Analogical Processes in Human Thinking and Learning

Dedre Gentner and Julie Colhoun

Abstract Much of humankind's remarkable mental aptitude can be attributed to analogical ability – the ability to perceive and use relational similarity. In this chapter, we present an overview of analogy and describe its component processes, including structural alignment and inference projection, evaluation, schema abstraction and re-representation. We discuss how these component processes lead to learning and the generation of new knowledge, and review evidence that suggests that greater use of analogy during learning can improve relational retrieval and transfer.

1 Introduction

Similarity and association are two great forces of mental organization that hold across species. Although humans probably experience the same kinds of intuitive connections as do hamsters, our species also experiences a more sophisticated form of each of these two forces: namely, analogy (a selective form of similarity) and causation (a selective form of association). In this chapter we focus on analogy – the perception of like relational patterns across different contexts. The ability to perceive and use purely relational similarity is a major contributor – arguably *the* major contributor – to our species' remarkable mental agility (Gentner 2003; Gentner and Christie 2008; Kurtz et al. 1999; Penn et al. 2008). Understanding how it works is thus important in any account of "why we're so smart" (Gentner 2003).

A good analogy both reveals common structure between two situations and suggests further inferences. For example, discussions of cell biology sometimes explain cell metabolism by analogy with a fire:

D. Gentner (✉) and J. Colhoun
Department of Psychology, Northwestern University, Evanston, 60208, IL, USA
e-mail: gentner@northwestern.edu

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- A fire consumes fuel using oxygen, thereby releasing energy; it releases carbon dioxide and water.
- Likewise, a cell's mitochondria obtain energy from glucose using oxygen, in a process called oxidation.

This analogy highlights the common relational structure: that cell metabolism can be seen as the burning of fuel, and fire as a form of oxidation. It also invites the (correct) inference that cell metabolism releases water and carbon dioxide. In such explanatory analogies, a familiar situation, referred to as the *base* or *source* analog, is used as a model by which to understand and draw new inferences to the unfamiliar situation or *target*. Recent research has also focused on another use of analogy in learning – namely, to reveal the common structure between two situations, neither of which needs to have been fully understood before the comparison. In this paper, we begin by presenting an overview of analogy and its component processes. We then discuss each component process in greater detail.

2 Analogical Processes

Theories of analogy distinguish the following processes: (1) *retrieval*: given some current situation in working memory, a prior similar or analogous example may be retrieved from long-term memory; (2) *mapping*: given two cases in working memory, mapping consists of *aligning* their representational structures to derive the commonalities and *projecting inferences* from one analog to the other. Mapping is followed by (3) *evaluation* of the analogy and its inferences and often by (4) *abstraction* of the structure common to both analogs. A further process that may occur in the course of mapping is (5) *re-representation*: adaptation of one or both representations to improve the match. We begin with the processes of mapping through re-representation, reserving retrieval for later.

2.1 Mapping

Mapping is the heart of analogy, and, not surprisingly, it has been a central focus in analogy research. According to Gentner's (Gentner 1983, 1989; Gentner and Markman 1997) structure-mapping theory, analogical mapping is the process of establishing a *structural alignment* between two represented situations and then projecting *inferences*. The theory assumes structured representations in which the elements are connected by labeled relations, and higher-order relations (such as causal relations) connect first-order statements (see Falkenhainer et al. 1989; Markman 1999). During the alignment process (as amplified below), possible matches are first found between individual elements of the two represented situations; then these matches are combined into structurally consistent clusters, and finally into an overall mapping. The resulting alignment consists of an explicit set of correspondences between the sets of representational elements of the two situations, with an emphasis on matching relational predicates. As a natural outcome of the alignment process, candidate inferences are projected from the base to the target. These inferences are propositions connected to the common system in one analog, but not yet present in the other. An example from our earlier analogy is the inference that cell metabolism produces CO_2 and water as by-products.

The alignment process is guided by a set of tacit constraints that lead to structural consistency: (a) there must be *one-to-one correspondence* between the mapped elements in the target and base, and (b) there must be *parallel connectivity,* such that the arguments of corresponding predicates also correspond. A further assumption is the *systematicity principle:* in selecting among possible interpretations of an analogy, a system of relations that are connected by higher-order constraining relations (such as causal relations) is preferred over an equal number of independent matches. This principle guides the selection of an alignment, such that the more systematic of two possible alignments will be chosen. The systematicity principle reflects an implicit preference for coherence and predictive power in analogical processing. Thus, a base domain that possesses a richly linked system of relations will yield candidate inferences by completing the corresponding structure in the target (Bowdle and Gentner 1997).

