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Analogy

Analogy is (1) similarity in which the same relations hold between different domains or systems; (2) inference that if two things agree in certain respects then they probably agree in others. These two senses are related, as discussed below.

Analogy is important in cognitive science for several reasons. It is central in the study of LEARNING and discovery. Analogies permit transfer across different CONCEPTS, situations, or domains and are used to explain new topics. Once learned, they can serve as MENTAL MODELS for understanding a new domain (Halford 1993). For example, people often use analogies with water flow when reasoning about electricity (Gentner and Gentner 1983). Analogies are often used in PROBLEM SOLVING and inductive reasoning because they can capture significant parallels across different situations. Beyond these mundane uses, analogy is a key mechanism in CREATIVITY and scientific discovery. For example, Johannes Kepler used an analogy with light to hypothesize that the planets are moved by an invisible force from the sun. In studies of microbiology laboratories, Dunbar (1995) found that analogies are both frequent and important in the discovery process.

Analogy is also used in communication and persuasion. For example, President Bush analogized the Persian Gulf crisis to the events preceding World War II, comparing Saddam Hussein to Hitler, Spellman and Holyoak 1992). The invited inference was that the United States should defend Kuwait and Saudi Arabia against Iraq, just as the Allies defended Europe against Nazi Germany. On a larger scale, conceptual metaphors such as "weighing the evidence" and "balancing the pros and cons" can be viewed as large-scale conventionalized analogies (see COGNITIVE LINGUISTICS). Finally, analogy and its relative, SIMILARITY, are important because they participate in many other cognitive processes. For example, exemplar-based theories of conceptual structure and CASE-BASED REASONING models in artificial intelligence assume that much of human categorization and reasoning is based on analogies between the current situation and prior situations (cf. JUDGMENT HEURISTICS).

The central focus of analogy research is on the mapping process by which people understand one situation in terms of another. Current accounts distinguish the following subprocesses: *mapping*, that is, *aligning* the representational structures of the two cases and projecting inferences; and *evaluation* of the analogy and its inferences. These first two are signature phenomena of analogy. Two further processes that can occur are *adaptation* or *rerepresentation* of one or both analogs to improve the match and abstraction of the structure common to both analogs. We first discuss these core processes, roughly in the order in which they occur during normal processing. Then we will take up the

Gentner, D. (1999). In R. A. Wilson & F. C. Keil (Eds.), The MIT encyclopedia of the cognitive sciences (pp. 17-20). Cambridge, MA: MIT Press.

issue of analogical *retrieval*, the processes by which people are spontaneously reminded of past similar or analogous examples from long-term memory.

In analogical *mapping*, a familiar situation—the base or source analog—is used as a model for making inferences about an unfamiliar situation—the target analog. According to Gentner's *structure-mapping* theory (1983), the mapping process includes a *structural alignment* between two represented situations and the *projection of inferences* from one to the other. The alignment must be *structurally consistent*, that is, there must be a one-to-one correspondence between the mapped elements in the base and target, and the arguments of corresponding predicates must also correspond (*parallel connectivity*). Given this alignment, candidate inferences are drawn from the base to the target via a kind of structural completion. A further assumption is the *systematicity principle:* a system of relations connected by higher-order constraining relations such as causal relations is more salient in analogy than an equal number of independent matches. Systematicity links the two classic senses of analogy, for if analogical similarity is modeled as common relational structure, then a base domain that possesses a richly linked system of connected relations will yield candidate inferences by completing the connected structure in the target (Bowdle and Gentner 1997).

Another important psychological approach to analogical mapping is offered by Holyoak (1985), who emphasized the role of pragmatics in problem solving by analogy—how current goals and context guide the interpretation of an analogy. Holyoak defined analogy as similarity with respect to a goal, and suggested that mapping processes are oriented toward attainment of goal states. Holyoak and Thagard (1989) combined this pragmatic focus with the assumption of structural consistency and developed a multiconstraint approach to analogy in which similarity, structural parallelism, and pragmatic factors interact to produce an interpretation.

Through *rerepresentation* or *adaptation*, the representation of one or both analogs is altered to improve the match. Although central to conceptual change, this aspect of analogy remains relatively unexplored. And through *schema abstraction*, which retains the common system representing the interpretation of an analogy for later use, analogy can promote the formation of new relational categories and abstract rules.

Evaluation is the process by which we judge the acceptability of an analogy. At least three criteria seem to be involved: structural soundness—whether the alignment and the projected inferences are structurally consistent; factual validity of the candidate inferences—because analogy is not a deductive mechanism, this is not guaranteed and must be checked separately; and finally, in problem-solving situations, goal-relevance—the reasoner must ask whether the analogical inferences are also relevant to current goals. A lively arena of current research centers on exactly how and when these criteria are invoked in the analogical mapping process.

