LEARNING

ANALOGICAL REASONING

Analogy plays an important role in learning and instruction. As John Bransford, Jeffrey Franks, Nancy Vye, and Robert Sherwood noted in 1989, analogies can help students make connections between different concepts and transfer knowledge from a well-understood domain to one that is unfamiliar or not directly perceptual. For example, the circulatory system is often explained as being like a plumbing system, with the heart as pump.

The Analogical Reasoning Process

Analogical reasoning involves several sub-processes: (1) retrieval of one case given another; (2) mapping between two cases in working memory; (3) evaluating the analogy and its inferences; and, sometimes, (4) abstracting the common structure. The core process in analogical reasoning is mapping. According to structure-mapping theory, developed by Dedre Gentner in 1982, an analogy is a mapping of knowledge from one domain (the base or source) into another (the target) such that a system of relations that holds among the base objects also holds among the target objects. In interpreting an analogy, people seek to put the objects of the base in one-to-one correspondence with the objects of the target so as to obtain the maximal structural match. The corresponding objects in the base and target need not resemble each other; what is important is that they hold like roles in the matching relational structures. Thus, analogy provides a way to focus on relational commonalities independently of the objects in which those relations are embedded.

In explanatory analogy, a well-understood base or source situation is mapped to a target situation that is less familiar and/or less concrete. Once the two situations are aligned—that is, once the learner has established correspondences between them—then new inferences are derived by importing connected information from the base to the target. For example, in the analogy between blood circulation and plumbing, students might first align the known facts that the pump *causes* water *to flow through* the pipes with the fact that the heart *causes* blood *to flow through* the veins. Given this alignment of structure, the learner can carry over additional inferences: for example, that plaque in the veins forces the heart to work harder, just as narrow pipes require a pump to work harder.

Gentner and Phillip Wolff in 2000 set forth four ways in which comparing two analogs fosters learning. First, it can highlight common relations. For example, in processing the circulation/plumbing analogy, the focus is on the dynamics of circulation, and other normally salient knowledge—such as the red color of arteries and the blue color of veins—is suppressed. Second, it can lead to new inferences, as noted above. Third, comparing two analogs can reveal meaningful differences. For example, the circulation/plumbing analogy can bring out the difference that veins are flexible whereas pipes are rigid. In teaching by analogy, it is important to bring out such differences; otherwise students may miss them, leading them to make inappropriate inferences. Fourth, comparing two analogs can lead learners to form abstractions, as amplified below.

What Makes a Good Analogy

As Gentner suggested in 1982, to facilitate making clear alignments and reasonable inferences, an analogy must be structurally consistent—that is, it should have one-to-one correspondences, and the relations in the two domains should have a parallel structure. For example, in the circulation/plumbing system analogy, the pump cannot correspond to both the veins and the heart. Another factor influencing the quality of an analogy is systematicity: Analogies that convey an interconnected system of relations, such as the circulation/pumping analogy, are more useful than those that convey only a single isolated fact, such as "The brain looks like a walnut." Further, as Keith Holyoak and Paul Thagard argued in 1995, an analogy should be goal-relevant in the current context.

In addition to the above general qualities, several further factors influence the success of an explanatory analogy, including base specificity, transparency, and scope. Base specificity is the degree to which the structure of the base domain is clearly understood. Transparency is the ease with which the correspondences can be seen. Transparency is increased by similarities between corresponding objects and is decreased by similarities between noncorresponding objects. For example, in 1986 Gentner and Cecile Toupin found that four- to six-year-old children succeeded in transferring a story to new characters when similar characters occupied similar roles (e.g., squirrel → chipmunk; trout → salmon), but they failed when the match was cross-mapped, with similar characters in different roles (e.g., squirrel → salmon; trout → chipmunk). The same pattern has been found with adults. Transparency also applies to relations. In 2001 Miriam Bassok found that students more easily aligned instances of "increase" when both were continuous (e.g., speed of a car and growth of a population) than when one was discrete (e.g., attendance at an annual event). Finally, scope refers to how widely applicable the analogy is.

Methods Used to Investigate Analogical Learning

Much research on analogy in learning has been devoted to the effects of analogies on domain understanding. For example, in 1987 Brian Ross found that giving learners analogical examples to illustrate a probability principle facilitated their later use of the probability formula to solve other problems. In classroom studies from 1998, Daniel Schwartz and John Bransford found that generating distinctions between contrasting cases improved students' subsequent learning. As reported in 1993, John Clement used a technique of bridging analogies to induce revision of faulty mental models. Learners were given a series of analogs, beginning with a very close match and moving gradually to a situation that exemplified the desired new model.

Another line of inquiry focuses on the spontaneous analogies people use as mental models of the world. This research generally begins with a questionnaire or interview to elicit the person's own analogical models. For example, Willet Kempton in 1986 used interviews to uncover two common analogical models of home heating systems. In the (incorrect) valve model, the thermostat is like a faucet: It controls the rate at which the furnace produces heat. In the (correct) threshold model, the thermostat is like an oven: It simply controls the goal temperature, and the furnace runs at a constant rate. Kempton then examined household thermostat records and found patterns of thermostat settings corresponding to the two analogies. Some families constantly adjusted their thermostats from high to low temperatures, an expensive strategy that follows from the valve model. Others simply set their thermostat twice a day—low at night, higher by day, consistent with the threshold model.

Analogy in Children

Research on the development of analogy shows a relational shift in focus from object commonalities to relational commonalities. This shift appears to result from gains in domain knowledge, as Gentner and Mary Jo Rattermann suggested in 1991, and perhaps from gains in processing capacity as suggested by Graeme Halford in 1993. In 1989 Ann Brown showed that young children's success in analogical transfer tasks increased when the domains were familiar to them and they were given training in the relevant relations. For example, three-year-olds can transfer solutions across simple tasks involving familiar relations such as stacking and pulling, and six-year-olds can transfer more complex solutions. In 1987 Kayoko Inagaki and Giyoo Hatano studied spontaneous analogies in five- to six-year-old children by asking questions such as whether they could keep a baby rabbit small and cute forever. The children often made analogies to humans, such as "We cannot keep the baby the same size forever because he takes food. If he eats, he will become bigger and bigger and be an adult." Children were more often correct when they used these personification analogies than when they did not. This suggests that children were using humans—a familiar, well-understood domain—as a base domain for reasoning about similar creatures.

