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11
ANALOGICAL REASONING

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Introduction

Analogical ability – the ability to recognize and reason about common relational structure across different contexts – is a core mechanism in human cognition and a key contributor to higher-order cognition. This chapter describes the processes that underlie analogical reasoning and reviews findings in the field as well as future directions for analogical research.

Defining analogy

Analogy is a kind of similarity in which the same system of relations holds across different sets of elements. Analogies thus capture parallels across different situations. The elements that belong to the two situations need not be similar, but the relations that hold the systems together must be alike. However, as discussed below, analogical processing is easier if some concrete features are also shared.

Analogical mapping is often used to connect a familiar situation – the *base* or *source* analog – with an unfamiliar or abstract situation – the *target* analog. When such an alignment has been established, the base situation provides a model that can be used to explain and draw predictions concerning the target situation. For example, an analogy used in explaining cell metabolism is "Mitochondria are the furnace (or powerhouse) of the cell." This analogy conveys that mitochondria produce energy for cells, and also highlights the shared relational structure – that both mitochondrial behavior and the behavior of a furnace carry out energy-generating transformations that consume fuel:

- A furnace takes in fuel and generates energy in the form of heat.
- Mitochondria take in fuel (glucose) and generate energy in the form of ATP (adenosine triphosphate, a molecule that the cell can use for energy).

An analogy often invites further reasoning. For example, knowing that burning requires oxygen, one might (correctly) guess that mitochondria might also require oxygen to perform their transformation, and whether CO_2 is produced as a byproduct.

Although analogical reasoning is prominent in explanation and instruction, it is also widely used in informal contexts, and in areas from visual perception to social cognition. For example, analogy is a common method of argumentation in the social and political arena. After the Supreme Court removed a major section of the Voting Rights Act in 2013, Ruth Bader Ginsburg stated,

> Throwing out preclearance when it has worked and is continuing to work to stop discriminatory changes is like throwing away your umbrella in a rainstorm because you are not getting wet.

Analogy is also used in advice and prediction. When the stock market plunged after the World Trade Center attack on September 11, 2001, many writers argued by analogy to the 1929 crash that the market would be higher after a few years. Although analogical thinking seems to come naturally to people, it nonetheless involves an intricate set of underlying processes. We next describe these processes.

Analogical mapping

Mapping is the central process involved in analogical reasoning, and has been the main focus of research in both psychology and computer science (Gentner & Forbus, 2011). Theories of analogy have largely converged on a set of assumptions laid out in Gentner's structure-mapping theory (Gentner, 1983; Gentner & Markman, 1997). According to this theory, the mapping process involves establishing a *structural alignment* between two representations based on their common relational structure.

The process of structural alignment is guided by tacit constraints that lead to the extraction of shared systems with maximal structural consistency. One such constraint is *one-to-one correspondence* – the requirement that each element of one representation may match with, at most, one element from the other. The second requirement for structural consistency is *parallel connectivity*: if two predicates correspond, their arguments must also correspond, playing like roles.

There is considerable empirical support for structural consistency in analogical processing (Krawczyk, Holyoak, & Hummel, 2005; Markman, 1997; Markman & Gentner, 1993a; Spellman & Holyoak, 1992). For example, Spellman and Holyoak (1992) asked people to draw analogies from a then-current political event (Operation Desert Storm) to a historically salient one (World War II). People differed on the best mapping, but they generally maintained structural consistency within their mappings. Those who matched George Bush with FDR went on to generate the structurally consistent mapping of the United States during Desert Storm to the United States in World War II. Those who matched George Bush with Winston Churchill went on to map the United States during Desert Storm to Britain during World War II. Even when reasoning about then-current events, people maintained internal consistency in the mappings they made, suggesting that this kind of structural consistency is important in the mapping process.

Markman and Gentner (1993a) used pairs like that, as shown in Figure 11.1, to test the claim that the comparison process involves structural alignment. To do this, they devised a *one-shot mapping task*. With both pictures in front of the participant, the researcher pointed to the woman in A and asked, "What does this go with in the other picture?" Subjects often choose the object match (e.g., the woman in B). A second group was asked to perform the same one-shot mapping

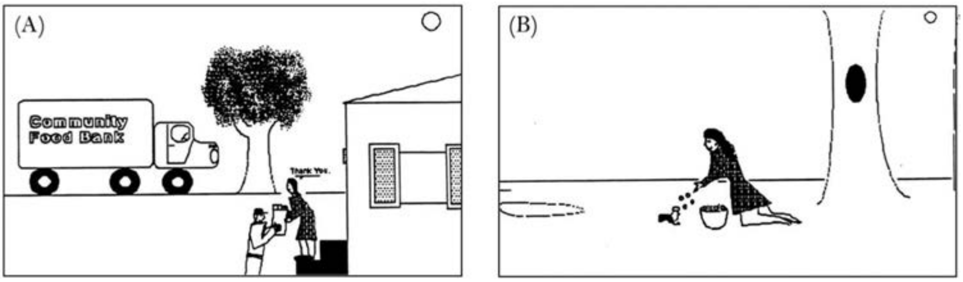

Figure 11.1 Example of a causal analogy (Markman & Gentner, 1993b). Scene (B) has both an object match (the woman) and a relational match (GIVING) with (A), though the role in which each object participates in the relation is different. After comparing the two scenes, people tend to match objects that have the same role (mapping woman in (A) to squirrel in (B)), based on the structural alignment between the scenes.

task, but before doing so they were asked to rate the similarity of each pair. These people were far more likely to choose the squirrel in B – evidence that the process of comparison induced a structural alignment based on common relational structure (man gives food to *woman*/woman gives food to *squirrel*). Further, the higher the similarity rating, the stronger was the tendency to choose the relational match, suggesting that finding a relational alignment induces a sense of similarity.

