematical procedures of connectionist modeling provide theoretical mechanisms for putting developmental change *in* models of performance. Developmental psychologists are becoming increasingly aware of the relevance of these computational devices to their field (e.g., Ellman, 1991; McClelland, 1991; Plunkett & Marchman, 1989; Siegler, 1989).

1. *A Brief Tutorial on Connectionism*

Before turning to Gasser and Smith's model, it is helpful to consider the basics of connectionism in terms of a simple sample network. The simplest connectionist network is one consisting of two layers of units as in Fig. 7. The bottom layer of units is the input layer and the top layer is the output layer. Each unit in the input layer is connected to every unit in the output layer. This pattern of connectivity is called complete connectivity. Activity on the input layer causes

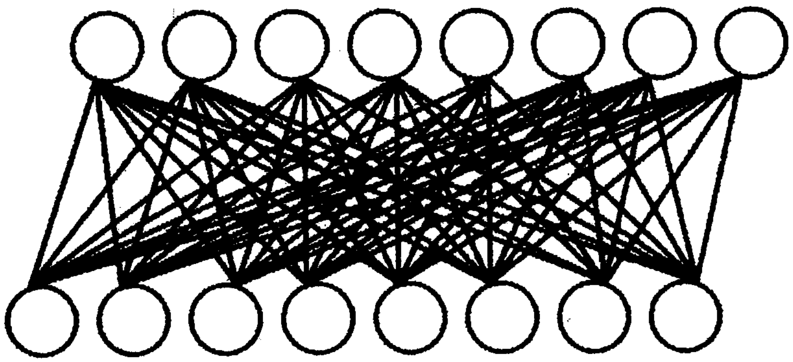

Fig. 7. A simple two-layer connectionist network.

activity on the output layer but not vice versa; in other words, the connections are unidirectional. Although each input unit is connected to every output unit in this example network, the pattern of connectivity of this network is not completely specified until we specify the strength of each individual connection and the function that combines all the inputs that converge on a single output unit. A typical approach in connectionist models is to assume that the total input to a unit is simply the weighted sum of the separate inputs. In other words, each input is multiplied by a weight and summed to get the total input to a unit. The pattern of connectivity is thus totally specified by specifying the weights for each of the connections in the network. In connectionist models that learn these weights are determined by learning. Thus, a connectionist theory must also include a definition of the learning rule and the learning environment.

Learning rules in connectionist models are based on the Hebbian learning rule (Hebb, 1949): If a unit u_i receives an input from another unit u_j and both are then highly active, the strength or weight of the connection between the two w_{ij} is increased. Many typical connectionist models employ a variant on this learning scheme in which there is a teaching function. The amount and direction of change of connection weights depend on whether the output was right or not. In terms of our simple example network in Fig. 7, it is as if there were a teacher looking down on the pattern of activation on the output layer and judging how close that output is to the target or right answer. The magnitude of the error between each output unit and the target output is then used in the rule that changes connection weights between individual units. This learning is often called *local* because the error is calculated separately for each output unit; there is no global measure of how close the pattern of output was overall. Rather, each output unit is evaluated independently, and changes to one connection weight in

the network are made independently of changes to other connection weights. In this learning scheme, the error and the resulting weight changes are propagated backward from output to input unit and thus one common learning algorithm—and the one used by Gasser and Smith—is called *back propagation*. The learning environment is the set of experiences presented to the network and the targets (or right answers) proscribed by the teacher to those inputs.

One final term to be defined is the *architecture* of a network. The example network in Fig. 7 has a very simple architecture: two layers of cells and complete connectivity between them. More complicated architectures are possible. For example, we might have three layers of units, with the input and output layers possessing lots of units but the middle layer (sometimes called the hidden layer) possessing very few. This bottleneck in the middle will cause a compression of many input patterns into fewer possible patterns on the middle layer. The architecture of an individual connectionist model (usually) constitutes the specific psychological claims of that model.