The mapping process has been operationalized in the Structure Mapping Engine (SME; Falkenhainer et al. 1989), a computational model that instantiates Gentner's (1983) structure-mapping theory. This system operates in a local to global fashion, first finding all possible local matches between the elements of two potential analogs. It combines these into structurally consistent clusters, and then combines the clusters (called kernels) into the largest and most deeply connected system of matches. As noted above, other propositions connected to the common system in one analog become candidate inferences about the other analog. Finally, SME generates a structural evaluation of the match (see Forbus et al. 1995, for details).

The claim that analogical processing is symmetric at the outset might seem surprising, given the strong directionality of many analogies. For example, the statement "My surgeon is like a butcher" conveys a very different set of inferences from "My butcher is like a surgeon." This strong directionality has led some researchers to suggest that the processing of metaphors (Glucksberg et al. 1997) and analogies (Greiner 1988; Hummel and Holyoak 1997) is asymmetric from the start. However, according to structure-mapping, although inference projection is directional, it is guided by an initial alignment that is symmetric.

To test whether the initial stage is indeed symmetric, Wolff and Gentner (2000) and Gentner and Wolff (1997) investigated the processing of highly directional metaphors. These metaphors, like many of the metaphors used in psychological research, were essentially analogies, in that they conveyed a matching relational system: e.g., "Some jobs are jails." Furthermore, they were highly directional (Ortony 1979): "Some jobs are jails" is not at all the same as saying (quite incomprehensibly) "Some jails are jobs." In one series of studies, Wolff and Gentner (in preparation) gave participants these forward and reversed metaphors in a speeded task (in either forward or reversed direction) and asked them to press either "comprehensible" or "not comprehensible." The results suggested that metaphor processing is symmetrical in the initial stages. At 600 ms, participants found forward and reversed metaphors equally comprehensible; not until roughly 1,200 ms did they show higher comprehension of the forward than of the reversed metaphors. This result did not stem from inability to process meaning at 600 ms, because even at this early deadline, participants rejected scrambled metaphors ("Some butchers are flutes") as incomprehensible and accepted literally true statements ("Some birds are robins") as comprehensible. This pattern of early symmetry followed by later directionality is in accord with the structure-mapping prediction of an initial symmetric alignment followed by later directional inferences from base to target (Gentner 1983, 1989; Falkenhainer et al. 1989).

2.2 *Structural Alignment in Similarity and Analogy*

The framework originally developed for analogy extends to literal similarity, as demonstrated by a series of studies at the University of Illinois in the 1990s (Gentner and Markman 1995, 1997; Goldstone et al. 1991; Markman and Gentner 1993a,b,c; Medin et al. 1993). The distinction between analogy and literal similarity can be thought of within a similarity space defined by the degree of object–attribute similarity and the degree of relational similarity, as shown in Fig. 1 (Gentner & Markman 1997). Analogy and literal similarity lie on a continuum based on the degree of object–attribute similarity between the items being compared. When a comparison exhibits a high degree of relational similarity with very little attribute similarity, we consider it an analogy. As the amount of attribute similarity increases, the comparison becomes one of literal similarity. This is not merely a matter of terminology. Literal similarity matches are easier to make (and

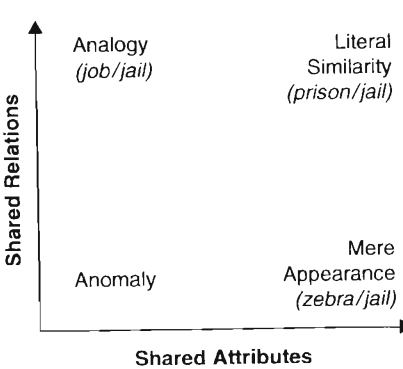

Fig. 1 Similarity space defined by the degree of object–attribute similarity and the degree of relational similarity. Adapted from Gentner and Markman (1997)

more accessible to novices and children) than analogies because the alignment of relational structure is supported by object matches.