Retrieval of Analogs: The Inert Knowledge Problem

Learning from cases is often easier than learning principles directly. Despite its usefulness, however, training with examples and cases often fails to lead to transfer, because people fail to retrieve potentially useful analogs. For example, Mary Gick and Holyoak found in 1980 that participants given an insight problem typically failed to solve it, even when they had just read a story with an analogous solution. Yet, when they were told to use the prior example, they were able to do so. This shows that the prior knowledge was not lost from memory; this failure to access prior structurally similar cases is, rather, an instance of "inert knowledge"—knowledge that is not accessed when needed.

One explanation for this failure of transfer is that people often encode cases in a situation-specific manner, so that later remindings occur only for highly similar cases. For example, in 1984 Ross gave people mathematical problems to study and later gave them new problems. Most of their later remindings were to examples that were similar only on the surface, irrespective of whether the principles matched. Experts in a domain are more likely than novices to retrieve structurally similar examples, but even experts retrieve some examples that are similar only on the surface. However, as demonstrated by Laura Novick in 1988, experts reject spurious remindings more quickly than do novices. Thus, especially for novices, there is an unfortunate dissociation: While accuracy of transfer depends critically on the degree of structural match, memory retrieval depends largely on surface similarity between objects and contexts.

Analogical Encoding in Learning

In the late twentieth century, researchers began exploring a new technique, called analogical encoding, that can help overcome the inert knowledge problem. Instead of studying cases separately, learners are asked to compare analogous cases and describe their similarities. This fosters the formation of a common schema, which in turn facilitates transfer to a further problem. For example, in 1999 Jeffrey Loewenstein, Leigh Thompson, and Gentner found that graduate management students who compared two analogical cases were nearly three times more likely to transfer the common strategy into a subsequent negotiation task than were students who analyzed the same two cases separately.

Implications for Education

Analogies can be of immense educational value. They permit rapid learning of a new domain by transferring knowledge from a known domain, and they promote noticing and abstracting principles across domains. Analogies are most successful, however, if their pitfalls are understood. In analogical mapping, it is important to ensure that the base domain is understood well, that the correspondences are clear, and that differences and potentially incorrect inferences are clearly flagged. When teaching for transfer, it is important to recognize that learners tend to rely on surface features. One solution is to minimize surface features by using simple objects. Another is to induce analogical encoding by asking learners to explicitly compare cases. The better educators understand analogical processes, the better they can harness them for education.

See also: LEARNING, ***subentry on*** TRANSFER OF LEARNING; LEARNING THEORY, ***subentry on*** HISTORICAL OVERVIEW.

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CAUSAL REASONING

A doorbell rings. A dog runs through a room. A seated man rises to his feet. A vase falls from a table and breaks. Why did the vase break? To answer this question, one must perceive and infer the causal relationships between the breaking of the vase and other events. Sometimes, the event most directly causally related to an effect is not immediately apparent (e.g., the dog hit the table), and conscious and effortful thought may be required to identify it. People routinely make such efforts because detecting causal connections among events helps them to make sense of the constantly changing flow of events. Causal reasoning enables people to find meaningful order in events that might otherwise appear random and chaotic, and causal understanding helps people to plan and predict the future. Thus, in 1980 the philosopher John Mackie described causal reasoning as "the cement of the universe." How, then, does one decide which events are causally related? When does one engage in causal reasoning? How does the ability to think about cause–effect relations originate and develop during infancy and childhood? How can causal reasoning skills be promoted in educational settings, and does this promote learning? These questions represent important issues in research on causal reasoning

Causal Perceptions and Causal Reasoning

An important distinction exists between causal perceptions and causal reasoning. Causal perceptions refer to one's ability to sense a causal relationship without conscious and effortful thought. According to the philosopher David Hume (1711–1776), perceptual information regarding contiguity, precedence, and covariation underlies the understanding of causality. First, events that are temporally and spatially contiguous are perceived as causally related. Second, the causal precedes the effect. Third, events that regularly co-occur are seen as causally related. In contrast, causal reasoning requires a person to reason through a chain of events to infer the cause of that event. People most often engage in causal reasoning when they experience an event that is out of the ordinary. Thus, in some situations a person may not know the cause of an unusual event and must search for it, and in other situations must evaluate whether one known event was the cause of another. The first situation may present difficulty because the causal event may not be immediately apparent. Philosophers have argued that causal reasoning is based on an assessment of criteria of necessity and sufficiency in these circumstances. A necessary cause is one that must be present for the effect to occur. Event A is necessary for event B if event B will not occur without event A. For example, the vase would not have broken if the dog had not hit the table. A cause is sufficient if its occurrence can by itself bring about the effect (i.e., whenever event A occurs, event B always follows). Often, more than one causal factor is present. In the case of multiple necessary causes, a set of causal factors taken together jointly produces an effect. In the case of multiple sufficient causes, multiple factors are present, any one of which by itself is sufficient to produce an effect.

The Development of Causal Perception and Causal Reasoning Skills

Causal perception appears to begin during infancy. Between three and six months of age, infants respond differently to temporally and spatially contiguous events (e.g., one billiard ball contacting a second that begins to roll immediately) compared to events that lack contiguity (e.g., the second ball begins to roll without collision or does not start to move until half a second after collision). Thus, the psychologist Alan Leslie proposed in 1986 that infants begin life with an innate perceptual mechanism specialized to automatically detect cause–effect relations based on contiguity. However, psychologists Leslie Cohen and Lisa Oakes reported in 1993 that familiarity with role of a particular object in a causal sequence influence ten-month-old infants' perception of causality. Therefore, they suggest that infants do not automatically perceive a causal connection when viewing contiguous events. The question of whether infants begin with an innate ability to automatically detect causality, or instead gradually develop casual perception through general learning processes remains a central controversy concerning the origins of causal thought.

Although infants perceive causal relationships, complex causal reasoning emerges during early childhood and grows in sophistication thereafter. Thus, information about precedence influences causal reasoning during childhood. When asked to determine what caused an event to occur, three-year-olds often choose an event that preceded it, rather than one that came later, but understanding of precedence becomes more consistent and general beginning at five years of age. Unlike contiguity and precedence, information about covariation is not available from a single casual sequence, but requires repeated experience with the co-occurrence of a cause and effect. Children do not begin to use covariation information consistently in their casual thinking before eight years of age. Because the various types of information relevant to causality do not always suggest the same causal relation, children and adults must decide which type of information is most important in a particular situation.

