1

Introduction: The Place of Analogy in Cognition

Keith J. Holyoak, Dedre Gentner, and Boicho N. Kokinov

Thinking about Relational Patterns

The celebration of the turn of a century is called a "centennial," and few people get to celebrate more than one of them. Even rarer is the celebration of the turn of a millennium. What should we call it? Why, a "millennial," of course. No need for prior experience, or even a dictionary—a simple verbal analogy provides an appropriate term to mark the dawn of the third thousand-year period of the Julian calendar. Not so simple, however, are the mental operations that underlie this pervasive form of human thinking. This volume is a kind of millennial marker in analogy research, a set of papers that collectively lay out the "state of the art" in our current scientific understanding of the mental processes involved in the use of analogy in cognition.

A millennial, though it may simply be a side effect of arbitrary calendar conventions, somehow seems to call attention to the way in which the present state of humanity connects to the broad sweep of our evolutionary and cultural history. If we consider what it means to be human, certain cognitive capabilities loom large—capabilities that subserve language, art, music, invention, and science. Precisely when these capabilities arose in the course of human evolution is unclear, but it seems likely they were well developed at least fifty thousand years ago, based on archeological findings of standardized stone tools and jewelry in East Africa. About forty thousand years ago, the Cro-Magnon people in southwestern Europe created magnificent cave paintings as well as statues and musical instruments, suggesting mental capabilities comparable to our own. We have been human for quite some time already.

What cognitive capabilities underlie our fundamental human achievements? Although a complete answer remains elusive, one basic component is a special kind of symbolic ability—the ability to pick out patterns, to identify recurrences of these patterns despite variation in the elements that compose them, to form concepts that abstract and reify these patterns, and to express these concepts in language. Analogy, in its most general sense, is this ability to think about relational patterns. As Douglas **Hofstadter** (chap. 15, this volume) argues, analogy lies at the core of human cognition.

Although we believe that analogy is indeed a central component of human cognition, it is not quite the exclusive province of our species. Indeed, we can illustrate the basic idea of a relational pattern using an example that is within the capacity of another primate species, the chimpanzee. Consider the pairs of geometric forms displayed in figure 1.1. It is readily apparent (at least to a typical adult human) that pair A is the "same" as the standard in a way in which pair B is not (because the two triangles in pair A have the same shape, just as do the two circles in the standard). But where is this "sameness" that connects the standard and pair A? It does not reside in the physical forms, which overlap not at all. Rather, it resides in the identity of the *relation* between the two triangles and the *relation* between the two squares—"sameness of shape," a shared relational pattern. In order to solve this problem one has to *explicitly* represent the relations between the objects and to match them. This type of explicit relational match has been shown to be within the capacity of a handful of chimpanzees that have received training with physical symbols for the concept "same." The first such symbol-trained chimpanzee to exhibit relational matching was Sarah (Premack 1978), whose analogy abilities are discussed by David **Oden**, Roger **Thompson**, and David **Premack** (chap. 14).

Critically, explicit relational matching is extremely difficult for chimpanzees that lack special training in symbol use, and apparently impossible for monkeys (Thompson and Oden 1998). In contrast to any other type of animal, analogy use develops spontaneously in very young members of the human species (see **Goswami**, chap. 13). The ability to

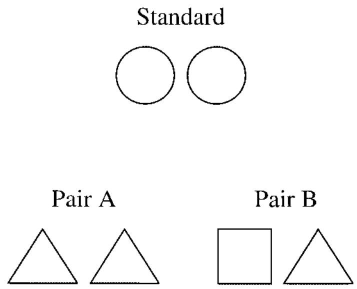

Figure 1.1
A test of relational matching. Pair A exhibits the same relation as does the standard ("same shape"), whereas pair B does not.

perceive and explicitly represent relational patterns thus appears to be intimately connected to the development of general representational abilities in humans (Gentner and Rattermann 1991).

The more complex the analogies, the more complex the representations they require. To draw an analogy, whole systems of connected relations are matched from one domain to another (Gentner 1983). To model this process, computational models must be able to build and maintain complex representational structures. Although this requirement is easily satisfied in models that make use of explicit symbols for individual concepts (see **Forbus**, chap. 2, and **Kokinov and Petrov**, chap. 3), it is much more difficult to satisfy it using models that represent symbols as patterns of activation over a neural substrate (**Holyoak and Hummel**, chap. 4, and **Wilson, Halford, Gray, and Phillips**, chap. 5; Plate 1998; Kanerva 1998). Solving this representational problem is one of the major goals for current modeling efforts.