The pair in Figure 11.1 is an example of a *cross-mapping* – a pair in which there are object similarities that are inconsistent with the best relational alignment (Gentner & Toupin, 1986). Cross-mappings are useful in analogical research, because they allow us to gauge whether a person can arrive at a relational alignment despite the immediate appeal of the object match. For example, early in learning, children often choose an object match over a relational match. Even for adults, overcoming a cross-mapping can be challenging, as discussed below.

Along with structural consistency, analogical mapping is guided by what Gentner (1983) termed the *systematicity principle*. In analogical mapping, people prefer to match large, deeply connected systems, rather than sets of unrelated matches. To put it more precisely, systematicity reflects a preference for common systems that include higher-order constraining relations, such as causal relations (Clement & Gentner, 1991). For example, Gentner, Rattermann, and Forbus (1993) asked people to rate the similarity and soundness of pairs of stories that shared a set of events. (Soundness was described as the extent to which inferences could be made from one story to the other; it was intended as a proxy for relational similarity.) Half the stories also shared higher-order relations that linked those events into a system; the other half did not. As predicted by the systematicity principle, people rated stories with shared higher-order structure (such as causal relations between events) as more sound than those without such structure. Perhaps surprisingly, they also rated these pairs as more similar than pairs without shared higher-order relational structure. We suggest that this desire for systematicity reflects an implicit preference for coherence and inferential power.

Work in cognitive modeling has bolstered these empirical findings. The Structure-Mapping Engine (SME) is a computational model of the structure-mapping process including both alignment and inference projection (Falkenhainer, Forbus, & Gentner, 1989; Forbus, Ferguson, Lovett, & Gentner, 2017; Forbus, Gentner, & Law, 1995). SME operates in a local-to-global fashion. It first finds all possible local matches between representational elements of the two analogs, without regard for structural consistency. Structural consistency is imposed at the next stage, when SME combines the local matches into structurally consistent clusters (called kernels), which are in turn combined into overall mappings. The largest and most deeply connected structures are favored in this consolidation process (following systematicity). Though SME is specifically built on the cognitive principles of structure-mapping, many of its features have been incorporated into other models of analogical reasoning, including ACME (Holyoak & Thagard, 1989), AMBR (Kokinov & Petrov, 2001), CAB (Larkey & Love, 2003), DORA (Doumas, Hummel, & Sandhofer, 2008), and LISA (Hummel & Holyoak, 1997, 2003; see Gentner & Forbus, 2011, for a review).

Inference projection

Analogical inference is important in learning and reasoning, but it poses a challenge for theories of analogy. Between any two nonidentical things there may be countless potential inferences. If we had to consider them all, analogy would be useless. This *selection problem* is dealt with in structure-mapping by requiring that inferences be connected to the common system. Once the representations have been aligned and the common relational structure identified, *candidate inferences* are projected from the base to the target. Candidate inferences are further assertions that belong to the common system and are present in the base but not (yet) in the target. Importantly, these inferences are not guaranteed to be valid in the target; they must be further evaluated, as discussed in the next section.

In a good explanatory analogy, the common system is more elaborated in the base than in the target. Once the two are aligned, candidate inferences from the base serve to complete the relational pattern in the target. For example, in the "Mitochondria are like a furnace" analogy, we might infer that just as oxidation of fuel in a furnace generates undesirable by-products (e.g., soot), so the oxidation of glucose by mitochondria produces undesirable by-products – in this case, free radicals (highly reactive atoms).

To make this clearer, consider a schematic representation of the process of structural alignment and inference projection (Figure 11.2). Once the base and target have been aligned and a common structure has been identified (Figure 11.2A), if there are additional assertions in the base representation connected to this common structure, they will be automatically projected to the target as candidate inferences (Figure 11.2B). Whether or not there are new inferences, the common system that emerges from structural alignment may be retained as an abstraction of the structure shared (Figure 11.2C).

These predictions are supported by psychological studies. For example, when making comparisons, people prefer to make inferences from structurally consistent mappings (Markman, 1997). Further, people project these inferences in a structurally sensitive way, attaching them to the appropriate role in the relational structure of the target domain (Clement & Gentner, 1991; Day & Gentner, 2007; Spellman & Holyoak, 1996).

Evaluation

As mentioned in the previous section, the inferences generated via analogical processing are only *plausible guesses;* discovering whether they are true in the target requires further reasoning. If an analogy produces inferences that are clearly false or untenable in the target, people will generally reject the analogy. One mitigating factor is *adaptability*: inferences that can readily be modified to fit the target are accepted more readily than those that are less so (Keane, 1996). In problem-solving, the adaptability of inferences from one domain to another can influence the