Recent developmental research has shown that young learners can take advantage of close literal similarity matches to gain the beginnings of relational insight. Even a highly concrete literal similarity match involves an alignment of the relational structure, and that carrying out an "easy" literal match can render learners to better carry out a difficult relational match. For example, Loewenstein and Gentner (2001) give children (aged 3½) a challenging search task (DeLoache 1987). Children watched the experimenter hide a toy in a small model room (the Hiding room), and then tried find the toy hidden "in the same place" in a second model room (the Finding room). The two rooms contained the same type of furniture (bed, table, etc.) in the same configuration, but were rather dissimilar in the specific shapes of their furniture, making the mapping task difficult for these young children. Before engaging in the task, all the children were shown the Hiding room along with another very similar room (identical except for color). Half the children saw the two rooms together and were encouraged to compare them; the other half talked about each room separately. Children in the comparison condition were significantly more likely to correctly locate the toy in the Finding room than those who saw the rooms separately.

These findings have two important implications. First, the finding that even comparing close literally similar examples can promote highlighting of the common relational structure is further evidence that "similarity is like analogy" in promoting a structural alignment (Gentner and Markman 1995). Second, the finding that an easily aligned literal match can bootstrap young children to a more distant relational mapping offers a route by which children's ordinary experiential learning can gradually lead them to the discovery of analogical matches (Gentner and Medina 1998).

This progressive alignment process can help to dispel the mystery of how abstract ideas can arise from experience. Consider the example of monotonic change as it might first be learned by a child in a highly concrete context, such as the descending heights of a "Daddy Mommy Baby" set of dolls. The relational structure of descending size is at first implicit and embedded in the specific family context. At this stage the child would not recognize that the same structure occurs in, say, a set of bowls of decreasing diameter. But if the child is given a close match – say, a different set of descending-size dolls – then the obvious similarities will prompt an alignment process and help to guide it. Miraculously, even such a close alignment can elevate the salience of the common relational structure, thereby potentiating a subsequent more distant match, such as that between the dolls and the bowls. If this process continues – with each new analog clarifying and refining the common structure further – the result can become steadily more abstract (see Kotovsky and Gentner 1996, as discussed later, for an example). These close alignments, so mundane as to be nearly invisible to adults, can nonetheless accumulate, resulting in significant gains in learning.

Literal similarity supports the mapping process, but in some cases, object matches among elements of compared items can be a pitfall. Specifically, when items are *cross-mapped* (Gentner and Toupin 1986) – that is, when similar (or identical) objects play different roles in the relational structure of each analog – the object match can be difficult to ignore. For example, if one analog describes a dog chasing a cat and the other describes a cat chasing a mouse, the cat is said to be cross-mapped. Such cross-mappings can be compelling for children and novices, especially if the object matches are rich and distinctive (Gentner and Rattermann 1991; Paik and Mix 2006). In general, the deeper and better-established the relational structure (as comes with expertise), the better a cross-mapping can be withstood (Gentner and Rattermann 1991; Gentner and Toupin 1986; Markman and Gentner 1993c).

2.3 Systematicity

The role of relational structure in analogical processing is more specific than a simple preference for relational commonalities over attribute or object matches. Ultimately, what makes comparison so revealing is that (for whatever reason) people like to find connected relational structure. Thus, the analogical interpretation process seeks matches that consist of interconnected systems of relations. As noted above, this preference for systematic interpretations is known as the systematicity principle. The claim that comparison promotes systems of interrelated knowledge is crucial to analogy's viability as a reasoning process. If the comparison process were to generate only isolated feature matches, there would be no natural basis for constraining which inferences are derived from the match.

In order to test whether systematicity constrains analogical matching, Clement and Gentner (1991) showed participants analogous scenarios and asked them to judge which of two lower-order assertions shared by the base and target was most important to the match. Participants chose the assertion that was connected to matching causal antecedents – their choice was based not only on the goodness of the local match, but also on whether it was connected to the larger matching system. Thus, matching lower-order relations such as (causal antecedents) that are interconnected by higher-order relations yield a better analogical match than an equal number of matching relations that are unconnected to each other.

A parallel result was found for inference projection: people were more likely to import a fact from the base to the target when it was connected to the common system (Clement and Gentner 1991; Markman 1997). In analogical matching, people are not interested in isolated coincidental matches; rather, they seek causal and logical connections, which give analogy its inferential power. The critical finding that systematicity guides inference also carries over to similarity comparisons. Bowdle and Gentner (1997) gave participants pairs of similar scenarios (without distinguishing base and target) and asked for inferences. Participants preferred to make inferences from a systematic structure to a less systematic structure and also judged comparisons to be more informative in this direction than the reverse. Similarly, Heit and Rubinstein (1994) demonstrated that people make stronger inferences when the kind of property to be inferred (anatomical or behavioral) matches the kind of similarity between the animals (anatomical or behavioral). For instance, people make stronger behavioral inferences from tuna to whales (because both share behavioral capacities related to swimming) than from bears to whales, but stronger anatomical inferences from whales to bears (because both are mammals and therefore share an internal system of anatomical relations). These findings are consistent with the claim that people are strongly influenced by systematicity when drawing inferences from comparisons.

