Reasoning and Learning by Analogy

Introduction

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Analogy is a powerful cognitive mechanism that people use to make inferences and learn new abstractions. The history of work on analogy in modern cognitive science is sketched, focusing on contributions from cognitive psychology, artificial intelligence, and philosophy of science. This review sets the stage for the 3 articles that follow in this Science Watch *section.*

People live in a world of perpetual novelty, in which no experience is ever exactly repeated. Yet paradoxically, many would agree that "there is nothing new under the sun." The "illusion of familiarity," as it might be called, depends on the power of the human mind to find—and, if necessary, to create—similarities between past experiences and the present situation. Perceived similarities enable one to organize objects and events into familiar categories—cats and dogs, friendships and love affairs. But how do categories first get formed? One basic mechanism is *analogy*—the process of understanding a novel situation in terms of one that is already familiar. The familiar situation—often termed the *base* or *source* analog—provides a kind of model for making inferences about the unfamiliar situation—the *target* analog. In the course of reasoning by analogy, the novel target comes to be seen as another example of "the same kind of thing" as the familiar analog. And the analogy between two specific situations may provide the "seed" for learning a more general category or schema that encompasses both.

The power of analogy to create similarities makes it a tool for a wide range of purposes, including solving problems, constructing explanations, and building arguments. Consider an example from recent history (Spellman & Holyoak, 1992). In order to muster support for the U.S.-led drive to liberate Kuwait after it was captured by Iraq, President George Bush explicitly compared Saddam Hussein to Adolf Hitler and the Persian Gulf crisis to events that led to World War II a half century earlier. By drawing the analogy between Saddam Hussein and Hitler, President Bush encouraged a reasoning process that led to the construction of a coherent system of roles for the players in the Gulf situation. Once the analogical correspondences were established (with Iraq identified as an expansionist dictatorship like Germany, Kuwait as its first victim, Saudi Arabia as the next potential victim, and the United States as the main defender of the Gulf states), the clear analogical inference was that both self-interest and moral considerations required immediate military intervention by the United States.

How does analogy actually operate? How is it connected with judgments of similarity? What roles does it play in everyday reasoning and decision making? Can an understanding of analogy provide insights of use to clinical psychologists and educators? This section of *Science Watch* features three articles that address these questions. These articles provide distinct but interrelated perspectives on a research topic that over the past two decades has been a major "success story" in the interdisciplinary field of cognitive science. The progress in understanding analogy is manifested in several ways. First, the study of analogy has been energized by fruitful collaborations between researchers in psychology and artificial intelligence, with significant influences from philosophy, linguistics, and history of science. Second, the empirical and computational work has led to a substantial degree of convergence between researchers in the field, indicating the stability of many of the fundamental theoretical assumptions. Finally, theories of analogy have been extended to account for data in areas that are near relatives, such as metaphor and mundane similarity, as well as to

areas that are more distant cousins, such as categorization and decision making.

Modern views of analogy can be traced to such pioneering influences as the philosopher Mary Hesse (1966), whose treatise on analogy in science argued that analogies are powerful forces in discovery and conceptual change. For some time, however, most psychological work on analogy focused on four-term analogy problems of the sort used in intelligence tests (e.g., "foot is to leg as arm is to what?") rather than on the richer analogies used in science and everyday life. In the early 1980s, two research projects in psychology began to take a broader view of analogy. Gentner (1982, 1983; Gentner & Gentner, 1983) began working on mental models and analogy in science. She was struck by the idea that in analogy, the key similarities lie in the relations that hold within the domains (e.g., the flow of electrons in an electrical circuit is analogically similar to the flow of people in a crowded subway tunnel) rather than in features of individual objects (e.g., electrons do not resemble people). Moreover, analogical similarities often depend on higher order relations—relations between relations. For example, adding a resistor to a circuit causes (a higher order relation) a decrease in the flow of electricity, just as adding a narrow gate in a subway tunnel would decrease the rate at which people could pass through. In her structure-mapping theory, Gentner set forth the view that analogy entails finding a structural alignment, or a *mapping*, between domains. This alignment between two representational structures is characterized by structural parallelism (consistent, one-to-one correspondences between mapped elements) and systematicity—an implicit preference for deep, interconnected systems of relations governed by higher order relations, such as causal, mathematical, or functional relations.

