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Analogical Learning and Reasoning

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Abstract and Keywords

Analogy is a kind of similarity in which the same system of relations holds across different objects. Analogies thus capture parallels across different situations. When such a common structure is found, then what is known about one situation can be used to infer new information about the other. This chapter describes the processes involved in analogical reasoning, reviews foundational research and recent developments in the field, and proposes new avenues of investigation.

Keywords: analogy, mapping, inference, reasoning, relational structure, structural alignment, relational similarity, structure mapping, metaphor

Analogical ability—the ability to perceive like relational structure across different contexts—is a core mechanism of human cognition. The ability to perceive and use purely relational similarity is a major contributor—arguably *the* major contributor—to our species' remarkable mental powers (Gentner, 2003; Kurtz, Gentner, & Gunn, 1999; Penn, Holyoak, & Povinelli, 2008). Understanding the processes that underlie analogy is thus important in any account of "why we're so smart" (Gentner, 2003).

Analogy is ubiquitous in human cognition. People often understand a new situation by drawing an analogy to a familiar situation. This can be seen in words like "iron horse" for a locomotive or "horsepower" as applied to cars. Studies of problem solving show that students often try to solve problems by mapping solutions from known problems (e.g., Ross, 1987). Analogical processes are central in learning and transfer, as discussed later. In educational settings, a familiar, well-structured domain is often used to help students grasp a less-well-understood domain. Even without instruction, in everyday life people draw on experiential analogies to form mental models of phenomena in the world. For example, it appears that people form an (erroneous) notion of "curvilinear momentum" by analogy with linear momentum (Kaiser & Profitt, 1985; McCloskey, 1983). Additionally, analogy is important in scientific discovery and creativity. Studies in the history of science show that analogy was a means of discovery for scientists like Faraday (Tweney, 1991), Maxwell (Nersessian, 1984), and Kepler (Gentner, 2002), as well as among contemporary scientists (Dunbar, 1995).

Analogical comparison is also used in social judgment. People often draw on experiences with familiar people or situations when asked to judge strangers (Andersen & Chen, 2002) or to evaluate new social experiences (Mussweiler & Rüter, 2003). Indeed, Mussweiler and Epstude (2009) found that people who were primed to use analogical comparison in social judgments were faster, but just as accurate, as those who did not use comparison—suggesting that social comparison is a natural processing strategy. Finally, analogy is used in persuasion and argumentation. For example, Jared Diamond (1995) offered the history of Easter Island as a cautionary analogy for the future of earth as a whole. Diamond (p. 669) argues that as the island, once rich in vegetation, became increasingly overpopulated, deforestation occurred. This caused the bird population to dwindle, and, without trees with which to build canoes, the islanders could no longer catch ocean fish. The result was famine, societal upheaval, and war, all of which put still more strain on the ecosystem. This analogy portrays the idea of the earth as an island, rich in resources but ultimately finite.

Thus, analogy is pervasive in human thought and speech. In this chapter, we begin by presenting an overview of analogical reasoning and its component processes. We then discuss each process in greater detail. We go on to review the role of analogy in learning and reasoning, including how analogy is used in everyday life and how it can go wrong. We discuss current research in analogy, including implicit uses of analogy and the neural basis of analogical processes.

Defining Analogy

A good analogy both reveals common structure between two situations and suggests further inferences. That is, analogical mapping involves recognizing a common relational system between two situations and generating further inferences guided by these commonalities (Gentner, 1983; Gentner & Markman, 1997; Holyoak & Thagard, 1989; Hummel & Holyoak, 1997; Kokinov & French, 2003). The commonalities may include concrete property matches between the situations, but this is not necessary; what is crucial is *similarity in relational structure*.

In the most typical case of analogy, a familiar concrete domain (the *base* or *source*) serves as a model by which one can understand and draw new inferences about a less familiar or abstract domain (the *target*). We illustrate with an analogy used in geoscience education, which explains processes within the earth’s mantle (the area between the core of the earth and the outer crust) by analogy with processes in a lava lamp (Tolley & Richmond, 2003):

> The bulb at the bottom of the lava lamp slowly begins to heat the solid lava on top of it. As its density is reduced by thermal expansion, the lava begins to rise. The lava continues to rise to the top of the lamp and away from its heat source; thus, it begins to cool and sinks back to the bottom of the lamp. As the lava begins to heat up again, the process starts anew.
>
> Likewise, the earth's outer core begins to heat the solid mantle above it. The mantle then begins to rise toward the surface and away from the outer core; consequently, the mantle begins to cool.

In this analogy, the bulb corresponds to the core, the lava to the mantle, and the top of the lamp to the earth's crust. This analogy highlights a common relational structure: the process of thermal convection. This analogy also invites the (correct) inference that the mantle rises when heated because its density is reduced by thermal expansion. A process that cannot be seen becomes easier to grasp by virtue of the analogy with a concrete base domain. This example illustrates the potential value of analogy as a tool for education.

Processes in Analogical Reasoning

As demonstrated in the earlier examples, analogies vary widely in their appearance, content, and usage. This raises an obvious question: Are all of these processed in the same way? Some theorists think not. For example, Lee and Holyoak (2008) argued that causal analogies are processed differently from other analogies. However, there is considerable evidence that the same kinds of analogical processes operate across many domains. The same basic set of phenomena has been found for perceptual analogies as for conceptual analogies, and for close similarity as for more distant analogies (Kokinov & French, 2003; Markman & Gentner, 1993b). Most theorists agree that all analogies share a basic set of processes:

> *Retrieval*: given some current topic that a person is thinking about, *analogical retrieval* occurs when a person is reminded of a prior relationally similar case.
> *Mapping:* given two cases that are simultaneously present (either physically or mentally), *mapping* involves a process of aligning the representations. This process of structural alignment often gives rise to new *inferences*, drawing a new abstraction and/or noticing a salient difference between the two cases, as amplified later.
> *Evaluation:* once the mapping has been achieved, *evaluation* involves judging the analogy, along with any inferences that have been generated.