A more specific aspect of this representational requirement for relational processing is to distinguish relational roles (e.g., "lover" and "beloved" in the relation "love") from the particular fillers of the role (e.g., "John" and "Mary"), while at the same time capturing the fact that those particular fillers are bound to the role. Providing a solution to this "binding problem" poses particular challenges for models that attempt to show how analogical processing might be realized in a neural architecture. Presumably, this difficult problem was solved in some manner during the evolution of the primate nervous system. Although we know little as yet about the neural substrate for processing relational patterns, progress has been made in understanding the cognitive operations involved.

Yet another representational problem arises from the need for flexible, dynamically changing, and context-sensitive representations. Often the representations of both target and source domains seem to change during the analogy-making process to fit each other as well as to fit the current context (see **Fauconnier**, chap. 7; Hofstadter and the Fluid Analogies Research Group 1995; **Hofstadter**, chap. 15; Kokinov 1998; and **Kokinov and Petrov**, chap. 3). This sort of dynamic reorganization of human representations is difficult for both symbolic and connectionist models.

From Gilgamesh to the Microbiology Lab

Although analogy has likely been a human cognitive ability for tens of thousands of years, its direct expression in the historical record awaited the development of written language. Uses of analogies—explicit mention of relational likenesses between distinct situations—are found in the world's earliest preserved literature. In the Babylonian epic *Gilgamesh*, written about four thousand years ago, the hero grieves over the corpse of his friend Enkidu (translated by Ferry 1993):

> . . . Gilgamesh covered
> Enkidu's face with a veil like the veil of a bride.
> He hovered like an eagle over the body,
> or as a lioness does over her brood.

In the same era, an ancient Egyptian poet (translated by Merwin 1968) wrote

> Death is before me today
> like the sky when it clears
> like a man's wish to see home after numberless years of captivity.

In ancient India, more than 2,500 years ago, concrete analogies were used to express abstract philosophical ideas. For example, in the Upanishads (translated by Mitchell 1989) it is written that

As a man in sexual union with his beloved
is unaware of anything outside or inside,
so a man in union with Self knows nothing, wants nothing,
has found his heart's fulfillment and is free of sorrow.

Analogies have figured in poetry across all times and cultures (see Washburn, Major, and Fadiman 1998, for these and many other examples). One basic function of analogy—perhaps its most ancient—is especially apparent in poetry. This is the transfer of emotions, a topic discussed by Paul **Thagard** and Cameron **Shelley** (chap. 10). The Babylonian text makes us feel that Gilgamesh's grief is as profound as the love of a bridegroom for his bride, his watchfulness and protectiveness as intense as those of an eagle or a lioness. Although the Egyptian writer says nothing directly about his emotions at the prospect of death, the analogies in that poem suggest a (perhaps surprising) sense of expectant joy at a long-awaited release, like that of a captive granted freedom. And the Indian poet uses his analogy with the experience of sexual union to convey not only an intellectual sense of what it means to be connected with the Self, but even more forcefully the emotional intensity of the experience. Emotional experiences are notoriously difficult or impossible to convey by literal language; but by connecting the relational pattern of a novel experience with that of a familiar, emotion-laden one, analogy provides a way of recreating a complex pattern of feelings.

The historical records of many cultures provide ample illustrations of the role of analogy in literature, religion and philosophy (see Holyoak and Thagard 1995). As Greek and Roman civilizations gave birth to Western science, analogy was enlisted as a tool for advancing this new kind of systematic and empirically verifiable analysis. At least two thousand years ago, the earliest recorded use of analogy to develop an enduring scientific theory produced the hypothesis that sound is propagated in the form of waves. During the reign of the emperor Augustus, a Roman architect and engineer named Vitruvius described the nature of sound by analogy to water waves (1960:138–139):

Voice is a flowing breath of air, perceptible to the hearing by contact. It moves in an endless number of circular rounds, like the innumerably increasing circular waves which appear when a stone is thrown into smooth water, and which keep on spreading indefinitely from the centre unless interrupted by narrow limits, or by some obstruction which prevents such waves from reaching their end in due formation.