In addition to the perceptual cues identified by Hume, knowledge of specific causal mechanisms plays a central role in causal reasoning. By three years of age, children expect there to be some mechanism of transmission between cause and effect, and knowledge of possible mechanisms influences both children's and adults' interpretation of perceptual cues. For instance, when a possible causal mechanism requires time to produce an effect (e.g., a marble rolling down a lengthy tube before contacting another object), or transmits quickly across a distance (e.g., electrical wiring), children as young as five years of age are more likely to select causes that lack temporal spatial contiguity than would otherwise be the case. Because causal mechanisms differ for physical, social, and biological events, children must acquire distinct conceptual knowledge to understand causality in each of these domains. By three to four years of age, children recognize that whereas physical effects are caused by physical transmission, human action is motivated internally by mental states such as desires, beliefs, and intentions, and they begin to understand some properties of biological processes such as growth and heredity. Furthermore, conceptual understanding of specific causal mechanisms may vary across cultures and may be learned through social discourse as well as through direct experience.

A fundamental understanding of causality is present during early childhood; however, prior to adolescence children have difficulty searching for causal relations through systematic scientific experimentation. Preadolescents may generate a single causal hypothesis and seek confirmatory evidence, misinterpret contradictory evidence, or design experimental tests that do not provide informative evidence. In contrast, adolescents and adults may generate several alternative hypotheses and test them by systematically controlling variables and seeking both disconfirmatory and confirmatory evidence. Nevertheless, even adults often have difficulty designing valid scientific experiments. More generally, both children and adults often have difficulty identifying multiple necessary or sufficient causes.

Teaching Causal Reasoning Skills

The psychologist Diane Halpern argued in 1998 that critical thinking skills should be taught in primary, secondary, and higher educational settings. Casual reasoning is an important part of critical thinking because it enables one to explain and predict events, and thus potentially to control one's environment and achieve desired outcomes.

Three approaches to teaching causal reasoning skills may be efficacious. First, causal reasoning skills can be promoted by teaching students logical deduction. For example, teaching students to use counterfactual reasoning may help them assess whether there is a necessary relationship between a potential cause and an effect. Counterfactual reasoning requires student to imagine that a potential cause did not occur and to infer whether the effect would have occurred in its absence. If it would occur, then there is no causal relationship between the two events.

Second, causal reasoning skills can be promoted by teaching students to generate informal explanations for anomalous events or difficult material. For instance, learning from scientific texts can be particularly challenging to students, and often students have the misconception that they do not have adequate knowledge to understand texts. The psychologist Michelene Chi demonstrated in 1989 that students who use their general world knowledge to engage in causal, explanatory reasoning while reading difficult physics texts understand what they read considerably better than do students who do not draw upon general knowledge in this way. Furthermore, in 1999 the psychologist Danielle McNamara developed a reading training intervention that promotes explanatory reasoning during reading. In this program, students were taught a number of strategies to help them to use both information in the text and general knowledge to generate explanations for difficult material. Training improved both comprehension of scientific texts and overall class performance, and was particularly beneficial to at-risk students.

Third, the psychologist Leona Schauble demonstrated in 1990 that causal reasoning skills can be promoted by teaching students the principles of scientific experimentation. A primary goal of experimentation is to determine causal relationships among a set of events. Students may be taught to identify a potential cause of an effect, manipulate the presence of the cause in a controlled setting, and assesses whether or not the effect occurs. Thus, students learn to use the scientific method to determine whether there are necessary and sufficient relationships between a potential cause and an effect. Because the principles of science are often difficult for students to grasp, teaching these principles would provide students with formal procedures for evaluating causal relationships in the world around them.

See also: Learning, ***subentry on*** Reasoning; Learning Theory, ***subentry on*** Historical Overview; Literacy, ***subentry on*** Narrative Comprehension and Production; Reading, ***subentries on*** Comprehension, Content Areas.

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CONCEPTUAL CHANGE

The term *conceptual change* refers to the development of fundamentally new concepts, through restructuring elements of existing concepts, in the course of knowledge acquisition. Conceptual change is a particularly profound kind of learning—it goes beyond revising one's specific beliefs and involves restructuring the very concepts used to formulate those beliefs. Explaining how this kind of learning occurs is central to understanding the tremendous power and creativity of human thought.

The emergence of fundamentally new ideas is striking in the history of human thought, particularly in science and mathematics. Examples include the emergence of Darwin's concept of evolution by natural selection, Newton's concepts of gravity and inertia, and the mathematical concepts of zero, negative, and rational numbers. One of the challenges of education is how to transmit these complex products of human intellectual history to the next generation of students.

Although there are many unresolved issues about how concepts are mentally represented, conceptual-change researchers generally assume that explanatory concepts are defined and articulated within theory-like structures, and that conceptual change requires coordinated changes in multiple concepts within these structures. New concepts that have arisen in the history of science are clearly part of larger, explicit theories. Making an analogy between the organization of concepts in scientists and children, researchers have proposed that children may have "commonsense" theories in which their everyday explanatory concepts are embedded and play a role. These theories, although not self-consciously held, are assumed to be like scientific theories in that they consist of a set of interrelated concepts that resist change and that support inference making, problem solving, belief formation, and explanation in a given domain. The power and usefulness of this analogy is being explored in the early twenty-first century.

A challenge for conceptual-change researchers is to provide a typology of important forms of conceptual change. For example, conceptual differentiation is a form of conceptual change in which a newer (descendant) theory uses two distinct concepts where the initial (parent) theory used only one, and the undifferentiated parent concept unites elements that will subsequently be kept distinct. Examples of conceptual differentiation include: Galileo's differentiation of average and instantaneous velocity in his theory of motion, Black's differentiation of heat and temperature in his theory of thermal phenomena, and children's differentiation of weight and density in their matter theory. Conceptual differentiation is not the same as adding new subcategories to an existing category, which involves the elaboration of a conceptual structure rather than its transformation. In that case, the new subcategories fit into an existing structure, and the initial general category is still maintained. In differentiation, the parent concept is seen as incoherent from the perspective of the subsequent theory and plays no role in it. For example, an undifferentiated weight/density concept that unites the elements *heavy* and *heavy-for-size* combines two fundamentally different kinds of quantities: an extensive (total amount) quantity and an intensive (relationally defined) quantity.