2. *Do These Assumptions about Learning Make Sense for a Model of Development?*

The attraction of connectionist models to developmental theorists is that they develop; they grow and change in response to the regularities in the input. Thus, the source of development in a connectionist model is not a maturational plan; no internal blueprint tells the network how to grow. Instead, development happens as a result of a network with a particular architecture being placed in a particular environment. Many (but not all) connectionist models involve a teacher. Criticisms have been lodged against connectionist models that require a "teacher" because in many developmental tasks, no external teacher is obviously present. These criticisms are relevant in the present case because the learning rule in NIEC presumes a teacher.

Although there is no obvious teacher for some developmental tasks, there is an obvious teacher in the case of just word learning, the learning that causes similarity to develop in Gasser and Smith's model. Children learn their first words through explicit teaching; adults provide both positive and negative evidence as to the objects and properties that a word refers to. Adults as part of their regular interaction with children set word learning tasks before them. They ask questions about what words apply to an object and they label objects. They say such things as "What is that? It's a dog" in the presence of an object. Adults provide appropriate feedback. When a child labels a dog as *cat* or a red object as *green*, parents tell the child what the correct labels are. Gasser and Smith asked how such learning might cause changes in similarity by asking what NIEC would learn when situated in a learning environment like the one that exists for children in learning words.

B. HOW THE MODEL WORKS

NIEC is much more complicated than the simple two-layer network shown in Fig. 7. Its architecture is shown in Fig. 8. By convention, the architecture is illustrated without showing the individual units. Each box is a layer of units. The number of units at each layer (in each box) varies from 28 at the visual input layer to just 1 at the similarity output layer. The large arrows indicate complete connectivity between layers of units. Thus, every unit in the visual input layer is connected to every other unit in the perceived object layer just as in the connection between the two layers in the simple example. The architecture of NIEC can be thought of in terms of two distinct but overlapping subnetworks: (1) the layers involved in implicit similarity judgments and (2) the layers involved in explicit similarity judgments.

1. Implicit Similarity Network

1. The *visual input* layer consists of 28 units. There are four units for each of four dimensions. Thus, the input at this layer uses a form of localized representation; individual inputs (color or size) are represented by specific units and not the distributed pattern across units. Localized representation is used for the sensory

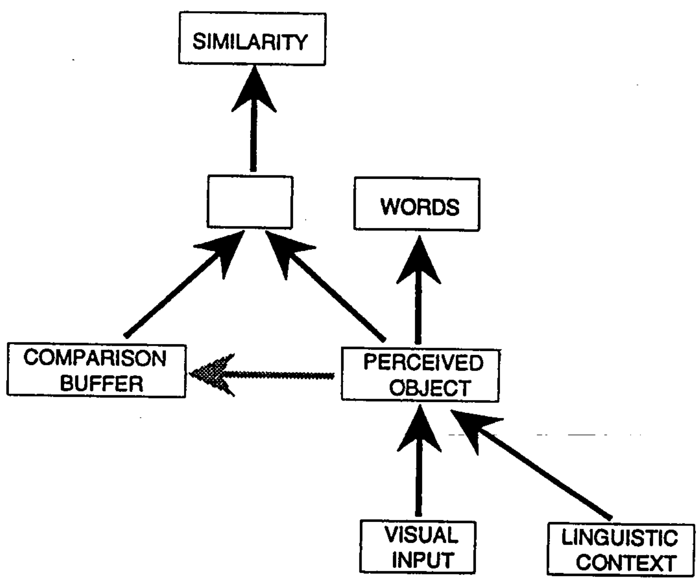

Fig. 8. Layers and interconnections that make up NIEC.

input because the extant research indicates the existence of separate sensory analyzers for individual dimensions.