The wave theory of sound became the seed of a new and insightful abstraction: the general conception of waves as a mode of transmission of patterns across space. This abstraction continued to be developed over the course of centuries. At first simply a qualitative explanation of sound transmission, the wave theory was eventually given a mathematical formulation. In the seventeenth century a wave theory of light was developed, by analogy with the wave theory of sound. The progression from highly specific, single-case analogies to more abstract concepts or schemas is one of the most powerful roles that analogy plays in cognition. This progression has been observed not only for scientific, mathematical, and problem-oriented concepts (see **Bassok**, chap. 12), but also for metaphorical concepts in everyday language (see **Gentner, Bowdle, Wolff, and Boronat**, chap. 6).

Although the development of large-scale theories based on analogy is a relatively rare event in science, smaller-scale uses are commonplace. Kevin **Dunbar** (chap. 9) describes some of his research on the use of analogies as they occur "on-line" in the activities of microbiology laboratories. In many situations, such as being faced with a series of unexpected findings, scientists will propose hypotheses based on analogical transfer from known examples (e.g., the possible function of a mysterious gene in one organism may be inferred from a similar and better-understood gene in a different organism).

The role of analogy in thinking manifests itself in many different cognitive tasks. The chapters in this volume give a sense of the scope of the human activities that involve analogy. These include the use of metaphor (**Gentner, Bowdle, Wolff, and Boronat**, chap. 6), conceptual blends (**Fauconnier**, chap. 7), translation (**Hofstadter**, chap. 15), scientific reasoning, political debate (**Dunbar**, chap. 9), creative design (Ward 1998), humor, empathy (**Thagard and Shelley**, chap. 10), computer-aided tutoring (**Forbus**, chap. 2), decision-making and choice (**Markman and Moreau**, chap. 11), mathematical problem-solving (**Bassok**, chap. 12), high-level perception (**Hofstadter**, chap. 15), memory recall (**Kokinov and Petrov**, chap. 3), and infant imitation (**Goswami**, chap. 13). Analogy is certainly not the sole basis for cognition (see **Keane and Costello**, chap. 8); but taken as a whole, these diverse manifestations of analogy support the claim that it forms a critical part of the core of cognition.

Analogy in Cognitive Science

The topic of analogy has a special place in the field of cognitive science. Modern cognitive science arose as a discipline in the final half-century of the millennium just ended—scarcely a tick on the clock of human life on earth. Although several converging factors led to the development of cognitive science, perhaps the most critical was an analogy—that between human information processing and the processing performed by the digital computer. This basic analogical insight, that cognition can be systematically analyzed as a form of computation, guided early work on such cognitive processes as memory, attention, perception, and problem-solving.

Although an analogy provided a major part of the foundation of cognitive science at its inception, the study of analogy itself as a cognitive process did not receive much attention until somewhat later. 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 research on analogy, both in artificial intelligence (Evans 1968) and in psychology (Piaget, Montangero, and Billeter 1977; Sternberg 1977) focused on four-term analogy problems of the sort used in intelligence tests (e.g., *cat is to kitten as dog is to what?*), rather than on the richer analogies used in science and everyday life.

About 1980, several research projects in artificial intelligence and psychology began to take a broader view of analogy. Researchers in artificial intelligence started to grapple with the use of complex analogies in reasoning and learning (Winston 1980; Schank 1982; Carbonell 1983, 1986; Hofstadter 1984). This exploration led to a more general focus on the role of experience in reasoning and the relationships among reasoning, learning, and memory, giving rise to an approach termed “case-based” reasoning (e.g., Kolodner 1993). In contrast to rule-based approaches to reasoning (the approach that was dominant 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.

In psychology, Gentner (1982, 1983; Gentner and 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 in series to a circuit *causes* (a higher-order relation) a decrease in flow of electricity, just as adding a narrow gate in the subway tunnel would decrease the rate at which people pass through. In her structure-mapping theory, Gentner set forth the view that analogy entails finding a structural alignment, or 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. Gentner and her colleagues carried out empirical studies to provide evidence for relational alignment (Gentner and Clement 1988; Markman and Gentner 1993), including alignments based on higher-order relations (Clement and Gentner 1991). The structure-mapping theory was eventually instantiated in computer simulations of analogical mapping and inference (the SME program; Falkenhainer, Forbus, and Gentner 1989) and analogical retrieval (the MAC/FAC program; Forbus, Gentner, and Law 1995; see **Forbus**, chap. 2, and **Gentner et al.**, chap. 6). It has been extended to ordinary similarity (Gentner and Markman 1997) and applied in diverse areas such as decision-making (Markman and Medin 1995; **Markman and Moreau**, chap. 11) and cognitive development (Gentner and Medina 1997).