2.4 *Evaluation*

Although we have already alluded to evaluation in the course of this discussion, a few further points require mention. Specifically, evaluating an analogy and its inferences involves several kinds of judgment. One criterion is structural soundness: whether the alignment and the projected inferences are structurally consistent. With respect to particular candidate inferences, this translates to the amount of structural support the alignment provides for the inference. In addition to structural support, Forbus et al. (1997) suggest that another criterion may be the amount of new knowledge generated. That is, inferences that potentially yield a significant gain in new knowledge may be desirable (even if somewhat risky), especially when brainstorming or dealing with unfamiliar domains.

Another criterion, of course, is the factual validity of the projected inferences in the target. Because analogy is not a deductive mechanism, these candidate inferences are only hypotheses; their factual validity is not guaranteed by their structural consistency and must be checked separately. Thus, this type of evaluation may involve other reasoning processes such as causal reasoning from existing knowledge in the target. A fourth criterion, which applies in problem-solving situations, is pragmatic relevance – whether the analogical inferences are relevant to the current goals (Holyoak and Thagard 1989). An analogy may be structurally sound and yield true inferences, but still fail the relevance criterion if it does not bear on the problem at hand. A related criterion, discussed by Keane (1996), is the adaptability of the inferences to the target problem.

The evaluation of inferences and of the whole analogy can mutually influence one another. Evaluation of particular inferences contributes to the larger evaluation of the analogy, and if particular inferences are clearly false, the analogy loses force. Likewise, if the analogy consists of a poor structural match, the inferences garner less confidence.

3 Learning

There are three main ways in which an analogy can lead to learning and representational change in one or both analogs: projection of candidate inferences, schema abstraction – in which the highlighted relational structure is extracted and stored – and re-representation of the constituent predicates of the analogs (Clement and Gentner 1991; Clement 1988; Holyoak and Thagard 1989). We have already discussed candidate inferences; we will now discuss each of the others in turn.

3.1 Schema Abstraction

One important kind of representational change is schema abstraction, which occurs when a common system derived from an analogy is highlighted, thereby increasing the possibility that it will be used again later (Gick and Holyoak 1983; Lowenstein et al. 1999). There are several lines of evidence that comparing structurally similar problems can lead to schema abstraction: (1) such comparison leads to improved performance on further parallel problems and promotes transfer from concrete comparisons to abstract analogies (as in the Loewenstein and Gentner (2001) developmental study discussed earlier; (2) several studies have shown that when participants write the commonalities resulting from an analogical comparison, the quality of their relational schema predicts the degree of transfer to another example with the same structure (e.g., Gentner et al. 2003; Gick and Holyoak 1983; Lowenstein et al. 1999).

Through schema abstraction, analogy can promote the formation of new relational categories (Gentner 2005) and abstract rules (Gentner and Medina 1998). One way this can occur is via *progressive alignment* – repeated schema abstraction across a series of exemplars. In this way, initially concrete, dimensionally specific representations are rendered more abstract by comparison and alignment. This kind of learning may be especially important in very young children. The idea is that close literal matches are easy for young children to perceive, because they are, in a sense, automatically aligned. This alignment results in a slight highlighting of the common relational structure, which can then seed further alignments with more distant examples.

A particularly dramatic example of early learning was found by Marcus et al. (1999), who found that through repeated exposure to relationally similar exemplars, infants can learn to recognize regularities in simple language-like stimuli. For example, if the infants had heard several instances of an ABA pattern, they would notice the shift to a novel (ABB) pattern. Kuehne et al. (Kuehne et al. 2000b) simulated this "infant rule-learning" using a model of learning by progressive alignment. This model, called SEQL (Kuehne et al. 2000a), forms abstractions across a set of exemplars by making successive structural comparisons (using SME) among exemplars. When a new exemplar is introduced, it is compared to the existing abstractions and (if sufficiently similar) assimilated into that abstraction, typically resulting in a slightly more abstract generalization. Exemplars that cannot be assimilated into any existing category (because they are too dissimilar from the existing generalizations) are maintained as separate exemplars.