2. The *perceived object layer* contains 21 units. The momentary activation on this layer corresponds to subjective experience at that moment. Because there is complete connectivity between the visual input layer and this layer and because the visual input layer contains more units than the perceived object layer, the four dimensions that are separate (localized) at the visual object layer are distributed at the perceived object layer. In other words, the perceived object layer compresses the visual input so that the sensory dimensions that are independent at the visual input layer are not directly recoverable (prior to training) in the activity of individual units at the perceived object layer. The psychological idea is that subjective experience is (most primitively) of unitary wholes (see also Smith, 1989a). The perceptual experience of dimensions and separate object attributes is not given. Rather, the dimensions that are separate in the sensory input and possibly new dimensions that are complicated combinations of the sensory dimensions are discoverable only through learning.

3. The *linguistic context* layer is a second input layer to the perceived object layer. This layer of units corresponds to the linguistic question or input posed by the "parent" and may consist of questions such as *What color is it? What is it? Is it red?* and *Is it a dax?* At present, the model uses a localized representation of linguistic context—one unit for each kind of question. Specifically, one unit is activated when there is a question about color, another when there is a question about size, another when there is a question about texture, and another when there is a question about category membership. With training, specific patterns of activation on the linguistic context layer should become associated with certain inputs and targets such that the pattern of activation on the linguistic input layer comes to shift attention among the learned dimensions. Thus, given a specific pattern of visual input (a specific object) and the linguistic input *what color is it?* the pattern of activation on the perceived object layer should correspond to the color of the object, but given the same visual input and the question *what is it?* the pattern of activation on the perceived object layer should look different and correspond to the shape information critical for naming objects. In this model, linguistic context serves as a modulator of attention; it is the joint input of the visual object with its particular properties and a question about the object that determine the connection weights and, hence, the patterns of activation. Thus, NIEC implements the finding that language acquires attention-recruiting properties; however, in terms of the operations of the model, the relevant context need not be linguistic. Any context (e.g., eyes) could acquire attention-recruiting powers. NIEC therefore has the potential to model prelinguistic changes in similarity as well as those caused by language learning.

4. The *word* level corresponds to the internal representation of words such as *red, big, dog,* and *chair.* In the illustrated version of the model, this layer is the

output layer: the network is presented with a visual input in a linguistic context, perceives that input, and labels the object with a nominal (*dog*) or a dimensional adjective (*red*). Again, this layer uses localized representations: one unit corresponds to each word.

2. *Explicit Similarity Network*

Explicit similarity is a two-place relation. It requires two perceived objects as inputs and it outputs a single judgment of similarity. Gasser and Smith's model accomplishes this comparison in a manner similar to that of Rumelhart, Hinton, and Williams (1986). Explicit similarity judgments make use of six of the eight layers. Three of these are identical to the layers involved in implicit judgments: the visual input layer, the linguistic context layer, and the perceived object layer.

The new layers consist of, first, a *comparison buffer*. Comparison requires the maintenance of two perceived objects in short-term memory. The comparison buffer copies the pattern of activation of the perceived object layer and maintains it for a first object while a second visual pattern is input to the perceived object layer. The patterns corresponding to the two compared objects thus appear on separate groups of units: the comparison buffer and the perceived object layer.

The remaining two new layers make up the pattern associator for explicit similarity judgments. These layers operate like the device introduced in Fig. 5. This associator includes what is called a hidden layer or bank of intervening units. The output layer, the *similarity layer,* consists of a single unit that fires when objects are the same. This similarity-detection device is thus "dumb"; it does not know what is being compared or the dimensions along which objects are compared. It is, however, a universal device that makes all kinds of sameness judgments. The work of making different kinds of sameness judgments—same thing, same color, same size—is accomplished at the perceived object layer through the same selective attention mechanisms involved in implicit similarity. So, for example, if the linguistic context is the question "Are these the same color?" then (given learning and changes in connection weights) the two patterns of activation at the perceived object layer should emphasize color, and if the objects are the same color these patterns of activation should be similar enough so that when they are input to the pattern associator, the output of the similarity layer is "same."