Over this period, Holyoak and his collaborators (Holyoak 1985; Gick and Holyoak 1980) also investigated the role of analogy in complex cognitive tasks. Their initial focus was on the role of analogy in problem solving, which led to a strong concern for the role of pragmatics in analogy—how current goals and context guide the interpretation of an analogy. Gick and Holyoak (1983) 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 et al. 1986). Holyoak and Thagard developed a multiconstraint approach to analogy in which similarity, structural parallelism, and pragmatic factors interact to produce an interpretation. They developed simulation models of analogical mapping and inference (ACME; Holyoak and Thagard 1989) and retrieval (ARCS; Thagard et al. 1990) based on algorithms for simultaneously satisfying multiple constraints. Thagard (1989, 2000) extended the constraint-satisfaction approach to other cognitive tasks, such as evaluating explanations and making decisions, and showed how analogy could interact with other constraints in these broader contexts (see **Thagard and Shelley**, chap. 10). Hummel and Holyoak (1997) developed a new computer simulation, LISA, that was based on the multiconstraint theory of analogy but introduced representational and processing assumptions more consistent with the operation of human memory as instantiated in a neural architecture (**Holyoak and Hummel**, chap. 5).

Since the late 1980s, the efforts of many cognitive scientists have contributed to an emerging consensus on many issues concerning analogy (e.g., Gentner 1989; Halford 1993; Hummel and Holyoak 1997; Keane, Ledgeway, and Duff 1994; Kokinov 1988, 1994; Ross 1989). The process of analogical thinking can be usefully decomposed into several basic constituent processes. In a typical reasoning scenario, one or more relevant analogs stored in long-term 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 accessed better in the future. All current computational models of analogy deal with some subset of these basic component processes, and progress has been made in integrating them (e.g., **Forbus**, chap. 2; Kokinov 1994; **Kokinov and Petrov**, chap. 3). In various ways and with differing emphases, all current models make use of some combination of structural information about the form of the analogs, an assessment of the similarity between the episode elements, and pragmatic information about the goals that triggered the reasoning episode.

One of the more general contributions of analogy research to cognitive science is that it has served as an example of the way in which multiple disciplines can jointly contribute to our understanding of cognition. The chapters in this volume illustrate many of these diverse but interrelated approaches to analogy, which include psychological experiments, naturalistic observation, linguistic analyses, and computer simulation. In addition to research on analogy use by adult humans, important findings have emerged from studies of the development of analogy abilities in children and the capabilities of other primates, notably chimpanzees.

Overview of the Book

The first section of this volume presents four chapters that describe theories of analogical thinking that are instantiated in running computer models. The first two chapters take a similar approach, both arguing for integration of analogy models with models of other cognitive processes, and both using localist symbolic representations of concepts. Kenneth **Forbus** provides a review of computational models developed within the framework of the structure-mapping theory, which include models of analogical retrieval (MAC/FAC), mapping and inference (SME), and learning (Phineas). His chapter describes the ways in which these models can operate together, and in combination with models of other forms of commonsense reasoning, to simulate reasoning in knowledge-rich domains such as commonsense qualitative physics. The chapter emphasizes the integration constraint on analogy models—the need to show how models of component processes can be integrated to perform complex reasoning tasks based on large quantities of information.

Boicho **Kokinov** and Alexander **Petrov** take an integrative approach that tries to bring analogy and memory together. Their chapter addresses phenomena emphasized by constructivist approaches to memory, such as memory distortions and memory illusions, and show how these phenomena interact with analogy-making. They provide evidence for omissions, blending of episodes, intrusions from generic knowledge, and effects of context, priming, and order in analogical reminding, and they explain these phenomena in terms of interactions among memory, mapping, and perception. The chapter presents the latest development of their AMBR model, which simulates these phenomena by the parallel work and interplay of many subprocesses. This model uses dynamic emergent representations and computations performed by a society of hybrid micro-agents. AMBR is built on a general cognitive architecture, which makes it possible to integrate analogy with other cognitive processes and to provides a basis for unified explanations of phenomena such as context-sensitivity that cut across virtually all cognitive processes.

Whereas the models in the SME family, and also AMBR, are based on localist representations of meaning, the next two chapters explore the potential use of distributed representations of relational knowledge within neural-network architectures. Within localist-symbolic models the operations needed to bind fillers to roles and to build hierarchical knowledge structures are straightforward; in contrast, these requirements of analogical thinking pose major hurdles when treated within neural networks. William **Wilson**, Graeme **Halford**, Brett **Gray**, and Steven **Phillips** describe the STAR-2 model, which provides mechanisms for computing analogies using representations based on the mathematics of tensor products. This model is directly related to a general theory of the relationship between the complexity of relational representations and human capacity limits. STAR-2 provides mechanisms for mapping complex knowledge structures using a combination of chunking and unchunking, serial processing of propositions, and constraint satisfaction. Simulations show that the model successfully scales up to handle complex mapping problems.