Another form of conceptual change is *coalescence,* in which the descendant theory introduces a new concept that unites concepts previously seen to be of fundamentally different types in the parent theory. For example, Aristotle saw circular planetary and free-fall motions as natural motions that were fundamentally different from violent projectile motions. Newton coalesced circular, planetary, free-fall, and projectile motions under a new category, *accelerated motion.* Similarly, children initially see plants and animals as fundamentally different: animals are behaving beings that engage in self-generated movement, while plants are not. Later they come to see them as two forms of "living things" that share important biological properties. Conceptual coalescence is not the same as simply adding a more general category by abstracting properties common to more specific categories. In conceptual coalescence the initial concepts are thought to be fundamentally different, and the properties that will be central to defining the new category are not represented as essential properties of the initial concepts.

Different forms of conceptual change mutually support each other. For example, conceptual coalescences (such as uniting free-fall and projectile motion in a new concept of accelerated motion, or plants and animals in a new concept of living things) are accompanied by conceptual differentiations (such as distinguishing uniform from accelerated motion, or distinguishing dead from inanimate). These changes are also supported by additional forms of conceptual change, such as re-analysis of the core properties or underlying structure of the concept, as well as the acquisition of new specific beliefs about the relations among concepts.

Mechanisms of Conceptual Change

One reason for distinguishing conceptual change from belief revision and conceptual elaboration is that different learning mechanisms may be required. Everyday learning involves knowledge enrichment and rests on an assumed set of concepts. For example, people use existing concepts to represent new facts, formulate new beliefs, make inductive or deductive inferences, and solve problems.

What makes conceptual change so challenging to understand is that it cannot occur in this way. The concepts of a new theory are ultimately organized and stated in terms of each other, rather than the concepts of the old theory, and there is no simple one-to-one correspondence between some concepts of the old and new theories. By what learning mechanisms, then, can scientists invent, and students comprehend, a genuinely new set of concepts and come to prefer them to their initial set of concepts?

Most theorists agree that one step in conceptual change for both students and scientists is experiencing some form of *cognitive dissonance*—an internal state of tension that arises when an existing conceptual system fails to handle important data and problems in a satisfactory manner. Such dissonance can be created by a series of unexpected results that cannot be explained by an existing theory, by the press to solve a problem that is beyond the scope of one's current theory, or by the detection of internal inconsistencies in one's thinking. This dissonance can signal the need to step outside the normal mode of *applying* one's conceptual framework to a more meta-conceptual mode of *questioning, examining, and evaluating* one's conceptual framework.

Although experiencing dissonance can signal that there is a conceptual problem to be solved, it does not solve that problem. Another step involves active attempts to invent or construct an understanding of alternative conceptual systems by using a variety of heuristic procedures and symbolic tools. Heuristic procedures, such as analogical reasoning, imagistic reasoning, and thought experiments, may be particularly important because they allow both students and scientists to creatively extend, combine, and modify existing conceptual resources via the construction of new models. Symbolic tools, such as natural language, the algebraic and graphical representations of mathematics, and other invented notational systems, allow the explicit representation of key relations in the new system of concepts.

In analogical reasoning, knowledge of conceptual relations in better-understood domains are powerful sources of new ideas about the less-understood domain. Analogical reasoning is often supported by imagistic reasoning, wherein one creates visual depictions of core ideas using visual analogs with the same underlying relational structure. These depictions allow the visualization of unseen theoretical entities, connect the problem to the well-developed human visual-spatial inferencing system, and, because much mathematical information is implicit in such depictions, facilitate the construction of appropriate mathematical descriptions of a given domain. Thought experiments use initial knowledge of a domain to run simulations of what should happen in various idealized situations, including imagining what happens as the effects of a given variable are entirely eliminated, thus facilitating the identification of basic principles not self-evident from everyday observation.

Case studies of conceptual change in the history of science and science education reveal that new intellectual constructions develop over an extended period of time and include intermediate, bridging constructions. For example, Darwin's starting idea of evolution via directed, adaptative variation initially prevented his making an analogy between this process and artificial selection. He transformed his understanding of this process using multiple analogies (first with wedging and Malthusian population pressure, and later with artificial selection), imagistic reasoning (e.g., visualizing the jostling effects of 100,000 wedges being driven into the same spot of ground to understand the tremendous power of the unseen force in nature and its ability to produce species change in a mechanistic manner), and thought experiments (e.g., imagining how many small effects might build up over multiple generations to yield a larger effect). Each contributed different elements to his final concept of natural selection, with his initial analogies leading to the bridging idea of selection acting in concert with the process of directed adaptive variation, rather than supplanting it.

Constructing a new conceptual system is also accompanied by a process of evaluating its adequacy against known alternatives using some set of criteria. These criteria can include: the new system's ability to explain the core problematic phenomena as well as other known phenomena in the domain, its internal consistency and fit with other relevant knowledge, the extent to which it meets certain explanatory ideals, and its capacity to suggest new fruitful lines of research.

Finally, researchers have examined the personal, motivational, and social processes that support conceptual change. Personal factors include courage, confidence in one's abilities, openness to alternatives, willingness to take risks, and deep commitment to an intellectual problem. Social factors include working in groups that combine different kinds of expertise and that encourage consideration of inconsistencies in data and relevant analogies. Indeed, many science educators believe a key to promoting conceptual change in the classroom is through creating a more reflective classroom discourse. Such discourse probes for alternative student views, encourages the clarification, negotiation, and elaboration of meanings, the detection of inconsistencies, and the use of evidence and argument in deciding among or integrating alternative views.

Educational Implications

Conceptual change is difficult under any circumstances, as it requires breaking out of the selfperpetuating circle of theory-based reasoning, making coordinated changes in a number of concepts, and actively constructing an understanding of new (more abstract) conceptual systems. Students need signals that conceptual change is needed, as well as good reasons to change their current conceptions, guidance about how to integrate existing conceptual resources in order to construct new conceptions, and the motivation and time needed to make those constructions. Traditional education practice often fails to provide students with the appropriate signals, guidance, motivation, and time.