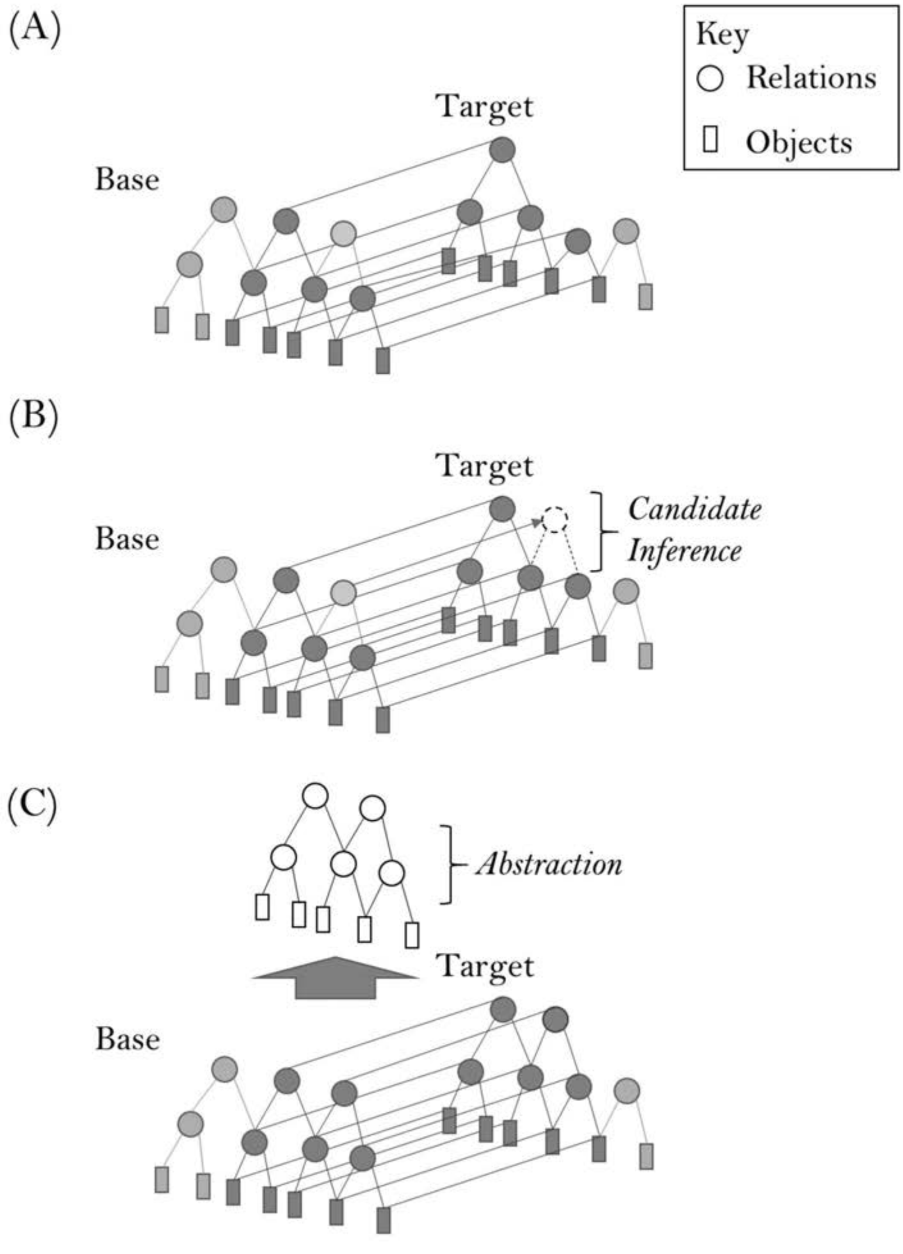

Figure 11.2 Analogy as structure-mapping. (A) Initial alignment of common relational structure. (B) Candidate inferences are generated by exporting structurally-consistent elements from target to base. (C) Abstraction of common structure.

ease with which subjects solve mathematical problems (Novick & Holyoak, 1991). An exception to this generality occurs in scientific inquiry: even if it is not possible to determine the truth of an inference, it may be retained as a prediction, especially if there is good support for the analogy as a whole (Forbus, Gentner, Everett, & Wu, 1997; Nersessian, 1984).

A second factor in the evaluation of inferences, especially in problem-solving contexts, is *goal relevance*. Even if an inference is both structurally consistent and valid, it is likely to be discarded if it is irrelevant to the task at hand (Clement & Gentner, 1991). Goal relevance has been explored as a major factor in analogical reasoning in the theories of Keith Holyoak (1985) and colleagues. They propose that inferences that are relevant to the current goals of the reasoner are more likely to be projected during analogical inference, and are more important in evaluating the analogy. For example, Spellman and Holyoak (1996) showed that when two possible mappings are available for an analogy, people prefer the one that generates candidate inferences most applicable to their current goals.

Another factor often considered in inference evaluation is the analogy's potential for *knowledge generation* (Forbus et al., 1997). Analogies that yield unexpected new inferences represent a greater potential gain of knowledge (as long as the inferences are not proven false). Though this strategy is potentially risky – huge leaps are not always warranted – it can prove advantageous. When reasoning about new domains or brainstorming for creative solutions, bold advances are often worth considering.

Analogy and similarity

The structure-mapping framework applies not only to analogy but also to overall similarity (Gentner & Markman, 1997; Goldstone, Medin, & Gentner, 1991; Markman & Gentner, 1993a). Analogy and similarity differ primarily in the overlap of shared relations and objects between base and target. In analogy, only the relational structure is shared, whereas in overall similarity the two representations share both relational structure and object properties.

Importantly, the difference between literal similarity and analogy is not dichotomous – it is a continuum. Examples of shared relational structure may be purely analogical (*anger is like a tea kettle*), literally similar (*my tea kettle is like your tea kettle*), or somewhere in the middle (*a steam engine is like a teakettle*). The continuum from overall similarity to analogy is psychologically important. Generally, it is easier for people to recognize and map overall similarity comparisons than pure analogies. For this reason, overall similarity comparisons often serve as points of entry for children and other novice learners, as discussed below.