We begin with mapping, the core process in analogical reasoning, reserving retrieval for later. While analogical reasoning invariably involves a mapping process, it does not always involve retrieval. For example, often both cases are presented to the reasoner, as in persuasive analogies like “Afghanistan is (p. 670) like Vietnam” or instructional analogies like “electric current is like waterflow.”

Mapping: Alignment and Inference Projection

Mapping is the core process of analogy, and it has been the central focus of much analogy research in both psychology and computer science (Gentner & Forbus, 2010). Theories of analogy have largely converged on a set of assumptions like those outlined in Gentner’s (Gentner, 1983; Gentner & Markman, 1997) structure-mapping theory (see reviews by Gentner & Forbus, 2010; Kokinov & French, 2003). According to this theory, analogical mapping involves establishing a *structural alignment* between two representations based on finding the maximal set of commonalities between them.

The structural alignment process is heavily dependent on finding common relational structure. This means that the corresponding objects in the base and target need not resemble each other; what is important is that they hold like roles in the matching systems of relations. However, as discussed later, both object matches and relational matches enter into the process of alignment, so it is easier to establish an alignment if the corresponding objects do resemble one another. For example, it should be faster to match ■■■ with ■■■ than with ●●●.

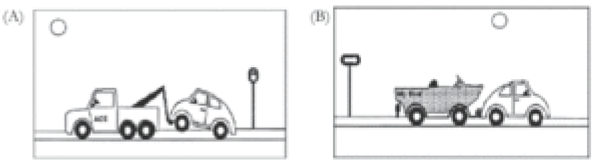

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Figure 42.1 Causal analogy (taken from Markman & Gentner, 1993b). The VW in the scene on the left (*A*) has both an object match (the VW) and a relational match (the boat) in the scene on the right (*B*). People who first compare the two scenes are likely to match the car with the boat, based on the structural alignment between the two scenes.

Nonetheless, people (especially adults) are highly likely to focus on relational commonalities even when there are conflicting object matches, as in the pair of scenes shown in Figure 42.1. The two scenes share a common relational system of a vehicle towing another conveyance. When asked to say what the VW in the left scene (Figure 42.1A) goes with in the right scene (Figure 42.1B), people often choose the other VW—an obvious object match. But if participants first compare the two scenes, they instead choose the boat, which plays the same role in the corresponding relational structure—both are being towed (Markman & Gentner, 1993b). Thus, analogy provides a way to focus on relational commonalities independently of the objects in which those relations are embedded.

Structural Alignment

The alignment process is guided by a set of tacit constraints that lead to structural consistency. Structural consistency entails *one-to-one correspondence*, which requires that each element of a representation match (at most) one element of the other representation. For example, in the analogy above, the VW in the top scene cannot correspond to both the boat and the VW in the bottom scene. Structural consistency also involves *parallel connectivity*, which requires that if two predicates (i.e., relations) are put into correspondence, then their arguments must also be placed into correspondence. Returning to the lava lamp analogy, if the relation HEATS is matched between the two cases, then the elements that fill the corresponding roles in the two relations will also be placed into correspondence; that is, the bulb will be mapped to core (both are the things that HEAT), and the lava will be mapped to the mantle (both are being HEATED):

HEATS (bulb, lava) → HEATS (core, mantle)

Bulb → Core

Lava → Mantle

There is considerable evidence that people abide by structural consistency in mapping (e.g., Krawczyk, Holyoak, & Hummel, 2005; Markman, 1997; Markman & Gentner, 1993b; Spellman & Holyoak, 1992). For example, Spellman and Holyoak (1992) asked people to analogize Operation Desert Storm to World War II, with Saddam Hussein corresponding to Hitler. People who mapped George Bush to FDR went on to map the United States during Desert Storm to the United States during World War II. Those who mapped George Bush to Winston Churchill almost always mapped the United States during Desert Storm to Britain during World War II. Thus, people varied in **(p. 671)** their preferred mapping but were structurally consistent within each mapping.

Analogical processing is also guided by an implicit preference for finding large connected systems of relations. This preference, termed the *systematicity principle*, can be stated more precisely as a bias to prefer interpretations in which the lower order matches (such as events) are connected by higher order constraining relations, such as causal relations (Clement & Gentner, 1991; Falkenhainer, Forbus, & Gentner, 1989). In other words, what people implicitly seek in an analogy is a common structure with a deeply connected system of relations. For example, the appeal of the lava lamp analogy stems from the sense that the same causal pattern of thermal convection applies in both cases.

Analogical Inference

Once two situations are aligned—that is, once correspondences have been established between them—further information can often be imported from base to target based on this alignment. This process of *analogical inference* is a crucial component of the mapping process. Two key points concerning analogical inference are (1) analogical inference is highly selective; we do not simply bring across everything known about the base; and (2) the inferences are *candidate inferences*; they are not guaranteed to be true. To begin with the first point, selectivity, a key issue for theories of analogy is capturing how potential inferences are constrained. Without such selection criteria, any fact known about the base could be posited about the target. Clearly, analogical reasoning would be useless if we had to spend time rejecting inferences such as the *earth's mantle comes in many* *attractive colors*, which could be derived from the lava lamp analogy. Thus, characterizing the constraints on analogical inference is essential to any account of analogy.