Conceptual change is a protracted process calling for a number of coordinated changes in instructional practice. First, instruction needs to be grounded in the consideration of important phenomena or problems that are central to the experts' framework—and that challenge students' initial commonsense framework. These phenomena not only motivate conceptual change, but also constrain the search for, and evaluation of, viable alternatives. Second, instruction needs to guide students in the construction of new systems of concepts for understanding these phenomena. Teachers must know what heuristic techniques, representational tools, and conceptual resources to draw upon to make new concepts intelligible to students, and also how to build these constructions in a sequenced manner.

Third, instruction needs to be supported by a classroom discourse that encourages students to identify, represent, contrast, and debate the adequacy of competing explanatory frameworks in terms of emerging classroom epistemological standards. Such discourse supports many aspects of the conceptual-change process, including making students aware of their initial conceptions, helping students construct an understanding of alternative frameworks, motivating students to examine their conceptions more critically (in part through awareness of alternatives), and promoting their ability to evaluate, and at times integrate, competing frameworks.

Finally, instruction needs to provide students with extended opportunities for applying new systems of concepts to a wide variety of problems. Repeated applications develop students' skill at applying a new framework, refine their understanding of the framework, and help students appreciate its greater power and scope.

See also: CATEGORIZATION AND CONCEPT LEARNING; LEARNING, ***subentry on*** KNOWLEDGE ACQUISITION, REPRESENTATION, AND ORGANIZATION.

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CAROL L. SMITH

KNOWLEDGE ACQUISITION, REPRESENTATION, AND ORGANIZATION

Knowledge acquisition is the process of absorbing and storing new information in memory, the success of which is often gauged by how well the information can later be remembered (retrieved from memory). The process of storing and retrieving information depends heavily on the representation and organization of the information. Moreover, the utility of knowledge can also be influenced by how the information is structured. For example, a bus schedule can be represented in the form of a map or a timetable. On the one hand, a timetable provides quick and easy access to the arrival time for each bus, but does little for finding where a particular stop is situated. On the other hand, a map provides a detailed picture of each bus stop's location, but cannot efficiently communicate bus schedules. Both forms of representation are useful, but it is important to select the representation most appropriate for the task at hand. Similarly, knowledge acquisition can be improved by considering the purpose and function of the desired information.

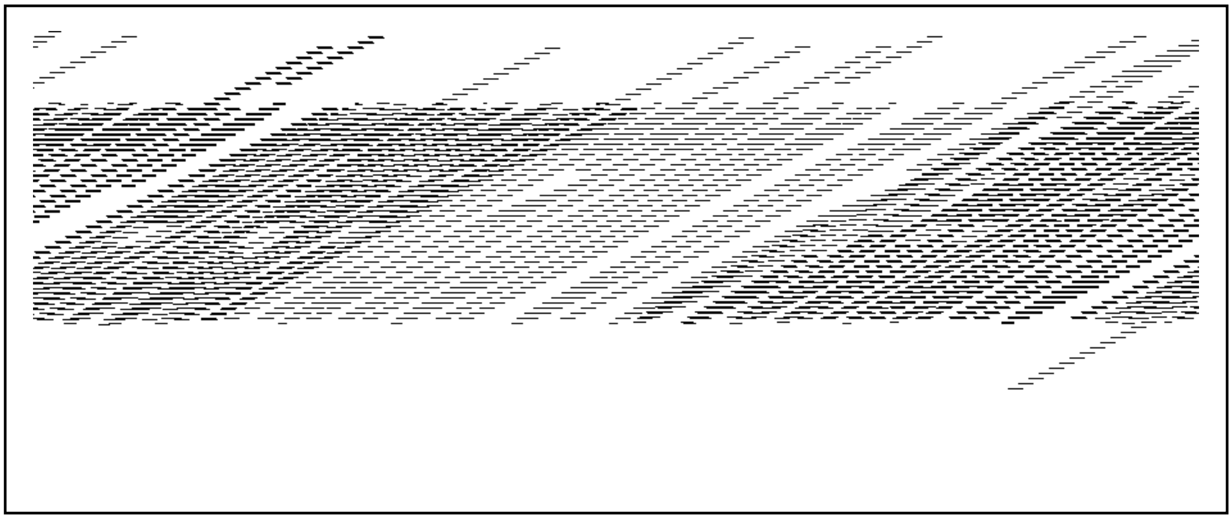
Knowledge Representation and Organization

There are numerous theories of how knowledge is represented and organized in the mind, including rule-based production models, distributed networks, and propositional models. However, these theories are all fundamentally based on the concept of *semantic networks.* A semantic network is a method of representing knowledge as a system of connections between concepts in memory.

Semantic Networks

According to semantic network models, knowledge is organized based on meaning, such that semantically related concepts are interconnected. Knowledge networks are typically represented as diagrams of nodes (i.e., concepts) and links (i.e., relations). The nodes and links are given numerical weights to represent their strengths in memory. In Figure 1, the node representing DOCTOR is strongly related to SCALPEL, whereas NURSE is weakly related to SCALPEL. These link strengths are represented here in terms of line width. Similarly, some nodes in Figure 1 are printed in bold type to represent their strength in memory. Concepts such as DOCTOR and BREAD are more memorable because they are

FIGURE 1



more frequently encountered than concepts such as SCALPEL and CRUST.

Mental excitation, or activation, spreads automatically from one concept to another related concept. For example, thinking of BREAD spreads activation to related concepts, such as BUTTER and CRUST. These concepts are *primed,* and thus more easily recognized or retrieved from memory. For example, in David Meyer and Roger Schvaneveldt's 1976 study (a typical semantic priming study), a series of words (e.g., BUTTER) and nonwords (e.g., BOTTOR) are presented, and participants determine whether each item is a word. A word is more quickly recognized if it follows a semantically related word. For example, BUTTER is more quickly recognized as a word if BREAD precedes it, rather than NURSE. This result supports the assumption that semantically related concepts are more strongly connected than unrelated concepts.

Network models represent more than simple associations. They must represent the ideas and complex relationships that comprise knowledge and comprehension. For example, the idea "The doctor uses a scalpel" can be represented as the proposition USE (DOCTOR, SCALPEL), which consists of the nodes DOCTOR and SCALPEL and the link USE (see Figure 2). Educators have successfully used similar diagrams, called concept maps, to communicate important relations and attributes among the key concepts of a lesson.