Analogical learning

Analogy is a powerful learning mechanism. As discussed above, analogies can project information from one analog to the other. Though the role of inference projection is widely studied and central to the mapping process, it is not the only process that facilitates learning. Analogy can augment and extend knowledge in at least three other ways: *schema abstraction* (generalization), *difference detection* (contrast), and *re-representation*. The following section discusses these processes and their role in analogical learning.

Schema abstraction

As just discussed, structural alignment highlights commonalities between two analogs. This promotes the abstraction of common relational structure across different exemplars. The common structure may be stored in memory as an abstraction and used again for later exemplars (Gick & Holyoak, 1983; Loewenstein, Thompson, & Gentner, 1999; Markman & Gentner, 1993b; Namy & Gentner, 2002). This may be seen in studies of analogical problem solving. When people compare two analogous cases before solving an analogous test case, they show high transfer of the study solution, relative to studying only one prior case (Gick & Holyoak, 1983) or studying the same two cases without comparing them (Catrambone & Holyoak, 1989; Loewenstein et al., 1999). For example, Loewenstein et al. (1999) gave business school students two cases to study. The cases were analogous to each other, although different in surface content – that is, they both depicted the same negotiation strategy. Half the students were told to compare the two scenarios; the other half read each scenario in succession and gave advice. Then pairs of students engaged in a test negotiation that was analogous to the cases. Those who had explicitly compared the two scenarios were over twice as likely to transfer the negotiation strategy to the new test case than those who had studied the same two scenarios without comparing them. Further, the quality of the relational schema that was abstracted from the two analogs predicted the degree of successful transfer (Gick & Holyoak, 1983; Loewenstein et al., 1999). This is evidence that the common schema generated through analogical comparison is an important mediator of transfer to new situations (Gentner & Kurtz, 2005; Gick & Holyoak, 1983).

Difference detection

In addition to facilitating the abstraction of relational commonalities, the structural alignment process also highlights *alignable differences* between analogs (Markman & Gentner, 1993b). These are differences that play the same role in the common system in both analogs. Psychologically, alignable differences tend to be rapidly noticed – there is a kind of pop-out effect. Consider the pairs in Figure 11.3. When asked to indicate whether the exemplars of a pair were *same* or *different*, people were faster for pair B than pair A, consistent with prior findings that 'different' judgments are faster the more different the pairs are (Goldstone & Medin, 1994; Luce, 1986). However, when asked to state a *specific* difference, the opposite was true – people were faster for pair A than for pair B (Sagi, Gentner & Lovett, 2012).

At first glance, this might seem counterintuitive – one might expect that the sheer number of differences in pair B would hasten finding any single difference, compared to having to find one of the many fewer differences in pair A. Yet on further examination, these findings are explained by considering that the high spatial alignability of pair A facilitates the alignment of shared structure. This alignment in turn leads to pop-out of alignable differences, such as the difference in petal color or shape (Sagi, Gentner, & Lovett, 2012).

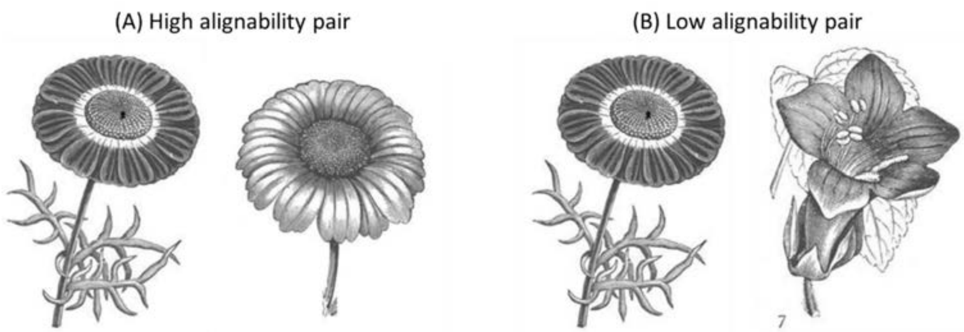

Figure 11.3 The relation between alignment and difference-detection. In pair (A), the shared spatial relational structure facilitates rapid structural alignment, leading to rapid identification of alignable differences (e.g. black versus white petals, or flat versus curved petals). Pair (B) lacks this spatial overlap, resulting in slower identification of specific differences (Sagi, Gentner, & Lovett, 2012).

The advantage of alignable differences is also seen for conceptual comparisons. For example, Gentner and Markman (1994) gave people a set of word pairs and asked them to list a difference for as many pairs as possible in a brief time period. Participants identified differences for many more high-similarity pairs than low-similarity pairs, and this surplus was chiefly made up of alignable differences. For instance, for the high-similar pair *hotel–motel*, people typically listed an alignable difference such as "A hotel is expensive; a motel is cheap". This is an alignable difference (because *expensive* and *cheap* play the same roles in their respective representations). In contrast, for the low-similarity pair *magazine–kitten*, those who listed differences often simply stated a fact about one item and negated it for the other: e.g., "You read a magazine, but you do not read a kitten" (a nonalignable difference).