C. A SIMULATION: LEARNING ATTRIBUTES AND DIMENSIONS

I present in some detail one set of simulations of the development of similarity. This set of simulations was concerned with the development of the ability to attend selectively to the individual attributes of object—the kind of selective attention that seems to underlie the ability to acquire dimensional adjectives such as *red* and *blue* and *big* and *little*. This simulation asks how a really good selective attention device might develop from one that has only global perceptual experiences (the perceived object layer) based on the holistic (compressed) combination of sensory inputs. The results of this simulation show how learning to attend selectively might be the product of language learning and, more specifically, the joint product of learning to solve implicit and explicit similarity tasks simultaneously.

One is tempted to assume that if a network (or a child) can label red objects *red,* it does so by isolating red from all other aspects of the perceptual information. There are, however, mechanisms, such as connectionist nets, in which this assumption is not correct. In the distributed representations of the perceived object layer, all that is needed for red objects to be called *red* is a pattern of connection weights that cause the correct output unit to reach threshold. How this unit reaches threshold does not matter and because there are a large number of connections to the right output unit; that unit can reach threshold in a variety of different ways. In other words, a large number of multiple patterns of activation at a preceding layer can lead to a single output at the next layer. This aspect of connectionist networks is what makes them such good pattern learners, but it also means that the network might not discover an invariant meaning when one actually exists, as in the case of red.

In one simulation, Gasser and Smith (1991) showed that learning attribute terms did not require learning to isolate particular object properties. They taught the network dimensional adjectives on three dimensions—*red, blue, green, big, little, bumpy, smooth*—by presenting the network with randomly selected visual inputs and randomly selected linguistic contexts: *What color is it? What size is it? What texture is it?* The network learned to correctly answer these questions, reaching an asymptote of 100% in 1000 trials. At this point, Gasser and Smith looked inside the network to see what the patterns of activation at the perceived object layer looked like. Were the patterns of activation for all red objects on trials on which the objects were correctly labeled *red* similar? Were the patterns of activation for all green objects correctly labeled *green* similar, for the *big* objects, the *little* objects, and so on? The answers to these questions should be "yes" if, in learning attribute terms, the network has discovered a common property that is present for all red objects. The answers to these questions will be no if the network has learned only to associate unique multiple patterns that include information about the unique properties of individual objects as well as information about the queried dimension.

The data showed that the network did not discover invariants in the input for each attribute. In other words, in learning to call red objects *red,* the network did not learn to isolate redness. The patterns of activation at the perceived object for objects being correctly labeled by the same label did not look at all alike; thus, in terms of the activation at the perceived object layer, *red* is a disjunctive category after this training.

This simulation constitutes a demonstration proof that young children could correctly use a dimensional adjective such as *red* without having an understanding or a conscious experience of all red things as containing a common component. Just like the network learned to use dimensional adjectives correctly without discovering invariants in the visual input, so children could achieve correct performance in complex and syncretic ways without isolating single attributes. The idea that children might correctly use dimensional adjectives without actually being able to attend selectively to the correctly labeled attributes fits the developmental data. By the time they are 3 or 4 years old, children know many dimensional adjectives; they can call red objects *red* and big objects *big* (e.g., Smith, 1984). At the same time, however, 3- and 4-year-old children perform poorly in other tasks that require them to attend selectively to one dimension and ignore another (e.g., Kemler, 1983; Smith, 1989a). These results also suggest that the shape bias, the association between attending to shape and the linguistic context of naming, does not require precise selective attention to shape.