The SEQL simulation was able to learn the language-like patterns within the same number of trials as the infants, and without pretraining (in contrast to connectionist simulations of the same phenomenon, which required extensive pretraining (e.g. 50,000 trials; Seidenberg and Elman 1999). For example, when presented with new strings it found those with the same structure far more similar than those with different structure. Interestingly, although the simulation matched the infant data beautifully, its generalization was not a fully abstract rule. Rather, the generalization retained some surface features; yet because of the structural character of the matching process, SEQL still found new instances with matching structure to be much more similar than those with a different structure. These findings raise the tantalizing possibility that some of the seemingly abstract rules of grammar and logic may in fact be simply near-abstractions resulting from progressive alignment.

3.2 *Re-representation*

The third way that representations can be altered is through re-representation of the relations to create a better match between the two analogs (see Holyoak et al. 1994; Keane 1996; Kotovsky and Gentner 1996; Yan et al. 2003). For example, when people are given the analogy below, they typically arrive at the commonality "Each *got rid of* something they no longer wanted."

Walcorp divested itself of Acme Tires.

Likewise, Martha divorced George.

The re-representation of relations can occur in conceptual analogies like the above, but it can also occur in perceptual analogies. For example, Kotovsky and Gentner (1996) gave 4-year-old children a similarity task in which they saw simple three-shape patterns like those shown in Fig. 2. When given triads that showed the same relational pattern – e.g., symmetry – across different dimensions (as in the right triad in Fig. 2), children had great difficulty recognizing the similar pattern; they chose randomly between the two alternatives. However, when children were first asked about triads that varied on the *same* dimension (e.g., squares and circles that varied on the size dimension), they were then more able to subsequently recognize the pattern cross-dimensionally. These results suggest that this method of

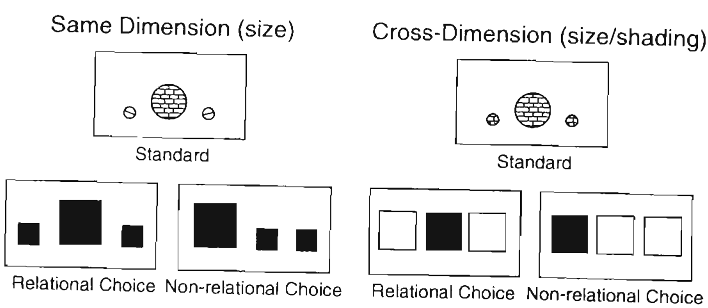

Fig. 2 Sample stimuli from Kotovsky and Gentner (1996)

progressive alignment – where highly similar items are compared first, followed by less similar items – fosters re-representation of the relevant relations.

Such re-representations could of course be temporary, in service of a particular task, but it seems likely that some re-representations can be learned and retained. Pervasive metaphors, such as "happy is up" (e.g., "After days of depression, his spirits finally lifted") (Lakoff and Johnson 1980) permeate natural language to an extent that suggests that at least some re-representations may become a more permanent part of our cognitive repertoire.

4 Analogical Retrieval

So far our focus has been on analogical mapping once the base and target have been mentally juxtaposed. However, explaining the use of analogy and similarity in reasoning requires some account of how potential analogs are accessed in long-term memory. Relational retrieval can be said to be the Achilles' heel of our relational capacity. There is considerable evidence that similarity-based retrieval, unlike the mapping process, is more influenced by surface similarity than structural similarity. Strong surface similarity and content effects seem to dominate remindings and to limit the transfer of learning across domains (Gentner et al. 1993; Holyoak and Koh 1987; Keane 1988; Novick 1988a,b; Reed 1987; Ross 1984, 1987, 1989).

In Gick and Holyoak's (1980, 1983) classic studies, participants often failed to access potentially useful analogs. For example, in one experiment (1980, E5), the rate of successfully solving a very difficult problem quadrupled (to 41%, from a baseline of 10%) for participants who were given an analogous story prior to the problem; but even so, the majority of participants failed to benefit from the analogy. However, when nonsolvers where given a hint to think about the story they had heard, the solution rate nearly doubled again to 76%. Because no new information was given about the story, it can be concluded that the analog was available in memory, but was not spontaneously retrieved. The structural similarity between the story and the problem was sufficient to carry out the mapping when both analogs were present in working memory, but not sufficient to produce spontaneous retrieval.