Keith **Holyoak** and John **Hummel** describe LISA, an integrated model of analogical access, mapping, inference, and learning that is based on the use of neural synchrony to code role bindings in working memory. Their chapter argues for the psychological and neural plausibility of this approach, which provides an account of how complex analogies can be processed within a system with inherent constraints on the capacity of working memory—constraints that also apply to biological symbol systems, such as that underlying human reasoning. Simulations show that the model scales up to handle realistic mapping problems based on large-scale knowledge representations. In addition to describing computational tests of the model, the chapter reviews various psychological experiments that test LISA's predictions about the role of working memory in constraining human analogical mapping, as well as research showing that the human prefrontal cortex may be a critical part of the neural substrate for relational reasoning.

In the second section of the volume, seven chapters address the roles that analogy plays in a wide range of complex cognitive tasks. The first three of these focus on processes closely linked to language. Dedre **Gentner**, Brian **Bowdle**, Phillip **Wolff**, and Consuelo **Boronat** show that analogical processing can account for much of the phenomenology of metaphor. One general issue that is explored is whether and when metaphor processing is based on on-line analogical mapping versus the more direct application of pre-stored conceptual categories. Their chapter presents a unified framework for the processing of analogy, similarity, and metaphor. It also reviews evidence for the "career of metaphor" hypothesis, which proposes that novel metaphors are processed as structural alignments based on specific analogical comparisons, whereas conventional metaphors are based on abstract meanings that are the product of repeated mappings.

The chapter by Gilles **Fauconnier** discusses conceptual blending, a cognitive operation that appears closely related to both metaphor and counterfactual reasoning. As his chapter documents with a variety of examples, people have a remarkable facility to integrate aspects of two situations to construct a novel mental representation that goes beyond either one (such as an imaginary "race" between two boats sailing a similar course, but a century apart in time). The chapter illustrates how analogy may serve as one component of more complex cognitive processes that also draw upon other mental operations. Fauconnier also argues for the dynamic construction of these blended representations.

Mark **Keane** and Fintan **Costello** address a different type of generative process that operates in language—various forms of conceptual combinations based on compound phrases, such as "soccer mom." Their chapter contrasts alternative theories of how conceptual combinations are interpreted, focusing on a theory based on multiple constraints (diagnosticity, plausibility, and informativeness). Their constraint theory (contrary to some previous claims) posits that conceptual combination does not depend on structural alignment, suggesting possible limits on the role of analogy in linguistic interpretation. At the same time, the chapter suggests how analogy may be related to a broader class of constraint-based mechanisms for performing complex cognitive tasks.

The chapter by Kevin **Dunbar** draws a contrast between the relative difficulty of triggering spontaneous use of analogies between remote domains in the psychology laboratory with the relatively frequent spontaneous use of analogies in a variety of naturalistic settings. The evidence discussed includes detailed observations of the use of analogies by scientists in microbiology laboratories, as well as analyses of analogies used in political debate. Whereas the scientific analogies that were observed tended to be drawn between relatively similar domains (e.g., between one type of virus and another), the political analogies often connected more remote topics (e.g., between governments and families). The political analogies also tended to have a strong emotional component. Interestingly, experimental work described in Dunbar's chapter suggests that the task of producing meaningful analogs encourages deeper relational encodings than does simply comprehending an individual analog. This chapter provides a good example of how naturalistic observations can be combined with controlled experiments to raise issues that might be overlooked if the phenomenon is studied only in the laboratory.

The chapter by Paul **Thagard** and Cameron **Shelley** explores the role played by analogy in situations that tap into emotions. These include the use of analogies as persuasive arguments, the use of metaphors in poetry, and the experience of empathy between one person and another. Their chapter argues that the transfer of emotions by analogy is best understood as part of a broader system for establishing coherence among beliefs, attitudes, and feelings. The chapter illustrates this overarching framework using the HOTCO model of how emotional coherence can be integrated with cognitive coherence using computational principles based on constraint satisfaction.