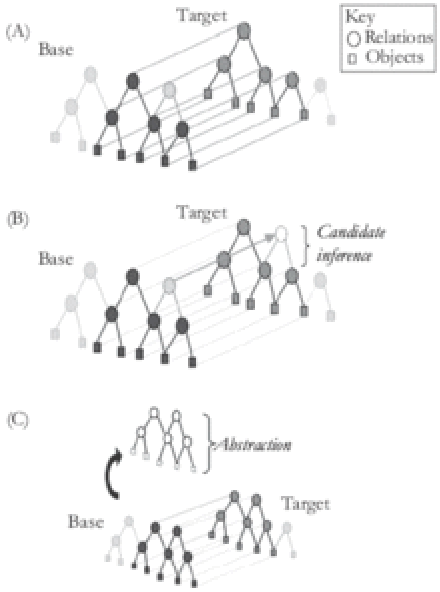

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Figure 42.2 Analogy as structure mapping. (*A*) Initial alignment of common relational structure. Relations are matched between domains, and their arguments are also matched. (*B*) Candidate inferences are generated by a process of structural pattern completion. (*C*) A possible outcome of structural alignment is abstraction of the common relational structure.

The structural consistency and systematicity preferences discussed earlier also guide inference projection. That is, candidate inferences are made in accord with the structural correspondences that were established during alignment. One way to think about inference generation is as a process of *structural pattern completion*: Once the base and target have been aligned and their common structure found (Fig. 42.2a), if there are additional assertions connected to that common structure in the base (and not yet present in the target), then this structure will be brought over as a candidate inference (Fig. 42.2b). Of course, these candidate inferences may not be correct; further evaluation is needed, as discussed later. Furthermore, not all analogies yield inferences; sometimes the point of an analogy is simply to convey a common abstraction (Fig. 42.2c).

Candidate inferences are derived by extending the common relational structure. This provides a natural filter on which inferences will be considered. For example, in the lava lamp analogy, suppose you make an initial alignment between *The bulb heats up the lava, and then the lava rises* with the fact that *The core heats up the mantle, and then the mantle rises*. If you then learn more about the causal connections in the lava lamp—for example, that *the lava rises because of its decreased density due to thermal expansion*—then you may carry this pattern over to the earth as a candidate inference: *Likewise, the mantle rises because of its decreased density due to thermal expansion*. This inference is warranted by its connection to the aligned relational structures between the two domains. The claim that inferences are guided by systematicity and structural consistency has empirical support. For example, people prefer to make inferences from structurally consistent mappings (Markman, 1997); and people are more likely to import an inference from base to target when that fact is causally connected to other matching facts (Clement & Gentner, 1991). (p. 672) This implicit preference for structurally consistent, deeply matching systems is what gives analogy its coherence and inferential power.

The structure-mapping process has been formalized in a computer model called the Structure-Mapping Engine (SME; Falkenhainer et al., 1989). SME 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 an overall mapping, with the largest and most deeply connected structure being favored (again, the systematicity principle). Many of the tenets of structure mapping are also incorporated into other current simulations of analogy, for example, ACME (Holyoak & Thagard, 1989), AMBR (Kokinov & Petrov, 2001), CAB (Larkey & Love, 2003), DORA (Doumas, Hummel, & Sandhofer, 2008), and LISA (Hummel & Holyoak, 1997; see Gentner & Forbus, 2010, for a review).

Evaluation

After the structural alignment between two analogs has been found and the inferences projected, both the analogy and its inferences are evaluated. Evaluation of particular inferences contributes to the larger evaluation of the analogy. At least three factors enter into evaluating the inferences from an analogy. The first is the *factual correctness* of the inferences. If an analogy yields inferences that are clearly false, people will generally reject both the inferences and the analogy that gave rise to them (Smith & Gentner, 2010). Of course, in some cases one cannot immediately identify whether an inference is true, as when making new predictions about a scientific outcome by analogy with another domain. In these cases we must decide whether the prediction is sufficiently interesting to justify trying to test it. A related factor in evaluating inferences is *adaptability* (Keane, 1996): how easy it is to modify a fact from the base to fit the target. People accept inferences that are highly adaptable to the target more readily than those that are less adaptable (Keane, 1996). Novick and Holyoak (1991) have demonstrated the importance of adaptation in solving mathematics problems by analogy to stories. They showed that even when subjects knew the correspondences between two domains, they often had difficulty applying the solution plan in the base story (the mathematical procedure of finding the lowest common multiple) to a target problem.

A second factor that governs the evaluation of inferences is *goal relevance*. Inferences that are relevant to the current goals of the reasoner are more important in evaluation of the analogy than those that are not (e.g., Clement & Gentner, 1991; Holyoak, 1985). This constraint is especially pertinent in problem solving. People often map solutions from previously solved problems to current problems; in these cases, the key issue is whether the analogy yields inferences relevant to the goal of solving the current problem. For example, Spellman and Holyoak (1996) showed that when two possible mappings are available for a given analogy, people select the mapping whose inferences are most applicable to their goals.

A third factor in evaluation is the amount of new knowledge generated by the analogy (Forbus, Gentner, Everett, & Wu, 1997). If an analogy yields startling new inferences, this could potentially constitute a significant gain in knowledge. Even if somewhat risky, such an analogy is often desirable, especially when brainstorming about a new domain.