Thus, alignment processes influence which differences people notice as well as which commonalities they notice. The high salience of alignable differences can be used to facilitate learning and reasoning. For example, in a study in the Chicago Children's Museum, children were shown two model buildings, one with a diagonal brace (conferring stability) and the other with a horizontal piece instead. All children were shown which building was stable and which was wobbly. But only if the two buildings were highly similar – supporting alignment and the pop-out of alignable differences – did children detect this critical difference and transfer it to their own constructions (Gentner et al., 2016).

Re-representation

In analogical mapping, people seek identical relations between the two analogs (Gentner, 1983). Of course, this refers to the conceptual relations, not to the words used to describe the relations. For example, *Attila burned the fort* and *Napoleon torched the castle* convey the same conceptual relation. But even when two potential analogs have nonidentical conceptual relations, they may still be found to be analogous, if processes of re-representation reveal relational identicalities. For example, *Attila burned the fort* and *Napoleon tore down the castle* can be considered analogous if the two relations *burned* and *tore down* are re-represented as *destroyed*. When there is evidence that initially non-identical relations should match, they may be re-represented to fit a consistent mapping (Forbus et al., 1995; Kotovsky & Gentner, 1996; Yan, Forbus, & Gentner, 2003). This flexibility allows for some of the productivity of analogical processing and provides another route by which analogy can lead to abstraction.

Summary

Structural alignment identifies common systems of relations between two analogs. This process potentiates learning and reasoning in several ways: (1) highlighting of common relational systems, often resulting in abstracting and retaining that common structure; (2) projection of candidate inferences from the base to the target; and (3) detection of alignable differences. We now turn to analogical retrieval from memory.

Analogical retrieval

As we have seen, people are quite sophisticated in analogical reasoning when both analogs are present (physically or mentally) during the mapping process. But what makes us think of an analogy in the first place? We now turn to another important case of analogy in action – namely, *analogical retrieval*. This refers to the phenomenon by which, while thinking about a topic or scenario, people are reminded of a similar past experience, which they then align (or attempt to align) with the current situation that sparked this retrieval. It is generally agreed that analogical reminding involves a set of overlapping but distinct processes (Forbus et al., 1995; Gentner et al., 1993; Holyoak & Koh, 1987; Novick, 1988):

- *Retrieval*: given some current topic in working memory, a person may be reminded of a prior analogous situation in long-term memory.
- *Mapping:* once the two cases are present in working memory (in this case, through analogical retrieval), mapping is carried out as already described: by aligning the representations (and if all goes well, noting their commonalities and or alignable differences, and projecting inferences from one analog to the other).
- *Evaluation:* once an analogical mapping has been done, the analogy and its inferences are judged for relevance and validity in the target.

We have already discussed mapping and evaluation. Now we turn to retrieval. The sad conclusion from a large body of research is that analogical retrieval often fails. The classic study was done by Gick and Holyoak (1980, 1983). They gave people a difficult thought problem (Duncker, 1945): how can a surgeon cure an inoperable tumor without using so much radiation that the surrounding flesh will be killed? Only about 10% of the participants came up with the ideal solution, which is to converge on the tumor with several weak beams of radiation. Performance improved if, prior to the tumor problem, participants read an analogous story (in which soldiers converged on a fort from many directions). In that case, about 30% produced convergence solutions. Yet the majority of participants still failed; they did not experience any reminding of the converging-army story, even though they had heard it earlier in the same session. Importantly, they had not forgotten the earlier story: when they were given the hint to "think about that story you heard before," the percentage of correct convergence solutions nearly tripled, to about 80%. This shows that even when a highly useful relational match is present in LTM, we often fail to retrieve it. Failure to access useful analogs is a major cause of failure to transfer in education.

Further research has shown that similarity-based retrieval relies heavily on surface similarities, such as similarities in object features, rather than on common relational structure (Brooks, Norman, & Allen, 1991; Catrambone, 2002; Gentner et al., 1993; Holyoak & Koh, 1987; Ross, 1984, 1987). For example, Gentner, Rattermann, and Forbus (1993) gave participants an initial set of stories to memorize. Participants were later given new stories that varied both in surface and relational similarity from the first set and were asked to indicate any previous stories of which they were reminded. Participants were reminded of many more stories that shared surface similarities than stories that shared common relational structure (including plot structure). Yet when asked to rate the similarity and inferential soundness of pairs of stories, the same participants rated stories that shared relational commonalities, such as plot structure, as more similar. Figure 11.4 shows the surprising dissociation between the kind of similarity that promotes memory and the kind that people consider useful for mapping and inference.

In sum, although we are highly effective at analogical mapping once we have two items co-present in our attention, the weak point in the chain is reminding. Not only do we fail to retrieve good matches, but we often instead retrieve poor matches – matches that share surface features, but not relational structure, with the situation we're reasoning about. On the positive side, retrieval of overall similarity matches is quite good: across studies, people retrieved about 60% of the overall similarity matches, as compared to 10% of the purely relational matches (Gentner et al., 1993). This is important, because overall similarity matches, though mundane,