Arthur **Markman** and Page **Moreau** discuss the role of analogy in decision-making, focusing on the selection of a preferred option from among a set of alternatives. The chapter describes how cross-domain analogies can function to frame decisions and thereby guide the choice of actions. Analogy also plays a role in choosing between options within one choice problem. In particular, experimental studies have shown that alignable differences—differences in values on corresponding dimensions or predicates—have a greater impact on choices than do nonalignable differences. Such evidence indicates that structure-mapping plays a role in making decisions among options.

The chapter by Miriam **Bassok** reviews research on the role of analogical mapping in solving mathematical word problems. In general, the application of mathematical knowledge to a concrete problem requires that the specific entities of the problems be mapped onto mathematical elements so as to align the relations in the concrete situation with the mathematical relations of the equation. Importantly, semantic and pragmatic knowledge about the specific entities and the relationships among them is likely to influence the preferred mappings. For example, symmetrical semantic relationships such as that between co-hyponyms of a common category (e.g., tulips and daffodils) seem to invite the symmetrical arithmetic operation of addition, whereas asymmetrical relationships such as containment (e.g., tulips and vases) invite the asymmetrical operation of division. More generally, the mapping of problem statements into equations is guided by schemas that suggest plausible relationships between the problem elements. This chapter exemplifies some of the important implications of analogy research for education.

The third section of the book includes two chapters that respectively address the development of analogical thinking in children and the possibility that nonhuman primates are capable of some form of analogy use. Usha **Goswami** reviews research on young children's analogical capacities, focusing on the earliest signs of sensitivity to relational similarity. Although children's performance varies with familiarity of the relations and other task factors, it is clear that basic analogical capabilities are present in preschool children. Early forms of imitation, such as facial imitation of gestures, may be precursors of more general analogical abilities. Analogy appears to be a powerful tool for reasoning and learning that arises early in the course of normal child development.

As we mentioned earlier, the chimpanzee Sarah was the first nonhuman primate observed to solve relational matching tasks, including four-term analogy problems. David **Oden**, Roger **Thompson**, and David **Premack** describe an extensive series of reanalyses of data from tests of Sarah's analogy ability, with the goal of assessing the possibility that her successes might be attributable to simpler nonanalogical strategies. The tasks Sarah performed were demanding, including tests of not only her ability to comprehend analogy problems, but also her ability to construct analogies by arranging items in a systematic manner on a board. These reanalyses confirm not only that Sarah can solve analogy problems, but also that she does so preferentially even in situations in which a simpler associative strategy would suffice. Our human analogical abilities appear to be shared to some extent with the best-educated members of cognitively sophisticated animals such as nonhuman primates.

Finally, the book concludes with an essay by Douglas **Hofstadter**, in which he argues for a broad view of analogy as the very core of cognition. His chapter draws links between analogy, high-level perception, and the formation of abstract categories. He emphasizes the fluidity of analogies and concepts—the way in which they vary as they mold themselves to fit specific situations—and suggests that this fluidity permits remindings that connect new experiences with memories of remote events that are relationally similar. Analogy, in the broad view taken in his chapter, encompasses tasks ranging from everyday application of simple concepts to the complex cross-linguistic mappings required to translate structured poetry from one language to another.

Taken as a whole, the chapters collected in this volume provide a broad and detailed portrait of the state of analogy research at the millennial divide. Much has been learned about this core cognitive process, particularly in the past two decades. The progress in understanding analogy has been manifested in several ways. First, the study of analogy has engendered and sustained collaborations between researchers in psychology and artificial intelligence, with significant influences from philosophy, linguistics, and history of science; the methods of cognitive neuroscience are also beginning to be applied. 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 phenomena in areas that are near relatives, such as metaphor and mundane similarity, as well as to more distant cousins, such as categorization and decision making. Systematic efforts are under way to integrate our understanding of analogical mechanisms with models of other cognitive processes and thus to view human cognition in a unified way.

The field of analogy research has indeed made progress. Nonetheless, the most important message of this volume is the large number of open questions that remain to be solved. A full understanding of analogy remains a challenge for the researchers of the new millennium.

Acknowledgments

Preparation of this chapter was supported by NSF Grant SBR-9729023 to John Hummel and Keith Holyoak, by NSF Grant SBR-95-11757 and ONR Grant N00014-92-J-1098 to Dedre Gentner, and by a joint CNR-BAS grant to Boicho Kokinov.

References

Carbonell, J. G. (1983). Learning by analogy: Formulating and generalizing plans from past experience. In R. S. Michalski, J. G. Carbonell, and T. M. Mitchell, Eds., *Machine learning: An artificial intelligence approach*, 137–161. Palo Alto, CA: Tioga.