Similarity Is Like Analogy

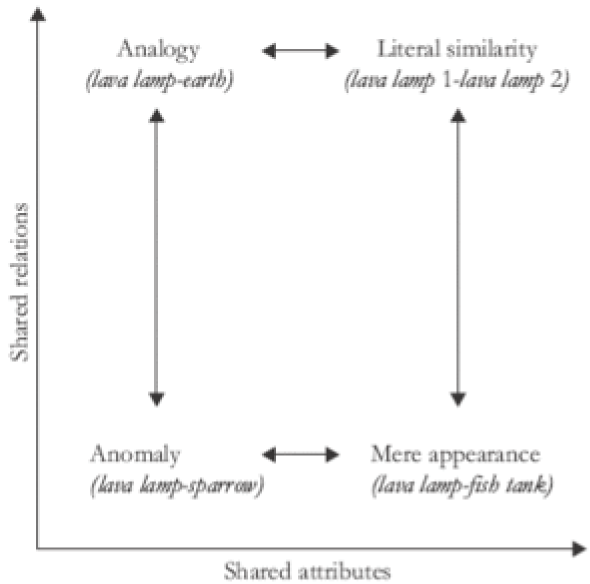

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Figure 42.3 Similarity space defined by the degree of relational similarity and object-attribute similarity (adapted from Gentner & Markman, 1997). These dimensions are continuous rather than categorical: A pair of cases can range from an overall similarity match to a purely relational (analogical) match (moving right to left along the top), and from an overall match to a purely surface match (moving top to bottom along the right).

The framework developed for analogy extends to literal similarity (Gentner & Markman, 1997; Goldstone, Medin, & Gentner, 1991; Markman & Gentner, 1993a, 1993b; Medin, Goldstone, & Gentner, 1993). The distinction between analogy and literal similarity is that in analogy, only the relational structure is shared, whereas in literal similarity (or overall similarity), both relational structure and object properties are shared. In the lava lamp analogy, there is no physical resemblance between the earth and the lava lamp. Contrast this to a literal similarity match in which one lava lamp is compared to another: The lava lamps physically resemble one another, in addition to sharing a causal structure. The difference between analogy and 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 Figure 42.3. When a comparison shares a high degree of relational similarity, but has very little attribute similarity, we consider it an analogy. As the amount of attribute similarity increases, the comparison becomes one of literal similarity. Thus, the distinction between literal similarity and pure analogy is a continuum, not a dichotomy: A pair of cases that shares relational structure can be purely analogical (*anger is like a* *teakettle*), literally similar (*this teakettle is like that teakettle*), or somewhere in between (p. 673) (*a steam engine is like a teakettle*). These distinctions are not merely a matter of terminology; they are important psychologically. Overall similarity comparisons are far easier to notice and map than purely analogical comparisons, and they can serve as the entry point for children and other novice learners, as discussed later in this chapter.

Analogical Learning

Analogy is an extremely powerful learning mechanism. One way in which analogy fosters knowledge acquisition is via *inference projection*—bringing across information from one analog to the other, as discussed earlier. While inference projection is perhaps the most obvious learning outcome of analogy (and also the most widely considered), analogy can augment knowledge in at least three other ways: schema abstraction (or generalization), difference detection (or contrast), and re-representation. We now discuss these in turn.

Schema Abstraction (Generalization)

In structural alignment, relational similarities between two exemplars are highlighted, which can lead to the extraction of this relational structure. Extracting the common relational structure increases the likelihood that it will be used again later (Gick & Holyoak, 1983; Loewenstein, Thompson, & Gentner, 1999; Markman & Gentner, 1993b; Namy & Gentner, 2002). In the lava lamp analogy, for example, one might extract the relational structure that describes thermal convection; this general schema can then be used to make sense of other convection systems, such as those that occur in the atmosphere.

Evidence that structural alignment promotes abstraction of relational schema comes from research in transfer of learning. Comparing two analogous scenarios (i.e., completing a structural alignment) dramatically increases the likelihood that a principle common to both exemplars will be transferred to a future item (relative to seeing just one exemplar, or even the same two items without encouragement to compare) (Catrambone & Holyoak, 1989; Gick & Holyoak, 1983). For example, Loewenstein et al. (1999) found that business school students who compared two negotiation scenarios were more than twice as likely to transfer the negotiation strategy to an analogous test negotiation as those who studied the same two scenarios separately. Additionally, when participants are asked to 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, Loewenstein, & Thompson, 2003; Gick & Holyoak, 1983; Loewenstein et al., 1999). Thus, through schema abstraction, analogy can promote the formation of new relational abstractions (Gentner & Kurtz, 2005) and abstract rules (Gentner & Medina, 1998); these generalizations can then be applied to new situations.

Difference Detection (Contrast)

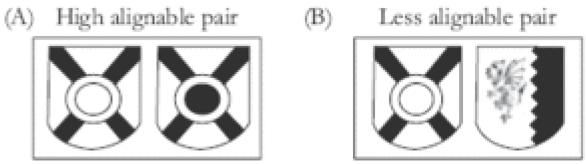

Figure 42.4 In the pair on the left (*A*), which is easy to align, people readily notice an alignable difference (the color of the center circles). People are faster to name a difference for pairs like (*A*) than for less alignable pairs like the pair on the right (*B*) (Gentner & Sagi, 2006; Sagi, Gentner, & Lovett, 2012).