As adults, we do perceive certain attributes of objects, the ones Garner (1974) called *separable,* as unitary and as independent of the other properties of an object. Moreover, adults easily attend selectively to separable attributes such as color and ignore other separable properties such as size and texture (e.g., Garner, 1974). Accordingly, Gasser and Smith (1991) asked whether their network could develop invariant patterns of activation for individual attributes through training in explicit similarity judgments. The network was trained to answer the questions "Are these the same color?" "Are these the same size?" and "Are these the same texture" about pairs of visual inputs. This explicit similarity task is far more demanding and more constraining than the implicit similarity task of learning to label the attributes of objects. For the network to judge explicitly that two objects that are vastly different on all dimensions but size are the same size, it must develop patterns of activation at the perceived object layer that are near identical (given the appropriate linguistic context). Put another way, when the network is asked a question about sameness in size, the network must somehow filter out all information about other dimensions. Even small contamination from irrelevant dimensions will adversely affect the output of the explicit similarity layer. How can a network filter out irrelevant dimensions? It can do so by developing a set of connections from the linguistic context and visual input to the perceived object layer that result in a common pattern of activation whenever the visual input contains a particular property and that property is the queried property.

Gasser and Smith (1991) trained the network to make explicit similarity judgments along color, size, and texture after the network had been trained in the implicit similarity task described earlier. During this second phase of training in explicit similarity, the network also continued to receive implicit similarity trials half the time. After this second phase of training, Gasser and Smith reexamined the patterns of activation at the perceived object layer in the implicit similarity task. The results showed that training in explicit similarity had caused the network to change the way it made implicit similarity judgments despite the fact that it had made such judgments perfectly at the start of training in explicit similarity. Training in explicit similarity resulted in each attribute term becoming associated with a specific and fixed pattern of activity on the perceived object layer. Put another way, *red* had become one thing.

Importantly, subsequent simulations showed that learning in both the implicit and explicit similarity tasks may be required for the development of a common pattern of internal activity for all instances of an attribute. Although the explicit similarity task alone should, in principle, be sufficient to develop unitary patterns of activation for each attribute, in practice, the explicit similarity task presented by itself without the prior learning of individual attribute labels is nearly impossible for the network to solve. Rather explicit similarity learning is best bootstrapped to implicit similarity learning. Apparently, the prior learning of attribute names pushes the connection weights between input and the perceived object layer sufficiently far enough in the proper direction that the network can discover the solution to the explicit similarity task. The discovery of invariants for individual attributes—the development of the ability to attend selectively—is thus the joint product of learning in two different kinds of similarity tasks.

Several implications may be drawn from these results. One implication concerns the development of selective attention and the differentiation of attributes and dimensions. The results of this simulation suggest that children may have to discover individual attributes and dimensions through learning and that the kind of learning that is critical involves explicit comparison but such explicit comparison may have to be bootstrapped on prior partial progress in the labeling of individual attributes. A second implication has more general significance for developmental theorizing. In learning to make explicit similarity judgments, the network learned more about both implicit and explicit similarity. In sum, there are multiple ways to solve different psychological tasks and the particular solution discovered may be constrained by the other tasks that must be simultaneously solved.

In subsequent simulations, Gasser and Smith showed that the network could simultaneously learn complex categories based on family resemblance, attributes, and explicit sameness judgments along dimensions. Consistent with the developmental data, family resemblance categories that required even less precise selective attention to single dimensions (though perhaps an emphasis on shape) were easier to learn than were attribute categories. The results from these other studies suggest that the reason a shape bias develops readily in nominal contexts but labeling attributes develops slowly may be found in the greater frequency of nominals relative to attribute terms and the relative ease of learning to emphasize (imprecisely) one dimension than to shift between weighting schemes depending on which specific dimension one is asked about.