Holyoak (1985; Gick & Holyoak, 1980, 1983; Holyoak & Koh, 1987) became convinced that analogy offered a richer approach to problem solving than those that were then available. His focus on problem solving led him to a strong concern for the role of pragmatics in analogy— how current goals and context guide the interpretation of an analogy. Holyoak and Thagard (1989) developed a multiconstraint approach to analogy in which similarity, structural parallelism, and pragmatic factors interact to produce an interpretation. In addition, Holyoak's research on problem solving provided evidence that analogy can provide the seed for forming new relational categories, by abstracting the relational correspondences between examples into a schema for a class of problems. Analogy was viewed as a central part of human induction (Holland, Holyoak, Nisbett, & Thagard, 1986).

At the same time, researchers in artificial intelligence began to grapple with the use of complex analogies in reasoning and learning (Winston, 1980). Schank and his colleagues were exploring the role of experience in understanding (Schank, 1982) and the relationship between understanding, learning, and memory (Kolodner, 1983). This exploration soon led to a more general focus on the role of experience in reasoning and the relation-

ships among reasoning, learning, and memory. *Case-based reasoning* (e.g., Kolodner, 1993; Kolodner & Simpson, 1989; Schank, Kass, & Riesbeck, 1994) was born from these explorations as a methodology for computer reasoning and as a plausible model of human reasoning. In contrast to rule-based approaches to reasoning (the dominant approach in artificial intelligence at the time), case-based reasoning emphasized the usefulness of retrieving and adapting cases or analogs stored in long-term memory when deriving solutions to novel problems.

During recent years, the efforts of many cognitive scientists have contributed to an emerging consensus on many issues concerning analogy (e.g., Halford, 1993; Keane, Ledgeway, & Duff, 1994; Ross, 1989). The process of analogical thinking can be usefully decomposed into several basic constituent processes. One or more relevant analogs stored in memory must be accessed. A familiar analog must be mapped to the target analog to identify systematic correspondences between the two, thereby aligning the corresponding parts of each analog. The resulting mapping allows analogical inferences to be made about the target analog, thus creating new knowledge to fill gaps in understanding. These inferences need to be evaluated and possibly adapted to fit the unique requirements of the target. Finally, in the aftermath of analogical reasoning, learning can result in the generation of new categories and schemas, the addition of new instances to memory, and new understandings of old instances and schemas that allow them to be better accessed in the future.

All current theories of analogy deal with some subset of these basic component processes. In various ways and with differing emphases, all these theories make use of some combination of structural information about the form of the analogs and pragmatic information about the goals that triggered the reasoning episode. Theories of analogy have been instantiated in computer simulations. The output of a simulation can be compared to human performance with analogies, providing empirical grounding for the theoretical principles underlying the computer model.

The three articles that follow illustrate some of the current research and theories of analogy use. Each article emphasizes particular issues and approaches. Holyoak and Thagard (1997) provide a number of examples of how analogies are used in contexts ranging from political debate to psychotherapy. They discuss these examples in terms of their multiconstraint theory, which posits a small number of basic principles that interact to guide analogical mapping and other aspects of analogy use. Gentner and Markman (1997) describe the structure-mapping theory, which emphasizes the structural principles on which mapping is based. They show how the structure-mapping theory provides insights into how similarities can be actively created as two analogs are aligned with one another. Kolodner (1997) provides an overview of the case-based reasoning approach as it applies to human and artificial intelligence and discusses some of its implications for design of educational practices and educational software.

Whereas the first two articles emphasize work on the mapping process, Kolodner's article focuses on how cases are retrieved and adapted. Each article sketches some of the computer simulations that have been developed to test theories of analogy and also raises some unanswered questions that invite further research.

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