Structural alignment not only makes salient the relational commonalities between analogs, but it also leads naturally to the highlighting of *alignable differences* between analogs (Gentner & Markman, 1994; Markman & Gentner, 1993a). Alignable differences are differences that are connected to the common relational structure. Research has shown that alignable differences are highly salient. For example, when asked to state a difference between (p. 674) two figures like those in Figure 42.4, people are much faster to identify a difference for pair A than for pair B. Because pair A is easily aligned, the difference in the central circle pops out (Gentner & Sagi, 2006; Sagi, Gentner, & Lovett, 2012). Using conceptual pairs, Markman and Gentner (1993a) found a high correlation between the number of commonalities listed and the number of alignable differences listed. Furthermore, these alignable differences were related to the commonalities people generated. For instance, for the pair *car-motorcycle*, participants frequently listed *both have wheels* as a commonality and *cars have four wheels while motorcycles have two* as a difference. These results suggest that structural alignment influences which differences people notice. Alignable differences become highly apparent to the learner, thus making them available for learning by contrast.

Re-Representation

Sometimes there is good reason to believe two nonidentical relations should match. This can happen, for example, if an instructor has provided an analogy between two seemingly disparate domains. In this case, the relations in the analogs may be re-represented to create a better match (e.g., Forbus et al., 1995; Kotovsky & Gentner, 1996; Yan, Forbus, & Gentner, 2003). Re-representation typically involves substituting a more abstract relation for the specific relations in the two analogs. For example, when people are given the following analogy, 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.

Re-representation can occur in perceptual as well as conceptual analogies (Hofstadter, 1995). Consider the perceptual analogy presented at the beginning of this chapter (Fig. 42.1). If you were to see either (A) or (B) by itself, you might well form a representation that was closely tied to the perceptual properties of the figure—for example, noting that (A) depicts *a car being towed* or that (B) shows *a boat hitched to a car*. However, once the figures are structurally aligned, these local descriptions are re-represented at a more abstract level: Both become seen as an instance of *a vehicle towing another conveyance*.

Summary

The structural alignment process is geared toward finding a system of identical relations between two representations. This process potentiates learning in at least four interrelated ways: (1) inference projection: spontaneous candidate inferences are made from a well-structured representation to one that is less complete; (2) abstraction: the common system resulting from the alignment becomes more salient and more available for future use; (3) difference detection: alignable differences—differences that occupy the same role in the common relational system—are highlighted, fostering learning by contrast; and (4) re-representation: the altering of one or both analog representations to improve the relational match.

Analogical Retrieval

So far, we have considered a scenario in which the two analogs are present (mentally and/or physically). However, analogies can also occur via spontaneous reminding: that is, while thinking about a topic, we may experience a reminding to some similar or analogous past experience. We now turn to the question of how this happens—what leads people to retrieve potential analogs from long-term memory? The news here is a bit on the gloomy side. People often fail to retrieve analogous cases, even ones that would be highly useful if retrieved. Gick and Holyoak (1980, 1983) were the first to show that people in a problem-solving situation often fail to be reminded of a prior analogous case that could help them solve the problem. This failure to access prior analogous cases is an example of "inert knowledge" (Whitehead, 1929)—knowledge that is not accessed when needed.

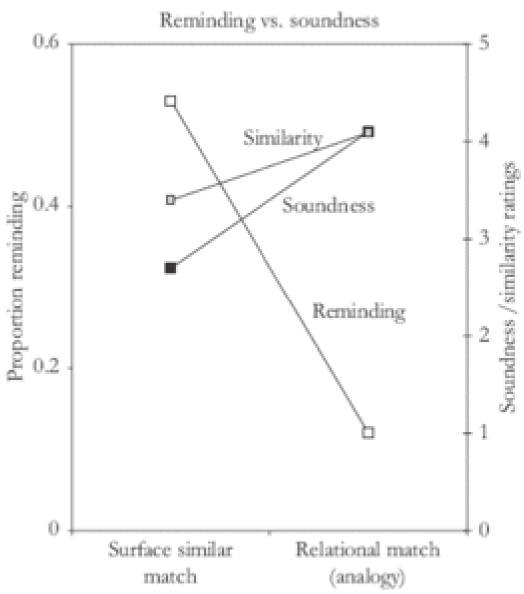

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Figure 42.5 Results from Gentner, Rattermann, and Forbus (1993), Experiment 2. Surface-similar matches produced more remindings, whereas relational matches were rated higher in soundness and in similarity.

Much research has shown that similarity-based retrieval of prior cases is typically driven largely by surface similarities, such as similar objects and contexts, rather than by similarities in relational structure (Brooks, Norman, & Allen, 1991; Catrambone, 2002; Gentner, Rattermann, & Forbus, 1993; Holyoak & Koh, 1987; Reed, 1987; Ross, 1984, 1987). Strong surface similarity and content effects seem to dominate remindings and to limit the transfer of learning across domains. For example, Gentner, Rattermann, and Forbus (1993) gave participants a large set of stories to remember. Later, participants were given new stories that varied in their surface and relational similarity to the originals and 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. In contrast, when asked to rate the similarity and inferential soundness of pairs of stories, the same participants (p. 675) relied primarily on higher order relational commonalities, such as matching causal structure. Participants even rated their own surface-similar remindings as poor matches. Figure 42.5 shows this striking dissociation between the kind of similarity that promotes memory retrieval and the kind of similarity that licenses mapping and inference. This pattern is also found in problem-solving tasks: Remindings of prior problems are strongly influenced by surface similarity, but success in solving the problem is best predicted by structural similarity (e.g., Ross, 1987).