Types of Knowledge

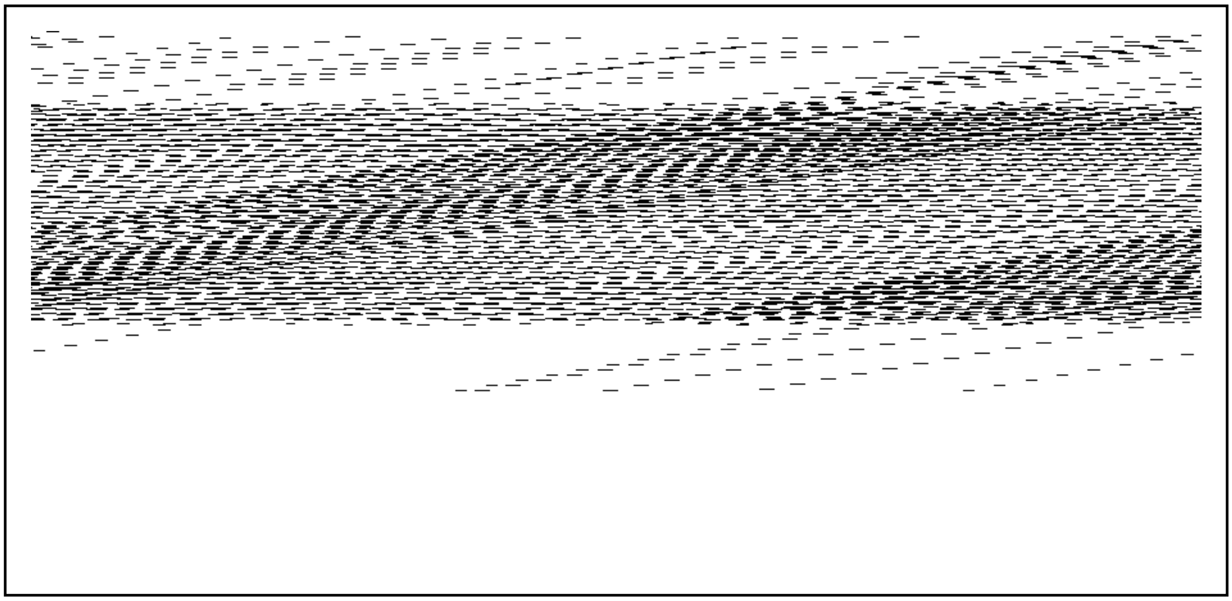
There are numerous types of knowledge, but the most important distinction is between *declarative* and *procedural* knowledge. Declarative knowledge refers to one's memory for concepts, facts, or episodes, whereas procedural knowledge refers to the ability to perform various tasks. Knowledge of how to drive a car, solve a multiplication problem, or throw a football are all forms of procedural knowledge, called *procedures* or *productions.* Procedural knowledge may begin as declarative knowledge, but is proceduralized with practice. For example, when first learning to drive a car, you may be told to "put the key in the ignition to start the car," which is a declarative statement. However, after starting the car numerous times, this act becomes automatic and is completed with little thought. Indeed, procedural knowledge tends to be accessed automatically and require little attention. It also tends to be more durable (less susceptible to forgetting) than declarative knowledge.

Knowledge Acquisition

Listed below are five guidelines for knowledge acquisition that emerge from how knowledge is represented and organized.

Process the material semantically. Knowledge is organized semantically; therefore, knowledge acquisition is optimized when the learner focuses on the meaning of the new material. Fergus Craik and Endel Tulving were among the first to provide evidence for the importance of semantic processing. In their studies, participants answered questions con-

FIGURE 2



cerning target words that varied according to the depth of processing involved. For example, semantic questions (e.g., Which word, *friend* or *tree,* fits appropriately in the following sentence: "He met a ____ on the street"?) involve a greater depth of processing than phonemic questions (e.g., Which word, *crate* or *tree,* rhymes with the word *late*?), which in turn have a greater depth than questions concerning the structure of a word (e.g., Which word is in capital letters: *TREE* or *tree*?). Craik and colleagues found that words processed semantically were better learned than words processed phonemically or structurally. Further studies have confirmed that learning benefits from greater semantic processing of the material.

Process and retrieve information frequently. A second learning principle is to test and retrieve the information numerous times. Retrieving, or self-producing, information can be contrasted with simply reading or copying it. Decades of research on a phenomenon called the *generation effect* have shown that passively studying items by copying or reading them does little for memory in comparison to self-producing, or *generating,* an item. Moreover, learning improves as a function of the number of times information is retrieved. Within an academic situation, this principle points to the need for frequent practice tests, worksheets, or quizzes. In terms of studying, it is also important to break up, or *distribute* retrieval attempts. Distributed retrieval can include studying or testing items in a random order, with breaks, or on different days. In contrast, repeating information numerous times sequentially involves only a single retrieval from long-term memory, which does little to improve memory for the information.

Learning and retrieval conditions should be similar. How knowledge is represented is determined by the conditions and context (internal and external) in which it is learned, and this in turn determines how it is retrieved: Information is best retrieved when the conditions of learning and retrieval are the same. This principle has been referred to as *encoding specificity*. For example, in one experiment, participants were shown sentences with an adjective and a noun printed in capital letters (e.g. The CHIP DIP tasted delicious.) and told that their memory for the nouns would be tested afterward. In the recognition test, participants were shown the noun either with the original adjective (CHIP DIP), with a different adjective (SKINNY DIP), or without an adjective (DIP). Noun recognition was better when the original adjective (CHIP) was presented than when no adjective was presented. Moreover, presenting a different adjective (SKINNY) yielded the lowest recognition. This finding underscores the importance of matching learning and testing conditions.

Encoding specificity is also important in terms of the questions used to test memory or comprehension. Different types of questions tap into different levels of understanding. For example, recalling information involves a different level of understanding, and different mental processes, than recognizing information. Likewise, essay and open-ended questions assess a different level of understanding than multiple-choice questions. Essay and open-ended questions generally tap into a conceptual or situational understanding of the material, which results from an integration of text-based information and the reader's prior knowledge. In contrast, multiple-choice questions involve recognition processes, and typically assess a shallow or text-based understanding. A text-based representation can be impoverished and incomplete because it consists only of concepts and relations within the text. This level of understanding, likely developed by a student preparing for a multiple-choice exam, would be inappropriate preparation for an exam with open-ended or essay questions. Thus, students should benefit by adjusting their study practices according to the expected type of questions.