Carbonell, J. G. (1986). Derivational analogy: A theory of reconstructive problem solving and expertise acquisition. In R. S. Michalski, J. G. Carbonell, and T. M. Mitchell, Eds., *Machine learning: An artificial intelligence approach*, vol. 2, pp. 371–392. Los Altos, CA: Morgan Kaufman.

Clement, C. A., and Gentner, D. (1991). Systematicity as a selection constraint in analogical mapping. *Cognitive Science* **15**:89–132.

Evans, T. G. (1968). A program for the solution of geometric-analogy intelligence test questions. In M. L. Minsky, Ed., *Semantic information processing*, pp. 271–353. Cambridge, MA: MIT Press.

Falkenhainer, B., Forbus, K. D., and Gentner, D. (1989). The structure-mapping engine: Algorithm and examples. *Artificial Intelligence* **41**:1–63.

Ferry, D. (1993). *Gilgamesh: A new rendering in English*. New York: Farrar, Straus and Giroux.

Forbus, K. D., Gentner, D., and Law, K. (1995). MAC/FAC: A model of similarity-based retrieval. *Cognitive Science* **19**:141–205.

Gentner, D. (1982). Are scientific analogies metaphors? In D. S. Miall, Ed., *Metaphor: Problems and perspectives*, pp. 106–132. Brighton: Harvester Press.

Gentner, D. (1983). Structure-mapping: A theoretical framework for analogy. *Cognitive Science* **7**:155–170.

Gentner, D. (1989). The mechanisms of analogical learning. In S. Vosniadou and A. Ortony, Eds., *Similarity and analogical reasoning*, pp. 199–241. Cambridge: Cambridge University Press.

Gentner, D., and Clement, C. (1988). Evidence for relational selectivity in the interpretation of metaphor. In G. H. Bower, Eds., *The psychology of learning and motivation*, vol. 22, pp. 307–358. New York: Academic Press.

Gentner, D., and Gentner, D. R. (1983). Flowing waters or teeming crowds: Mental models of electricity. In D. Gentner and A. L. Stevens, Eds., *Mental models*, pp. 99–129. Hillsdale, NJ: Erlbaum.

Gentner, D., and Markman, A. B. (1997). Structure mapping in analogy and similarity. *American Psychologist* **52**:45–56.

Gentner, D., and Medina, J. (1997). Comparison and the development of cognition and language. *Cognitive Studies: Bulletin of the Japanese Cognitive Science Society* **4**:112–149.

Gentner, D., and Rattermann, M. J. (1991). Language and the career of similarity. In S. A. Gelman and J. P. Brynes, Eds., *Perspectives on thought and language: Interrelations in development*, pp. 225–277. London: Cambridge University Press.

Gick, M. L., and Holyoak, K. J. (1980). Analogical problem solving. *Cognitive Psychology* **12**:306–355.

Gick, M. L., and Holyoak, K. J. (1983). Schema induction and analogical transfer. *Cognitive Psychology* **15**:1–38.

Halford, G. S. (1993). *Children's understanding: The development of mental models*. Hillsdale, NJ: Erlbaum.

Hesse, M. (1966). *Models and analogies in science*. Notre Dame, IN: Notre Dame University Press.

Hofstadter, D. (1984). The CopyCat Project: An experiment in nondeterminism and creative analogies. AI Memo No. 775. Cambridge, MA: MIT.

Hofstadter, D., and the Fluid Analogies Research Group. (1995). *Fluid concepts and creative analogies*. New York: Basic Books.

Holland, J. H., Holyoak, K. J., Nisbett, R. E., and Thagard, P. (1986). *Induction: Processes of inference, learning, and discovery*. Cambridge, MA: MIT Press.

Holyoak, K. J. (1985). The pragmatics of analogical transfer. In G. H. Bower, Ed., *The psychology of learning and motivation*, **vol. 19**, pp. 59–87. New York: Academic Press.

Holyoak, K. J., and Thagard, P. (1989). Analogical mapping by constraint satisfaction. *Cognitive Science* **13**:295–355.

Hummel, J. E., and Holyoak, K. J. (1997). Distributed representations of structure: A theory of analogical access and mapping. *Psychological Review* **104**:427–466.

Kanerva, P. (1998). Dual role of analogy in the design of a cognitive computer. In K. J. Holyoak, D. Gentner, and B. N. Kokinov, Eds., *Advances in analogy research: Integration of theory and data from the cognitive, computational, and neural sciences*, pp. 164–170. Sofia: New Bulgarian University Press.