Of course, it is important to bear in mind that in all of these studies, some people show genuine relational retrieval. It is not the case that relational remindings never occur; it is just that they are much rarer than remindings and overall similarity remindings (Forbus, Gentner, & Law, 1995). This may be partly because people often encode cases in a content-specific manner, so that later retrieval occurs only for highly surface-similar cases. In this case we would expect that experts, whose encodings presumably include more relational knowledge, will show better retrieval of structurally similar examples. Novick (1988) found this pattern when she compared people with varying degrees of mathematics expertise. Compared to novices, experts were more likely to retrieve structurally similar cases, rather than surface-similar ones; and when they did retrieve prior surface-similar cases, they were quicker to reject them.

Development of Analogical Ability

When given an analogy, young children are highly influenced by object matches and are less able to attend to relational matches than are older participants (e.g., Gentner, 1988; Halford, 1993; Mix, 2008; Paik & Mix, 2006; Richland, Morrison, & Holyoak, 2006). This shift from a focus on objects to a focus on relations has been termed the *relational shift* (Gentner, 1988). Although there is widespread agreement that such a shift occurs, developmental researchers differ on why. One proposal is that the relational shift is driven primarily by gains in relational knowledge (Gentner & Rattermann, 1991). Another proposal is that the shift results from maturational increases in processing capacity (Halford, 1993); the idea is that making relational matches requires more processing capacity than making attribute matches. A third view explains the relational shift as stemming from a maturational increase in inhibitory control, which permits the child to suppress object matches in favor of relational matches (Richland et al., 2006; Thibaut, French, & Vezneva, 2010). These views are not mutually exclusive; it could well turn out that the best explanation for the relational shift will be some combination of these proposals.

Perhaps rather surprisingly, one way young children can come to perceive relational commonalities is through processing very close similarity comparisons (DeLoache, Kolstad, & Anderson, 1991; Kotovsky & Gentner, 1996; Loewenstein & Gentner, 2001)—a phenomenon described as *progressive alignment* (Gentner & Medina, 1998). Developmental research has shown (a) that young children can succeed with overall similarity matches well before they can succeed with purely relational matches and (b) that young learners can benefit from close literal similarity matches to gain the beginnings of relational insight. For example, in DeLoache's (1987) classic search task, children watched an experimenter hide a toy in a small model room and had to find another toy hidden "in the same place" in the full-sized room. Children under 3 years of age did very poorly at this task. Building on these results, Marzolf and DeLoache (1994) showed (a) if 2 ½-year-olds are given a similar-scale search task (so that model and room are highly similar) they perform very well (67% correct searches); and (b) when these children are brought back the next day and tested in the standard model-room task (small model and full-sized room), they are far more successful than age-mates who did not receive the highly similar pair first (35% correct).

(p. 676) This is related to the pattern discussed for adults, wherein comparing a pair of examples results in abstracting a relational schema, which can then be transferred to future examples. For adults, the initial comparison pair can be quite dissimilar—presumably because adults possess firm enough relational knowledge to allow them to align purely on the basis of relational similarity. But for young children, whose relational knowledge may be limited, close literal matches are important steppingstones, because they are very easy to align; the object matches support the relational alignment. This alignment results in a slight highlighting of the common relational structure, which then permits further alignments with more distant exemplars.

The finding that an easily aligned literal match can bootstrap young children to a more distant relational mapping via progressive alignment offers a route by which children's ordinary experiential learning can gradually lead them to the discovery of analogical matches (Gentner & Medina, 1998; Kotovsky & Gentner, 1986). Such overall similarity comparisons are far easier to notice and map than purely analogical comparisons, and they can serve as the entry point for children and other novice learners.

Supports and Pitfalls

Analogy can be a valuable tool for learning and reasoning, but it can also be misleading. Several kinds of factors influence the outcome of an analogical mapping: first, factors internal to the mapping process itself, such as systematicity; second, characteristics of the reasoner, such as age and expertise; and, third, task factors such as processing load and time pressure, and context.

Among internal factors, *systematicity*—whether two analogs share a deeply connected relational structure—is crucial; people are more likely to make a relational alignment when they perceive a substantial relational match. Another factor internal to the mapping process is *transparency*: the degree to which the relationally corresponding objects in the two domains appear similar. A high-transparency analogy is one in which objects that share the same role are highly similar and noncorresponding objects are highly dissimilar. Such analogies are generally obvious and easy to align. For example, we noted earlier that *literal similarity* matches—which constitute the prototypical case of high-transparency matches—are more reliably retrieved from memory than are purely relational analogies. We also noted that young children are more likely to succeed in the alignment process when given a high-transparency (literal-similarity) match. To this we can now add that even in online processing, literal-similarity matches are processed faster than purely relational matches (Gentner & Kurtz, 2006). This fits with our intuitions; for example, it is easier to see how one bodyguard is like another bodyguard than to see how a bodyguard is like antivirus software (both shield from external harm). However, although high-transparency matches are natural and easy to process, many useful explanatory analogies are of low transparency. When designing an analogy to convey a particular principle, it is often best to choose a base domain in which that principle is clear, even if this results in a low-transparency match. For example, in the lava lamp/earth analogy, the corresponding objects (e.g., the bulb of the lava lamp and the core of the earth) are quite dissimilar. In explanatory analogies, the value of having a familiar, well-structured base domain often outweighs the advantages of transparency.

Similarity between corresponding objects facilitates structural alignment, but similarity between noncorresponding objects impedes it. A *cross-mapped* comparison (Gentner & Toupin, 1986) is one in which similar (or identical) objects play different roles in the common relational structure. These extraneous matches can slow processing or even interfere with arriving at a relational match (Ross, 1987). Cross-mapped comparisons are very low in transparency; not only is the relationally correct object match not obvious, but also there is a competing object match.