D. RELATING RELATIONS

How could the network solve one of Gentner's analogy tasks? For example, how could the NIEC know that sameness in color is *like* sameness in size? How might this network solve Premack's problem and know that two *sames* are like two *differents?* Gasser and Smith have not yet addressed the problem of relating relations; however, one solution to the relating relations problem is clearly suggested by the network's architecture. This solution is to allow the network to reenter its own outputs into the perceived object layer. This is illustrated in Fig. 9. The implicit and explicit similarity judgments would then be based on a mix of the visual input, the linguistic context, *and* the specific judgment the network had just made. With training, NIEC could (perhaps) learn to attend to its own outputs. If the network reentered its own output and learned in certain contexts to attend principally to its own output, it would have a mechanism for knowing that two *sames* and two *differents* were both instances of *same.*

This suggested mechanism for the development of relational similarity suggests a key role for language. Relational similarity would await the development

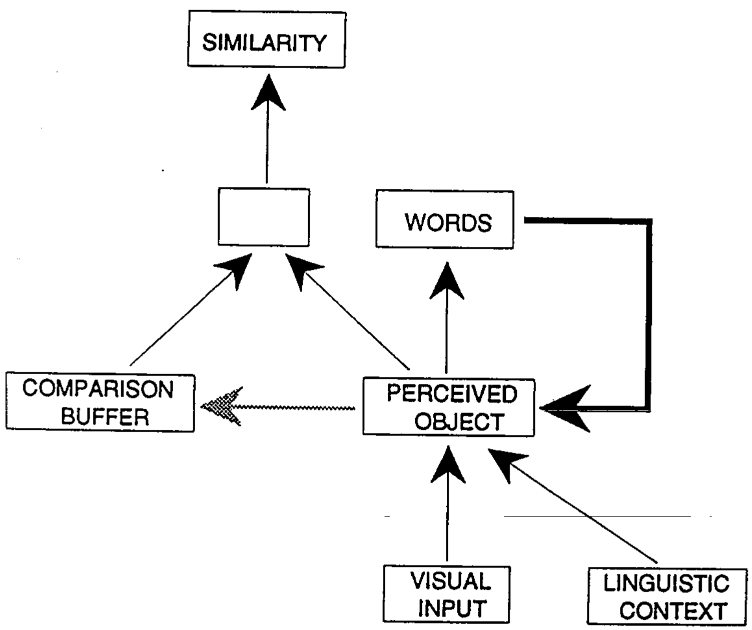

Fig. 9. Proposed addition to NIEC for the handling of relations between relations.

of outputs that could be input back into the system. Both Premack (1978) and Gentner and Rattermann (1991) have suggested that learning the words for relations may be the critical factor in the development of the ability to relate relations. The present suggestion is that the labeling of the relations provides a mechanism through which relations themselves can be re-input into the system as the arguments of other relations.

E. ROLE OF LANGUAGE

NIEC places a heavy burden on language learning generally. Language learning is the causal force behind the development of implicit similarity and dimensional forms of explicit similarity, as well as perhaps relational similarity. Language training is the variable that moves the network from holistic implicit and explicit similarity to category-specific similarity judgments and dimensional kinds of similarity. The question asked of the network is the linguistic context, that is, the critical input that enables the network to attend to different properties of the same perceptual input for different purposes.

One might argue, reasonably, that this model gives language and language learning too much power and that it is just a modern-day version of mediation theory (e.g., Kendler, 1964) or a later-day equating of symbolic thought with verbal thought (e.g., Bruner, 1957). This argument can be answered in two ways. First, language is just one kind of context that the child might learn about and that might serve as useful input that effectively recruits attention. The model would operate in precisely the same way if we labeled the linguistic context "bodily position" context or "nesting cups" context or "the sound of mother's voice" context. That is, if the relationships between the dimensions relevant for categorization and situational cues exhibit regularities of any kind, this network can learn to shift its attention weights in category- and task-relevant ways in response to the presence of those contextual cues. Although language learning is emphasized here, the development of similarity is likely to begin considerably prior to language learning (see Smith & Heise, in press, for a relevant discussion).