As discussed above, processing an analogy typically results in a common schema. Accounts of how *cognitive simulation* occurs fall into two classes: projection-first models, in which the schema is derived from the base and mapped to the target; and alignment-first models, in which the abstract schema is assumed to arise out of the analogical mapping process. Most current cognitive simulations take the latter approach. For example, the structure-mapping engine (SME) of Falkenhainer, Forbus, and Gentner (1989), when given two potential analogs, proceeds at first rather blindly, finding all possible local matches between elements of the base and target. Next it combines these into structurally consistent kernels, and finally it combines the kernels into the two or three largest and deepest matches of connected systems, which represent possible interpretations of the analogy. Based on this alignment, it projects candidate inferences—by hypothesizing that other propositions connected to the common system in the base may also hold in the target. The analogical constraint-mapping engine (ACME) of Holyoak and Thagard (1989) uses a similar local-to-global algorithm, but differs in that it is a multiconstraint, winner-take-all connectionist system, with soft constraints of structural consistency, semantic similarity, and pragmatic bindings. Although the multiconstraint system permits a highly flexible mapping process, it often arrives at structurally inconsistent mappings, whose candidate inferences are indeterminate. Markman (1997) found that this kind of indeterminacy was rarely experienced by people solving analogies. Other variants of the local-to-global algorithm are Hofstadter and Mitchell's Copycat system (1994) for perceptual analogies and Keane's incremental analogy machine (IAM; 1990), which adds matches incrementally in order to model effects of processing order. In contrast to alignment-first models, in which inferences are made after the two representations are aligned, projection-first models find or derive an abstraction in the base and then project it to the target (e.g., Greiner 1988). Although alignment-first models are more suitable for modeling the generation of new abstractions, projection-first models may be apt for modeling conventional analogy and metaphor.

Finally, analogy has proved challenging to subsymbolic connectionist approaches. A strong case can be made that analogical processing requires structured representations and structure-sensitive processing algorithms. An interesting recent "symbolic connectionist" model, Hummel and Holyoak's LISA (1997), combines such structured symbolic techniques with distributed concept representations.

Thus far, our focus has been on how analogy is processed once it is present. But to model the use of analogy and similarity in real-life learning and reasoning we must also understand how people think of analogies; that is, how they *retrieve* potential analogs from long-term memory. There is considerable evidence that similarity-based *retrieval* is driven more by surface similarity and less by structural similarity than is the mapping process. For example, Gick and Holyoak (1980; 1983) showed that people often fail to access potentially useful analogs. People who saw an analogous story prior to being given a very difficult thought problem were three times as likely to solve the problem as those who did not (30 percent vs. 10 percent). Impressive as this is, the majority of subjects nonetheless failed to benefit from the analogy. However, when the nonsolvers were given the hint to think back to the prior story, the solution rate again tripled, to about 80–90 percent. Because no new information was given about the story, we can infer that subjects had retained its meaning, but failed to think of it when reading the problem. The similarity match between the story and the problem, though sufficient to carry out the mapping once both analogs were present in working memory, did not lead to spontaneous retrieval. This is an example of the inert knowledge problem in transfer, a central concern in EDUCATION.

Not only do people fail to retrieve analogies, but they are often reminded of prior surface-similar cases, even when they know that these matches are of little use in reasoning (Gentner, Rattermann, and Forbus 1993). This relative lack of spontaneous analogical transfer and predominance of surface remindings is seen in problem solving (Ross 1987) and may result in part from overly concrete representations (Bassok, Wu, and Olseth 1995).

Computational models of similarity-based retrieval have taken two main approaches. One class of models aims to capture the phenomena of human memory retrieval, including both strengths and weaknesses. For example, analog retrieval by constraint satisfaction (ARCS; Thagard et al. 1990) and Many are called/but few are chosen (MAC/FAC; Forbus, Gentner, and Law 1995) both assume that retrieval is strongly influenced by surface similarity and by structural similarity, goal relevance, or both. In contrast, most case-based reasoning (CBR) models aim for optimality, focusing on how to organize memory such that relevant cases are retrieved when needed.

Theories of analogy have been extended to other kinds of similarity, such as METAPHOR and mundane literal similarity. There is evidence that computing a literal similarity match involves the same process of structural alignment as does analogy (Gentner and Markman 1997). Current computational models like ACME and SME use the same processing algorithms for similarity as for analogy.