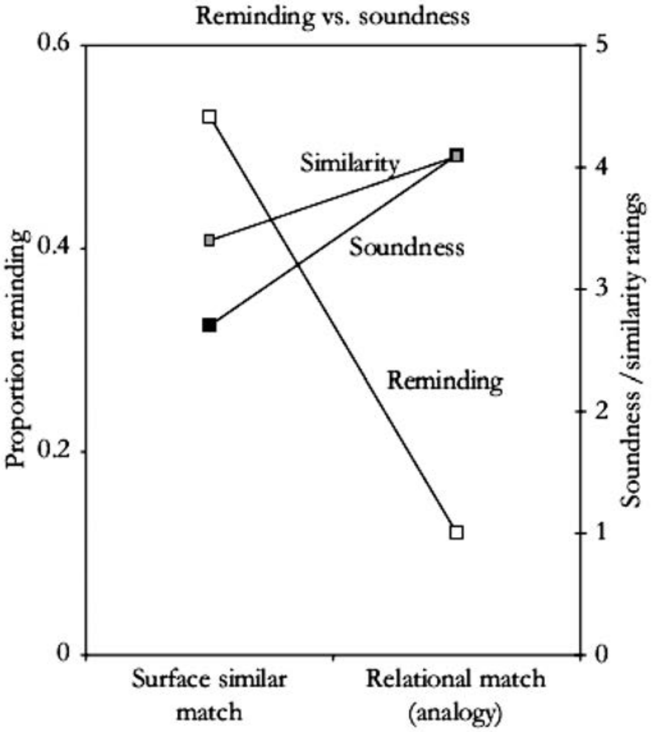

Figure 11.4 Results from Gentner, Rattermann, and Forbus (1993), Experiment 2. Surface-similar matches produce more remindings, even though relational matches were rated higher in both soundness and similarity.

have strong predictive power. If your jammed toaster reminds you of another jammed toaster, it is likely that the same solution will work.

Some researchers have argued that the above studies underestimate the level of relational reminding in real life and that with familiar materials, people would show more relational reminding (Blanchette & Dunbar, 2001). Trench and Minervino (2015) addressed this issue by using an arena in which participants had considerable prior experience – namely, popular films such as *Jurassic Park*. (All participants were tested after this study to ensure familiarity with the films.) The researchers gave people new situations that were analogous to key situations from these films, but which varied in surface similarity. The task was to generate a persuasive analogy that would guide the new character's behavior. This allowed participants to draw on personal experience, while controlling for prior knowledge and the similarity of the prior knowledge items. The results bore out the laboratory results, showing strong effects of surface similarity. When the target was highly surface-similar to a prior film, people retrieved and used that film as an analogy about 70% of the time; however, when the prior film was relationally similar but not surface similar, people retrieved it only 30% of the time.

Although retrieving pure relational analogs from memory is challenging, there are some mitigating factors. First, as people gain expertise in a domain, they become better able to retrieve true relational remindings (Novick, 1988). This effect may be due in part to learning a unifying conceptual vocabulary (Jamrozik & Gentner, 2013). Second, surface similarity is often correlated with relational similarity in real experience. This is the *kind world* hypothesis (Gentner, 1989): what looks like a tiger is very likely to *be* a tiger, with the relational characteristics of a tiger, such as 'eats other animals'. Third, when we do retrieve matches that have only surface similarity, and no deeper relational match to what we're thinking about, we can often quickly reject the reminding as irrelevant. For example, in the story-memory task described earlier Gentner, Rattermann, and Forbus (1993) asked people to rate story pairs (consisting of the probe story along with a story from the memory list) after they completed the memory task. The pairs they were given included the surface-similar stories they had been reminded of, as well as pairs that were relationally similar. People rated the surface-similar stories – even the ones they had been reminded of – as poor matches to the probes, and considered relational matches to be highly similar and inferentially sound (whether or not they had retrieved them). In other words, we are not at the mercy of our remindings; people are often able to filter out the poor matches that memory may provide.

Indeed, there is evidence that people can generate good analogies by an iterative process of retrieving, adjusting, and filtering candidate analogs. For example, Clement (1988) gave physicists challenging problems to solve, such as deciding which (if either) would stretch more: a spring with a weight hung on it or another spring with the same weight whose coils are twice the diameter of the first spring. People used a variety of methods to generate and test analogies. For example, some subjects analogized the spring problem to long and short horizontal rods bent by the same weight; the long rod would bend more, so they inferred (correctly) that the larger spring would extend more. This and other productive analogies were not simply retrieved from memory. Clement observed active construction and adaptation processes during the reasoning sessions, which typically required over 20 minutes. The active generation and filtering of analogies also occurs in less formal domains. For example, Blanchette and Dunbar (2000) gave participants the task of generating an analogy to defend a political decision to cut the national deficit. They found that people were able to generate relationally appropriate analogies, often without relying on surface similarity. As Blanchette and Dunbar point out, participants in this task were not obliged to report their first reminding; they had the opportunity to select among possible analogs.

Development of analogical ability

When young children are given an analogy they tend to be influenced strongly by object matches, attending less to relational matches than do adults and older children (Gentner, 1988; Gentner & Rattermann, 1991; Honomichl & Chen, 2006; Mix, 2008; Paik & Mix, 2006; Richland, Morrison, & Holyoak, 2006). The transition in the course of development from a focus on objects to a focus on relations has been termed the *relational shift* (Gentner, 1988). In the past 30 years there has been widespread agreement that this shift occurs. Gentner and Rattermann (1991) proposed that the shift is primarily driven by gains in domain knowledge, based on two kinds of evidence: (1) the same kind of relational shift is seen in adults as they learn a new domain (e.g., Chi, Feltovich, & Glaser, 1981); and (2) if young children are given new relational knowledge, they can make rapid gains in analogical performance within a single session (Gentner & Rattermann, 1991; Loewenstein & Gentner, 2005). However, the shift could also be driven by developmental increases in relational processing capacity (Halford, 1993), or executive functioning (e.g., better ability to inhibit a focus on object matches) (Richland et al., 2006; Thibaut, French, & Vezneva, 2010). Of course, these views are not mutually exclusive; it is likely that some combination of these factors explains the relational shift in development.