Alternatively, students may benefit from reviewing the material in many different ways, such as recognizing the information, recalling the information, and interpreting the information. These latter processes improve understanding and maximize the probability that the various ways the material is studied will match the way it is tested. From a teacher's point of view, including different types of questions on worksheets or exams ensures that each student will have an opportunity to convey their understanding of the material.

Connect new information to prior knowledge. Knowledge is interconnected; therefore, new material that is linked to prior knowledge will be better retained. A driving factor in text and discourse comprehension is prior knowledge. Skilled readers actively use their prior knowledge during comprehension. Prior knowledge helps the reader to fill in contextual gaps within the text and develop a better global understanding or situation model of the text. Given that texts rarely (if ever) spell out everything needed for successful comprehension, using prior knowledge to understand text and discourse is critical. Moreover, thinking about what one already knows about a topic provides connections in memory to the new information—the more connections that are formed, the more likely the information will be retrievable from memory.

Create cognitive procedures. Procedural knowledge is better retained and more easily accessed. Therefore, one should develop and use cognitive procedures when learning information. Procedures can include shortcuts for completing a task (e.g., using *fast 10s* to solve multiplication problems), as well as memory strategies that increase the distinctive meaning of information. Cognitive research has repeatedly demonstrated the benefits of memory strategies, or *mnemonics,* for enhancing the recall of information. There are numerous types of mnemonics, but one well-known mnemonic is the *method of loci.* This technique was invented originally for the purpose of memorizing long speeches in the times before luxuries such as paper and pencil were readily available. The first task is to imagine and memorize a series of distinct locations along a familiar route, such as a pathway from one campus building to another. Each topic of a speech (or word in a word list) can then be pictured in a location along the route. When it comes time to recall the speech or word list, the items are simply *found* by mentally traveling the pathway.

Mnemonics are generally effective because they increase semantic processing of the words (or phrases) and render them more meaningful by linking them to familiar concepts in memory. Mnemonics also provide ready-made, effective cues for retrieving information. Another important aspect of mnemonics is that mental imaging is often involved. Images not only render information more meaningful, but they provide an additional route for finding information in memory. As mentioned earlier, increasing the number of meaningful links to information in memory increases the likelihood it can be retrieved.

Strategies are also an important component of *meta-cognition,* which is the ability to think about, understand, and manage one's learning. First, one must develop an awareness of one's own thought processes. Simply being aware of thought processes increases the likelihood of more effective knowledge construction. Second, the learner must be aware of whether or not comprehension has been successful. Realizing when comprehension has failed is crucial to learning. The final, and most important stage of meta-cognitive processing is fixing the comprehension problem. The individual must be aware of, and use, strategies to remedy comprehension and learning difficulties. For successful knowledge acquisition to occur, all three of these processes must occur. Without thinking or worrying about learning, the student cannot realize whether the concepts have been successfully grasped. Without realizing that information has not been understood, the student cannot engage in strategies to remedy the situation. If nothing is done about a comprehension failure, awareness is futile.

Conclusion

Knowledge acquisition is integrally tied to how the mind organizes and represents information. Learning can be enhanced by considering the fundamental properties of human knowledge, as well as by the ultimate function of the desired information. The most important property of knowledge is that it is organized semantically; therefore, learning methods should enhance meaningful study of new information. Learners should also create as many links to the information as possible. In addition, learning methods should be matched to the desired outcome. Just as using a bus timetable to find a bus-stop location is ineffective, learning to recognize information will do little good on an essay exam.

See also: Learning, ***subentry on*** Conceptual Change; Reading, ***subentry on*** Content Areas.

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NEUROLOGICAL FOUNDATION

Learning is mediated by multiple memory systems in the brain, each of which involves a distinct anatomical pathway and supports a particular form of memory representation. The major aim of research on memory systems is to identify and distinguish the different contributions of specific brain structures and pathways, usually by contrasting the effects of selective damage to specific brain areas. Another major strategy focuses on localizing brain areas that are activated, that is, whose neurons are activated during particular aspects of memory processing. Some of these studies use newly developed functional imaging techniques to view activation of brain areas in humans performing memory tests. Another approach seeks to characterize the cellular code for memory within the activity patterns of single nerve cells in animals, by asking how information is represented by the activity patterns within the circuits of different structures in the relevant brain systems.

Each of the brain's memory systems begins in the vast expanse of the cerebral cortex, specifically in the so-called cortical association areas (see Figure 1). These parts of the cerebral cortex provide major inputs to each of three main pathways of processing in subcortical areas related to distinct memory functions. One system mediates *declarative memory,* the memory for facts and events that can be brought to conscious recollection and can be expressed in a variety of ways outside the context of learning. This system involves connections from the cortical association areas to the hippocampus via the parahippocampal region. The main output of hippocampal and parahippocampal processing is back to the same cortical areas that provided inputs to the hippocampus, and are viewed as the long-term repository of declarative memories.

The other two main pathways involve cortical inputs to specific subcortical targets that send direct outputs that control behavior. One of these systems mediates *emotional memory,* the attachment of affiliations and aversions towards otherwise arbitrary stimuli and modulation of the strength of memories that involve emotional arousal. This system involves cortical (as well as subcortical) inputs to the amygdala as the nodal stage in the association of sensory inputs to emotional outputs effected via the hypothalamic-pituitary axis and autonomic nervous system, as well as emotional influences over widespread brain areas. The second of these systems mediates *procedural memory,* the capacity to acquire habitual behavioral routines that can be performed without conscious control. This system involves cortical inputs to the striatum as a nodal stage in the association of sensory and motor cortical information with voluntary responses via the brainstem motor system. An additional, parallel pathway that mediates different aspects of sensori-motor adaptations involves sensory and motor systems pathways through the cerebellum.

The Declarative Memory System

Declarative memory is the "everyday" form of memory that most consider when they think of memory. Therefore, the remainder of this discussion will focus on the declarative memory system. Declarative memory is defined as a composite of episodic memory, the ability to recollect personal experiences, and semantic memory, the synthesis of the many episodic memories into the knowledge about the world. In addition, declarative memory supports the capacity for conscious recall and the flexible expression of memories, one's ability to search networks of episodic and semantic memories and to use this capacity to solve many problems.