The investigation of analogy has been characterized by unusually fruitful interdisciplinary convergence. Important contributions have come from philosophy, notably Hesse's analysis (1966) of analogical models in science, and from artificial intelligence (AI), beginning with Winston's research (1982), which laid out computational strategies applicable to human processing. Recent research that combines psychological investigations and computational modeling has advanced our knowledge of how people align representational structures and compute further inferences over them. Theories of analogy and structural similarity have been successfully applied to areas such as CATEGORIZATION, DECISION MAKING, and children's learning. At the same time, cross-species comparisons have suggested that analogy may be especially well developed in human beings. These results have broadened our view of the role of structural similarity in human thought.

See also CONSTRAINT SATISFACTION; FIGURATIVE LANGUAGE; LANGUAGE AND COMMUNICATION; METAPHOR AND CULTURE; SCHEMATA

—*Dedre Gentner*

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Anaphora

The term *anaphora* is used most commonly in theoretical linguistics to denote any case where two nominal expressions are assigned the same referential value or range. Discussion here focuses on noun phrase (NP) anaphora with pronouns (see BINDING THEORY for an explanation of the types of expressions commonly designated "anaphors," e.g., reflexive pronouns).

Pronouns are commonly viewed as variables. Thus, (1b) corresponds to (2), where the predicate contains a free variable. This means that until the pronoun is assigned a value, the predicate is an open property (does not form a set). There are two distinct procedures for pronoun resolution: *binding* and *covaluation*. In binding, the variable gets bound by the λ-operator, as in (3a), where the predicate is closed, denoting the set of individuals who think they have the flu, and where the sentence asserts that Lili is in this set.

(1) a. Lucie didn't show up today.
    b. Lili thinks she's got the flu.

(2) Lili (λx (x thinks z has got the flu))

(3) a. *Binding:* Lili (λx (x thinks x has got the flu))
    b. *Covaluation:* Lili (λx (x thinks z has got the flu) & z = Lucie)

In covaluation, the free variable is assigned a value from the DISCOURSE storage, as in (3b). An assumption standard since the 1980s is that, while processing sentences in context, we build an inventory of discourse entities, which can further serve as antecedents of anaphoric expressions (Heim 1982; McCawley 1979; Prince 1981). Suppose (1b) is uttered in the context of (1a). We have stored an entry for *Lucie*, and when the pronoun *she* is encountered, it can be assigned this value. In theory-neutral terms, this assignment is represented in (3b), where *Lucie* is a discourse entry, and the pronoun is covalued with this entry.

The actual resolution of anaphora is governed by discourse strategies. Ariel (1990) argues that pronouns look for the most accessible antecedent, and discourse topics are always the most accessible. For example, (3b) is the most likely anaphora resolution for (1b) in the context of (1a), since *Lucie* is the discourse topic that will make this minimal context coherent.

Given the two procedures, it turns out that if *Lili* is identified as the antecedent of the pronoun in (1b), the sentence has, in fact, two anaphora construals. Since *Lili* is also in the discourse storage, (1b) can have, along with (3a), the covaluation construal (4).

(4) Lili (λx (x thinks z has got the flu) & z = Lili)

(5) Lili thinks she has got the flu, and Max does too.

Though (3a) and (4) are equivalent, it was discovered in the 1970s that there are contexts in which these sentences display a real representational ambiguity (Keenan 1971). For example, assuming that *she* is *Lili*, the elliptic second conjunct of (5) can mean either that Max thinks that Lili has the flu, or that Max himself has it. The first is obtained if the elided predicate is construed as in (4), and the second if it is the predicate of (3a).

Let us adopt here the technical definitions in (6). ((6a) differs from the definition used in the syntactic binding theory). In (3a), then, *Lucie* binds the pronoun; in (4), they are covalued.

(6) a. Binding: α binds β iff α is an argument of a λ-predicate whose operator binds β.
    b. Coevaluation: α and β are covalued iff neither binds the other and they are assigned the same value.

Covaluation is not restricted to referential discourse-entities—a pronoun can be covalued also with a bound variable. Indeed, Heim (1998) showed that covaluation-binding ambiguity can show up also in quantified contexts. In (7a), the variable *x* (*she*) binds the pronoun *her*. But in (7b) *her* is covalued with *x*.

(7) Every wife thinks that only she respects her husband.
    a. Binding: Every wife (λx (x thinks that [only x (λy(y respects y's husband))]))
    b. Covaluation: Every wife (λx (x thinks that [only x (λy(y respects x's husband))]))

In many contexts the two construals will be equivalent, but the presence of *only* enables their disambiguation here: (7a) entails that every wife thinks that other wives do not respect their husbands, while (7b) entails that every wife thinks other wives do not respect her husband. This is so, because the property attributed only to *x* in (7a) is respecting one's own husband, while in (7b) it is respecting *x*'s husband.

The binding interpretation of pronouns is restricted by syntactic properties of the derivation (see BINDING THEORY).