How do children learn to focus on relational commonalities? One way is by learning and using relational language, which can invite and support the use of relational representations (Gentner & Rattermann, 1991). For example, three-year-old children perform at chance in a challenging spatial analogy task (Figure 11.1); they often mistakenly choose an object match instead of a relational match. However, if the array is described using spatial relational language (*top, middle, bottom*) the children do much better (Loewenstein & Gentner, 2005); further, they retain their ability to do the task even after a few days' delay, with no reinstatement of the language – evidence that the spatial relational language invited a relational representation.

When does analogical mapping fail?

As we have reviewed, analogy can be valuable in learning and reasoning. However, analogical mapping does not always succeed. Three kinds of factors influence the outcome of an analogical mapping: first, factors internal to the mapping process itself; second, individual characteristics of the reasoner; and, third, task and context factors such as cognitive load and processing time.

Factors internal to the mapping. Transparency and systematicity have been found to be important in analogical problem-solving. The *transparency* of the mapping between two analogous situations – that is, the degree of similarity between corresponding objects – is a good predictor of people's ability to notice and apply solutions from one problem to the other. Highly transparent analogies are both readily noticed and easy to align. For example, Gentner and Kurtz (2006) asked adults to judge whether pairs of sentences were analogous. People were faster for highly transparent pairs than for equally analogous (but less surface-similar) matches. High transparency also aids transfer, not only by contributing to memory reminding (as discussed earlier), but also by facilitating the process of aligning the earlier problem with the current problem. Ross (1989) taught people algebra problems and later gave them new problems that followed the same principles. People were better able to map the solution from a prior problem to a current problem when the corresponding objects were highly similar between the two problems: for example, "How many golf balls per golfer" ◊ "How many tennis balls per tennis player." They performed worst in the cross-mapped condition, in which similar objects appeared in different roles across the two problems: for example, "How many golf balls per golfer" ◊ "How many tennis players per tennis ball."

The second internal factor is *systematicity* – the degree to which the common system forms a coherent, interconnected system connected by higher-order constraining relations, such as causality. When relational matches form an interconnected system, people are more likely to preserve a relational match, as amplified just below.

Characteristics of the reasoner. These factors internal to the analogy interact with characteristics of the reasoner, including age and experience. For example, cross-mapped analogies are especially difficult for children (Gentner & Rattermann, 1991; Gentner & Toupin, 1986; Richland et al., 2006), especially in cases where the object matches are rich and distinctive (Gentner & Rattermann, 1991; Paik & Mix, 2006). However, the ability to represent systematic relational structure can compensate for low transparency as learners progress in a domain. For example, Gentner and Toupin (1986) gave six- and nine-year-olds simple stories (illustrated with stuffed animals) and asked the children to reenact them with a new set of characters. The accuracy of retelling varied with the transparency of the stories. Children were nearly perfect in the high-transparency condition (where similar characters occupied corresponding roles), less accurate in the medium-transparency condition (where dissimilar characters had corresponding roles), and least accurate in the cross-mapped condition (where similar characters played different roles). Notably, older (but not younger) children benefited strongly from a manipulation that highlighted systematicity; when nine-year-olds were given a statement that summarized the higher-order structure of the plot, their mapping accuracy remained high across all conditions. This suggests that older children (like adult experts) were able to use the relational constraints provided by the higher-order structure to avoid tempting (but incorrect) object-mappings. These findings are emblematic of general principles of learning and development – the deeper and better-connected the relational knowledge structure, the better we are able to maintain the structure in the face of surface-level competition (Gentner & Toupin, 1986; Markman & Gentner, 1993a).

A final characteristic of the reasoner that affects analogical ability is damage to the cortical systems that support reasoning. Morrison et al. (2004) studied patients suffering from frontal or temporal lobe degeneration, using a one-shot mapping task similar to that used by Markman and Gentner (1993a) (with object matches competing with the relational alignment; see Figure 11.1). Both groups of patients showed deficits in analogical reasoning relative to age-matched controls. However, although both patient groups were impaired in selecting a relation-based match when there was a competing object match, the results suggested that the inability to inhibit the competing object match may have been a larger factor for patients with frontal degeneration. Other studies have also implicated the prefrontal cortex in relational reasoning. Using a task akin to Raven's matrix task (which requires relational alignment), Waltz et al. (1999) found that patients with prefrontal cortical damage showed selective impairment on problems requiring integrating multiple relations, relative to patients with anterior temporal lobe damage and to control subjects.

Task conditions. The third class of factors that can affect analogical processing are task conditions such as time pressure and processing load. For example, Goldstone and Medin (1994) found that when people were forced to terminate an analogy matching task early, they were strongly influenced by local object matches; with more time, they were more likely to choose a relational match. Another factor is cognitive load. Waltz et al. (2000) gave participants a task modeled on Markman and Gentner's (1993a) one-shot mapping task (with cross-mappings, as described earlier). Participants who were given a working memory load – a digit string to hold in memory during the task – performed worse than those who were not. Under memory load, people were more likely to match objects instead of following a relational match than were people who carried out the task with no load.