Transparency and systematicity interact with each other and with characteristics of the reasoner, notably age and experience. For example, cross-mapped comparisons are particularly difficult for children and novices (Gentner & Rattermann, 1991; Gentner & Toupin, 1986; Richland et al., 2006), especially if the object matches are rich and distinctive (Gentner & Rattermann, 1991; Paik & Mix, 2006). But systematicity of relational structure can sometimes compensate for low transparency. For example, Gentner and Toupin (1986) gave children a simple story and asked them to re-enact the story with new characters. Both both 6- and 9-year-olds were sensitive to the transparency of the correspondences. Their mappings were highly accurate in the high-transparency condition (similar characters in corresponding roles), less accurate in the medium-transparency condition (dissimilar characters in corresponding roles), and least accurate in the cross-mapped condition (similar characters in different roles). In addition, older (but not younger) children benefited strongly from (p. 677) systematicity: When they were given a summary statement that provided a higher order plot structure, their mapping accuracy stayed high regardless of transparency. They were able to use the relational constraints provided by the higher order structure to maintain relational correspondences despite the tempting object matches. This finding is a microcosm of learning and development: the deeper and better-established our relational knowledge, the better we can maintain that structure in the face of competing local matches (Gentner & Toupin, 1986; Markman & Gentner, 1993b).

The third class of factors affecting analogical processing involves task conditions and their interaction with processing capacity. One generalization that emerges from several studies is that making relational matches requires more time and processing resources than making object attribute matches. For example, Goldstone and Medin (1994) found that when people are forced to terminate comparison processing early, they are strongly influenced by local attribute matches, even in cases where they would choose a relational match if given sufficient time. Waltz et al. (1999) asked people to state correspondences between two cross-mapped scenes taken from Markman and Gentner's (1993b) study (see Fig. 42.1) while carrying out a dual task designed to tax working memory and/or executive control—either generating random numbers or continually repeating the word *the*. Both dual tasks decreased the frequency with which participants identified relational correspondences and increased the frequency of choosing matching objects, suggesting that achieving a relational alignment requires more processing resources than does the process of matching objects.

One additional factor that influences whether an analogy will be useful involves the selection of the base domain. When we talk about analogical processing, it is usually with the assumption that an appropriate base domain has been selected. However, people sometimes choose inappropriate source analogs, which can lead to misguided inferences and faulty knowledge. For example, Kempton (1986) examined heating patterns used by households in winter and discovered that some households used a costly and ecologically wasteful strategy of constantly moving their thermostat setting from very high to very low and back. He concluded based on a series of interviews that this behavior stemmed from an incorrect model formed by analogy with other devices—namely, that the higher the thermostat setting, the more heat pours out, analogous to the way a faucet works. (In fact, most furnaces work at a constant rate; the thermostat simply determines when they turn off and on.) Because such incorrect mental models can be an impediment to science learning, some educators advise diagnosing and debugging these models in science classes (Collins, Stevens, & Goldin, 1979).

Analogy in the Real World

Analogy researchers believe that analogy—and structural alignment more generally—is ubiquitous in human thinking. However, most of the research on analogy has been carried out in the experimental psychology laboratory, where people are explicitly provided with analogies and asked to respond in some way. Is real-world analogy guided by the same constraints seen in experimental studies? We now turn to research on analogy in naturalistic settings.

In a pioneering study of scientific reasoning, Dunbar (1993, 1995) studied the day-to-day processes of scientists in microbiology laboratories, Dunbar (1993, 1995) found that analogical thinking was a key component of all aspects of scientific reasoning, ranging from hypothesis generation to experimental design and data interpretation. Interestingly, Dunbar observed that many of the analogies scientists made were of high transparency, sharing not only causal structure but also many superficial features. For example, a scientist trying to determine the function of a gene in one organism (e.g., a gene in oysters) might draw an analogy to a gene in another organism (e.g., a similar gene in clams), whose function is well understood (Dunbar, 1997). These findings suggest that surface similarity aids in noticing potential comparisons, as many theories of analogy would predict. However, historical analyses reveal that scientists do sometimes use the kind of far-domain analogies that constitute a true leap in understanding (Holyoak & Thagard, 1997; Nersessian, 1984). These more dramatic analogies may be vehicles for large shifts in paradigm (Thagard, 1992).

We noted in the introduction that analogies are often used in argumentation and persuasion. In cases of disagreement, opponents often attack the analogy by pointing out critical differences. For example, after the BP oil spill in April of 2010, critics of the

Obama administration offered an analogy exemplified by a *Washington Examiner* headline: “Gulf oil spill becoming Obama’s Katrina: A timeline of presidential delay.” The invited parallel is:

The Bush administration’s mismanagement exacerbated the results of Hurricane Katrina.

(p. 678) *The Obama administration’s mismanagement is exacerbating the results of the oil spill.*

Those who disagreed with this assessment denied the analogy’s applicability. For example, a CNN correspondent stated that “unlike naturally occurring events such as Hurricane Katrina, the oil spill was something unforeseen and a never-before-happened moment.” This move argues that the two situations are not causally analogous because Katrina was predictable from weather patterns, while the BP spill was unforeseen.