To test the functional distinction between kinds of similarity, Gentner et al. (1993) gave participants a large set of stories to remember and then later provided new stories that varied in their surface and relational similarity to the originals. Participants were asked to write out any original stories they were reminded of – the remindings that resulted were strongly governed by surface commonalities such as similar characters. However, as shown in Fig. 3, when asked to rate the similarity and inferential soundness of pairs of stories, the same participants relied primarily on higher-order relational commonalities, such as matching causal structure. Participants even rated their own surface-similar remindings as poor matches. This dissociation is also found in problem-solving tasks: remindings of prior problems are strongly influenced by surface similarity, but structural similarity better predicts success in solving the problem (e.g., Ross 1987).

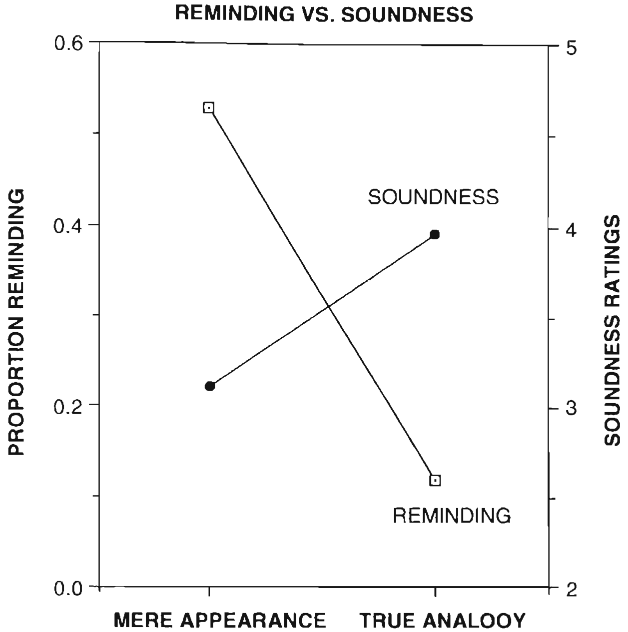

Fig. 3 Results from Gentner et al. (2003) showing that mere appearance matches produced more remindings, whereas true analogies were given higher soundness ratings

Overall, these are rather gloomy findings. Our poor capacity capacity for relational retrieval seems to belie our vaunted human ability for relational cognition. Yet, perhaps paradoxically, one remedy for poor relational retrieval is to make greater use of analogy during online learning and reasoning (e.g., Gick and Holyoak 1983). Studies by Loewenstein et al. (1999) and Gentner et al. (2003), for example, have shown that comparing analogous cases instantiating a complicated negotiation principle greatly improves transfer, such that those who were encouraged to compare the cases were more likely to apply the principle in a face-to-face negotiation task (in which it was appropriate) than were those who studied the cases without comparing.

Furthermore, these researchers (Gentner et al. in press) suggest that alignment-induced re-representation can even improve access to representations stored *prior* to the alignment. Whereas the above studies have shown that comparison during encoding facilitates future relational transfer, Gentner et al.'s recent work has shown that comparison at a later time can facilitate retrieval of material previously stored. Gentner et al. gave participants two cases instantiating a certain negotiation principle, then asked them to recall prior cases of the same principle. Those who were encouraged to compare the training cases were more likely to retrieve matching prior cases than those who read the training cases individually. This finding suggests that analogical encoding can provide a potent means of accessing our vast stores of relational knowledge.

5 Concluding Remarks

As an account of similarity and comparison, the alignment-based approach contrasts sharply with the featural and geometric (or distance) models, such as Tversky's (1977) contrast model and Shepard's (1962) multi-dimensional scaling model. Those models are concerned with the matching of features, with little or no attention to the relations among such features, and thus have difficulty coping with structured representations (see Goldstone et al. (2009), for a detailed discussion).

The alignment-based approach, in contrast, gives due priority to finding common relational structure. Structural alignment depends crucially on the relations among the entities being compared. It highlights the common relational structure, which in turn leads to re-representation and abstraction. Guided by systematicity, alignment also engenders new inferences – a key to generating knowledge.

Analogical processes are at the core of relational thinking, a crucial ability that, we suggest, is key to human cognitive prowess and separates us from other intelligent creatures. Our capacity for analogy ensures that every new encounter offers not only its own kernel of knowledge, but a potentially vast set of insights resulting from parallels in the past and future.

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