Analogy in the real world

Our discussion so far has emphasized laboratory studies. We now turn to analogy in real-world contexts. As we will see, many of the phenomena studied in the lab can be seen in the world at large. The history of science offers many examples of analogical thinking. Great pioneering figures such as Kepler and Faraday relied heavily on analogy in arriving at their discoveries (Gentner et al., 1997; Nersessian, 1984; Thagard, 1992), and the same pattern is seen among contemporary scientists (Dunbar, 1997). In pioneering work investigating the day-to-day reasoning of contemporary microbiologists, Dunbar (1993, 1997) found that analogical thinking was a central element in nearly all aspects of scientific reasoning, including hypothesis generation, experimental design, and data interpretation. Interestingly, many of the analogies Dunbar observed were high-transparency, sharing both causal structure and surface features. For example, a scientist investigating the functionality of a gene in one organism (e.g., an oyster) might draw an analogy to a gene in a similar organism (e.g., another kind of oyster), that had a well-understood function (Dunbar, 1997). It seems that scientists at the cutting edge of their field rely mainly on high-transparency analogies, just like college students and young children. This pattern is less surprising if we reflect that (a) high-transparency analogies are readily retrieved from memory; and (b) strong overall similarity matches allow for high confidence that the candidate inferences are likely to be correct. Although great breakthroughs are sometimes made by invoking far analogies that lead to major paradigm shifts (Gentner et al., 1997; Holyoak & Thagard, 1997; Nersessian, 1984; Thagard, 1992), science (like other kinds of human learning) often makes progress by mundane overall similarity.

Analogy is also prevalent in informal situations, such as politics and social judgment. People often make use of previous experience with familiar individuals when judging strangers (Andersen & Chen, 2002) or making sense of new social experiences (Mussweiler & Rüter, 2003). For example, Mussweiler and Rüter (2003) found that people make social judgments faster when they are primed to make analogical comparisons, with no loss of accuracy relative to a control group. People often argue for or against positions by analogy, and it is common to attack elements of an opponent's position by pointing out weakness in an analogy they have used. For instance, during the 2012 presidential election, Mitt Romney criticized President Obama's economic record and claimed that he, Romney, would be "the coach that leads America to its winning season," continuing, "If you have a coach that is zero and 23 million [referring to unemployment numbers], you say it's time to get a new coach." As reported in *New York* magazine (Amira, 2013), President Obama responded in kind by extending the analogy:

> He said he's going to be the coach that leads America to a winning season. The problem is everybody's already seen his economic playbook. We know what's in it. On first down, he hikes taxes by nearly $2,000 on the average family with kids. . . . On second down, he calls an audible and undoes reforms that are there to prevent another financial crisis and bank bailout. . . . And then on third down, he calls for a Hail Mary: ending Medicare as we know it. . . . That's their playbook.

Argument by analogy can be effective in politics. In addition to vividly describing the issue, such analogies may convey a relational structure – such as "Romney's plan doesn't make sense" – through a domain more accessible to some voters, such as sports. Likewise, Blanchette and Dunbar (2001) surveyed a large set of newspaper articles on the issue of Québécois secession, and found that they often used analogies, which tended to be from familiar arenas such as agriculture, family, and sports.

Part of the appeal of President Obama's analogy is its humor; a humorous analogy can bring home a conceptual point. For example, Frank Oppenheimer, the brother of Robert Oppenheimer and a noted physicist in his own right, offered this analogy: "understanding is a lot like sex. It's got a practical purpose, but that's not why people do it normally" (Cole, 1997, p. 5).

Oppenheimer's point – that pursuing understanding is intrinsically and intensely rewarding – is all the more persuasive in its humorous clothing. Loewenstein and Heath (2009) conducted a large-scale survey of jokes and discovered that many of them follow a specific analogical pattern, which they call the *repetition-break* sequence.[1] This is a three-part structure that begins with two highly similar episodes – high-transparency matches for which structural alignment is virtually automatic, leading the common schema to emerge. The third episode breaks the structure – it is partly parallel, but differs in some striking way. This incongruity generates a humorous outcome, as in "A doctor, a lawyer, and a psychologist walk into a bar . . ."

The final instance of everyday analogical reasoning that we will discuss concerns the use and adaptation of figurative language. Conventional metaphor systems, extensively studied by George Lakoff and colleagues, serve to connect abstract domains with more concrete domains

(Lakoff & Johnson, 1980). Metaphors like "their relationship has reached a crossroads" and "the last few months of our marriage have been rocky, but we'll reach the other side" belong to a larger metaphorical system, characterized as "a relationship is a journey." Such metaphorical systems may begin as series of literal comparison statements, entering the language over time through repeated structural alignment (Bowdle & Gentner, 2005). Such systematic mappings may affect how people conceptualize policy issues (Thibodeau & Boroditsky, 2011), though the extent of this effect is debated (Steen, Reijnierse, & Burgers, 2014).

Conclusion

Analogical ability – the ability to recognize relational similarity across situations – is a core capacity of higher-order learning and reasoning. We have reviewed research on the cognitive processes that underlie analogical reasoning and support analogical learning and abstraction. We have provided examples of the use of analogical reasoning from politics, scientific investigation, and learning and development.

Over the roughly thirty years that analogy has been the subject of committed research in cognitive science, great strides have been made in understanding and modeling analogical processing. Yet there are still many open questions. We are only beginning to probe the neural underpinnings of analogical processing and to investigate the analogical abilities of other species. As the study of relational reasoning progresses, we will better understand its role in the range of human cognitive experience.

Note

1 The repetition-break structure is also used in many children's stories – for instance, *The Three Little Pigs*. Here the high similarity of the first two episodes invites alignment, allowing the child to see a pattern; this makes the change in the third episode salient.

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