Analogy underlies much of humor. For example, Benjamin Franklin observed that “Genius without education is like silver in the mine.” A more elaborate example comes from John Cassidy, writing in the *New Yorker* of November 29, 2010: “I came across an announcement that Citigroup, the parent company of Citibank, was to be honored …for ‘Advancing the Field of Asset Building in America.’ This seemed akin to, say, saluting BP for services to the environment or praising Facebook for its commitment to privacy.” Loewenstein and Heath (2009) surveyed jokes, children’s stories, and advertisements from around the world and found that they often follow a *repetition-break plot structure*—essentially a progressive alignment structure. This structure is familiar to anyone who has heard a “rule of three” joke (e.g., “A doctor, a lawyer, and a psychologist walk into a bar …”) or the story of the Three Little Pigs. Jokes and stories of this form begin with two highly similar episodes. Aligning these is essentially effortless, and this results in abstracting the common plot structure. The third episode is partly similar but contains a *break*—a sudden departure from this parallel plot structure. The humor or surprise comes from this break with expectations.

A further case of everyday analogy is the use of conceptual metaphors such as “their relationship has reached a crossroads” or “their marriage has been rather rocky” (Lakoff & Johnson, 1980). These are instances of the *A RELATIONSHIP IS A JOURNEY* metaphor, one of many widely used metaphoric systems. These kinds of metaphoric systems chiefly convey relational commonalities, and there is evidence that they are processed as conventionalized structure mappings (Bowdle & Gentner, 2005). Another everyday use of analogy occurs in the introduction of new technical concepts, such as (*computer*) *virus* (Gust, Kühnberger, & Schmid, 2006).

Recent Avenues of Research in Analogy

Neuropsychology of Analogical Reasoning

Recent studies have begun investigating the neural correlates of analogical processing (e.g., Green, Kraemer, Fugelsang, Gray, & Dunbar, 2010; Green, Fugelsang, Shamosh, Kraemer, & Dunbar, 2006; Krawczyk et al., 2008; Morrison et al., 2004; Wharton et al., 2000). Studies so far converge on areas within the left prefrontal cortex (l-PFC) as important in analogical reasoning. For example, Krawzyck et al. (2008) found that damage to the left prefrontal cortex was associated with poor performance on pictorial analogies of the form A:B::C:?. Several studies have implicated the left rostrolateral PFC in analogical mapping during semantic analogy problems (Green et al., 2006, 2010; Bunge, Wendelken, Badre, & Wagner, 2005; Krawczyk, McClelland, Donovan, Tillman, & Maguire, 2010). For example, Bunge, Helskog, and Wendelken (2009) showed that the rostrolateral prefrontal cortex was more heavily involved in a task that required relational comparison than in a task that required only featural processing. Of course, much remains to be discovered. For example, much of this work has involved four-term analogies of the form A:B::C:?. While these have the advantage of being tractable to investigate, they are fairly simple analogies. As neuroimaging techniques develop, we should be able to explore a greater range of depth and complexity in analogical materials and arrive at a more complete picture.

Analogical Reasoning Without Awareness

Most experimental work tends to focus on the deliberate, conscious use of analogy; people retrieve or are given an analogy and are asked to interpret it and/or to derive new inferences. However, research in the past decade has demonstrated that not all analogical reasoning is deliberate. Blanchette and Dunbar (2002) first demonstrated the *analogical insertion effect*, in which analogical inferences are integrated unknowingly into mental representations of the target domain. They gave participants passages that explained a target issue (legalizing marijuana) by analogy with a familiar scenario (legalizing alcohol by repealing Prohibition). When asked to recognize assertions from the target passage, participants often misidentified analogical inferences as facts actually presented about the target; that is, they thought they had read statements about marijuana when what they had actually read were the analogous statements about alcohol. These (p. 679) findings show that analogical inference may occur without explicit awareness. But in these studies, the analogy was explicitly given to participants.

Day and Gentner (2007) took this phenomenon one step further. They asked whether analogical inference can occur without explicit awareness of the analogy itself. In their studies, people read a series of brief passages and then answered questions about them. Unbeknownst to the participants, each set of passages contained a later passage (the target) that was analogous to a prior passage. Participants' responses to the target passage revealed that they had aligned the target with the earlier passage and had mapped inferences from the prior passage to the target. Yet people reported that each passage had been understood on its own, without invoking other passages. Further studies of online reading time showed that these unaware analogical inferences were made during the processing of the target story.

These results show that information from a single analogous instance can spontaneously influence the way in which another situation is understood and remembered. Many questions remain. For example, in the Day and Gentner study the initial and final passages shared surface similarity as well as relational similarity. Would unaware inferences occur without this kind of strong overlap? Although there is much to discover, this line of research suggests that analogy may be the mechanism by which we apply existing knowledge to structure new situations.

Conclusion

Analogy is at the core of higher order cognition (Gentner, Holyoak, & Kokinov, 2001; Hofstadter, 2001). Analogical processes underlie complex cognition, from scientific discovery to humor. The same basic processes of alignment and mapping also come into play in a vast range of human cognition, from perceptual similarity to categorization and decision-making.

Three decades of analogy research has led to great gains in our understanding of analogical processing. But there remain many open questions. We need a better understanding of how analogy plays out in everyday life and in how children and adults learn about the world. For example, how prevalent is the phenomenon of spontaneous, nonaware analogy? Could it account for the development of stereotypes? Another area that is largely open is that of the neural underpinnings of analogical processing. Aside from the left PFC areas noted earlier, are other areas of the brain involved, and do they differ for (for example) spatial versus causal analogies? Finally, we are just beginning to explore analogical processing in other species (e.g., Haun & Call, 2009). Cross-species comparisons will help to delineate the cognitive components of analogical ability.

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