Second, I suspect that the dimensionalization and articulation of similarity relations do depend heavily on language learning. The learning of dimensional language both presents and systematically demands the differentiation of dimensional kinds of similarity and may present the key information for certain aspects of dimensional structure (Landau & Gleitman, 1985; Smith & Sera, 1992). The argument is not that language is necessary for the development of a dimensionalized similarity system, but it may be sufficient and, moreover, language learning may be the most typical and most demanding kind of learning that pushes for such developments in the human species.

F. LABELED AND UNLABELED SIMILARITY

In NIEC, implicit similarity judgments are achieved without the isolation of separate features and attributes, even for implicit similarity judgments that ostensibly name perceptual attributes such as *red* and for judgments of complex categories. In Gasser and Smith's simulations, the patterns of activity that underlie the network's judgments of membership in complex categories such as *dogs* do not look like anything. The clusters of activity at the perceived object layer do not look like conjunctions of the patterns of activity that give rise to attribute names. Complex categories are not made up of lists of namable features. In brief, the features of categorization need not be the features of explicit comparison and the features we talk about need not be the features that are used in all similarity judgment tasks.

These facts of NIEC have profound consequences for how we proceed as psychologists. They mean that we cannot decide between theories of similarity simply by introspection and logical argument (see Keil, 1989; Murphy & Medin, 1985, for examples of such attempts). For example, when we look at the set of objects in Fig. 1, we are tempted to describe the perceptual similarities with terms such as *same shape and color* and *different shape and color*. In doing so, we describe the stimuli in terms of the dimensions and features that language learning has made articulate; however, these labeled similarities may not correspond in any one-to-one fashion to the inarticulate similarities that subjects are actually using to identify category members and that depend systematically on task and linguistic context. In other words, both unlabeled and labeled forms of similarity are products of our complex similarity system; one is not the progenitor of the other. We have to understand the processes that lead to each kind of similarity judgment and we must avoid the temptation of trying to explain one kind of similarity in terms of the other.

V. Psychological Facts and Philosophical Problems

The psychological facts of similarity are these: A single concept of *same* applies across diverse perceptual inputs. Similarity is dynamic and context dependent and thus the similarity between individual objects is not constant. Multiple kinds of features, dimensions, and relations can enter into the calculation of similarity and whether or not they do depends on the stimuli and task context. Similarity develops and, through experience, comes to embody the systematic relations that exist between words and the perceptual properties of objects. With development, attention to particular properties and relations becomes associated with other properties and linguistic contexts. With development, namable attributes, dimensions, and relational forms of similarity emerge.

Thus, the concept of *same* is unitary but variable. The concept of *same* is unitary because a single mechanism (the explicit similarity device) takes internal representations corresponding to individual objects (or relations) and compares them. *Same* has multiple forms as in same thing, same color, same relation, because the internal representations that are input to the explicit similarity device vary. But they vary in ways that make the device intelligent, in ways that reflect the regularities between the properties of objects and language. Similarity is adaptively dynamic.

Psychological similarity, however, may seem incoherent to philosophers, rather than laudably "adaptively dynamic," because the multiple forms of similarity—implicit and explicit and unlabeled and labeled—are easy to confuse. Philosophers worry that the different aspects of similarity do not logically fit together. They may not logically fit together but they psychologically and developmentally do. The developmental data and NIEC's fit of them suggest that the facts of similarity derive from the operation of an adaptive network composed of heterogeneous yet overlapping processes. The philosopher Goodman worried that similarity is incoherent. If it is, it is a good kind of incoherence. The very properties of similarity that give philosophers pause—the unitary, dynamic, multiple-feature, context-dependent nature of similarity—may be the properties that give similarity its psychological power, utility, and creativity.

ACKNOWLEDGMENTS

I thank Michael Gasser, Rob Goldstone, Susan Jones, Dedre Gentner, Doug Medin, and Hayne Reese for comments on the manuscript. The research reported in this article was partially supported by a Multiventures Research Award (Indiana University) to Linda Smith and Michael Gasser and US-PHS Grant R01 HD-28675 to Linda Smith.

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