Keane, M. T., Ledgeway, T., and Duff, S. (1994). Constraints on analogical mapping: A comparison of three models. *Cognitive Science* **18**:387–438.

Kokinov, B. N. (1988). Associative memory-based reasoning: How to represent and retrieve cases. In T. O'Shea and V. Sgurev, Eds., *Artificial intelligence III: Methodology, systems, applications*, pp. 51–58. Amsterdam: Elsevier.

Kokinov, B. N. (1994). A hybrid model of analogical reasoning. In K. J. Holyoak and J. A. Barnden, Eds., *Advances in connectionist and neural computation theory*, vol. 2, *Analogical connections*, pp. 247–318. Norwood, NJ: Ablex.

Kokinov, B. N. (1998). Analogy is like cognition: Dynamic, emergent, and context-Sensitive. In K. J. Holyoak, D. Gentner, and B. N. Kokinov, Eds., *Advances in analogy research: Integration of theory and data from the cognitive, computational, and neural sciences*, pp. 96–105. Sofia: New Bulgarian University Press.

Kolodner, J. (1993). *Case-based reasoning*. San Mateo, CA: Morgan Kaufmann.

Markman, A. B., and Gentner, D. (1993). Structural alignment during similarity comparisons. *Cognitive Psychology* **25**:431–467.

Markman, A. B., and Medin, D. L. (1995). Similarity and alignment in choice. *Organizational Behavior and Human Decision Processes* **63**:117–130.

Merwin, W. S. (1968). *Selected translations 1948–1968*. New York: Atheneum.

Mitchell, S. (1989). *The enlightened heart: An anthology of sacred poetry*. New York: HarperCollins.

Piaget, J., Montangero, J., and Billeter, J. (1977). La formation des correlats. In J. Piaget, Ed., *Recherches sur L'abstraction reflechissante*, pp. 115–129. Paris: Presses Universitaires de France.

Plate, T. (1998). Structured operations with distributed vector representations. In K. J. Holyoak, D. Gentner, and B. N. Kokinov, Eds., *Advances in analogy research: Integration of theory and data from the cognitive, computational, and neural sciences*, pp. 154–163. Sofia: New Bulgarian University Press.

Premack, D. (1978). On the abstractness of human concepts: Why it would be difficult to talk to a pigeon. In S. Hulse, H. Fowler, and W. K. Honig, Eds., *Cognitive processes in animal behavior*, pp. 423–451. Hillsdale, NJ: Erlbaum.

Ross, B. (1989). Distinguishing types of superficial similarities: Different effects on the access and use of earlier problems. *Journal of Experimental Psychology: Learning, Memory, and Cognition* **15**:456–468.

Schank, R. C. (1982). *Dynamic memory*. New York: Cambridge University Press.

Sternberg, R. J. (1977). *Intelligence, information processing, and analogical reasoning: The componential analysis of human abilities*. Hillsdale, NJ: Erlbaum.

Thagard, P. (1989). Explanatory coherence. *Behavioral and Brain Sciences* **12**:435–467.

Thagard, P. (2000). *Coherence in thought and action*. Cambridge, MA: MIT Press.

Thagard, P., Holyoak, K. J., Nelson, G., and Gochfeld, D. (1990). Analog retrieval by constraint satisfaction. *Artificial Intelligence* **46**:259–310.

Thompson, R., and Oden, D. (1998). Why monkeys and pigeons, unlike certain apes, cannot reason analogically. In K. J. Holyoak, D. Gentner, and B. N. Kokinov, Eds., *Advances in analogy research: Integration of theory and data from the cognitive, computational, and neural sciences*, pp. 38–48. Sofia: New Bulgarian University Press.

Vitruvius (1960). *The ten books on architecture*. Translated by M. H. Morgan. New York: Dover.

Ward, T. (1998). Mental leaps versus mental hops. In K. J. Holyoak, D. Gentner, and B. N. Kokinov, Eds., *Advances in analogy research: Integration of theory and data from the cognitive, computational, and neural sciences*, pp. 221–230. Sofia: New Bulgarian University Press.

Washburn, K., Major, J. S., and Fadiman, C., Eds. (1998). *World poetry: An anthology of verse from antiquity to our time*. New York: Quality Paperback Book Club.

Winston, P. H. (1980). Learning and reasoning by analogy. *Communications of the ACM* **23**:689–703.