Each of the major components of the declarative memory system contributes differently to declarative memory, although interactions between these areas are also essential. Initially, perceptual information as well as information about one's behavior is processed in many dedicated neocortical areas. While the entire cerebral cortex is involved in memory processing, the chief brain area that controls this processing is the prefrontal cortex. The processing accomplished by the prefrontal cortex includes the acquisition of complex cognitive rules and concepts and *working memory,* the capacity to store information briefly while manipulating or rehearsing the information under conscious control. In addition, the areas of the cortex also contribute critically to memory processing. Association areas in the prefrontal, temporal, and parietal cortex play a central role in cognition and in both the perception of sensory information and in maintenance of short-term traces of recently perceived stimuli. Furthermore, the organization of perceptual representations in cerebral cortical areas, and connections among these areas, are permanently modified by learning experiences, constituting the long term repository of memories.

The parahippocampal region, which receives convergent inputs from the neocortical association areas and sends return projections to all of these areas, appears to mediate the extended persistence of these cortical representations. Through interactions between these areas, processing within the cortex can take advantage of lasting parahippocampal representations, and so come to reflect complex associations between events that are processed separately in different cortical regions or occur sequentially in the same or different areas.

These individual contributions and their interactions are not conceived as sufficient to link representations of events to form episodic memories or to form generalizations across memories to create a semantic memory network. Such an organization requires the capacity to rapidly encode a sequence of events that make up an episodic memory, to retrieve that memory by re-experiencing one facet of the event, and to link the ongoing experience to stored episodic representations, forming the semantic network. The neuronal elements of the hippocampus contain the fundamental coding properties that can support this kind of organization.

However, interactions among the components of the system are undoubtedly critical. It is unlikely that the hippocampus has the storage capacity to contain all of one's episodic memories and the hippocampus is not the final storage site. Therefore, it seems likely that the hippocampal neurons are involved in mediating the reestablishment of detailed cortical representations, rather than storing the details themselves. Repetitive interactions between the cortex and hippocampus, with the parahippocampal region as intermediary, serve to sufficiently coactivate widespread cortical areas so that they eventually develop linkages between detailed memories without hippocampal mediation. In this way, the networking provided by the hippocampus underlies its role in the organization of the permanent memory networks in the cerebral cortex.

See also: Brain-Based Education.

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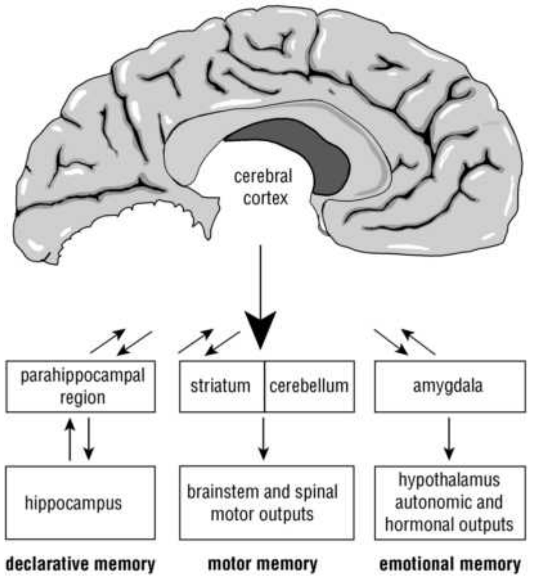
FIGURE 1

Memory systems of the brain



SOURCE: Courtesy of author.

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Howard Eichenbaum

PERCEPTUAL PROCESSES

As Eleanor Gibson wrote in her classic text *Principles of Perceptual Learning and Development,* perceptual learning results in changes in the pickup of information as a result of practice or experience. Perception and action are a cycle: People act in order to learn about their surroundings, and they use what they learn to guide their actions. From this perspective, the critical defining features of perception include the exploratory actions of the perceiver and the knowledge of the events, animate and inanimate objects, and surrounding environment gained while engaged in looking, listening, touching, walking, and other forms of direct observation. Perception often results in learning information that is directly relevant to the goals at hand, but sometimes it results in learning that is incidental to one's immediate goals.

Perception becomes more skillful with practice and experience, and perceptual learning can be thought of as the education of attention. Perceivers come to notice the features of situations that are relevant to their goals and not to notice the irrelevant features. Three general principles of perceptual learning seem particularly relevant. First, unskillful perceiving requires much concentrated attention, whereas skillful perceiving requires less attention and is more easily combined with other tasks. Second, unskillful perceiving involves noticing both the relevant and irrelevant features of sensory stimulation without understanding their meaning or relevance to one's goals, whereas skillful perceiving involves narrowing one's focus to relevant features and understanding the situations they specify. And third, unskillful perceiving often involves attention to the proximal stimulus (that is, the patterns of light or acoustic or pressure information on the retinas, cochleae, and skin, respectively), whereas skillful perceiving involves attention to the distal event that is specified by the proximal stimulus.

Different Domains

Perceptual learning refers to relatively durable gains in perception that occur across widely different domains. For example, at one extreme are studies demonstrating that with practice adults can gain exquisite sensitivity to vernier discriminations, that is, the ability to resolve gaps in lines that approach the size of a single retinal receptor. At the opposite extreme, perceptual learning plays a central role in gaining expertise in the many different content areas of work, everyday life, and academic pursuits.

In the realm of work, classic examples include farmers learning to differentiate the sex of chickens, restaurateurs learning to differentiate different dimensions of fine wine, airplane pilots misperceiving their position relative to the ground, and machinists and architects learning to "see" the three-dimensional shape of a solid object or house from the top, side, and front views.

In the realm of everyday life, important examples include learning to perceive emotional expressions, learning to identify different people and understand their facial expressions, learning to differentiate the different elements of speech when learning a second language, and learning to differentiate efficient routes to important destinations when faced with new surroundings.

In "nonacademic" subjects within the realm of academic pursuits, important examples involve music, art, and sports. For example, music students learn to differentiate the notes, chords, and instrumental voices in a piece, and they learn to identify pieces by period and composer. Art students learn to differentiate different strokes, textures, and styles, and they learn to classify paintings by period and artist. Athletes learn to differentiate the different degrees of freedom that need to be controlled to produce a winning "play" and to anticipate what actions need to be taken when on a playing field.

Finally, perceptual learning plays an equally broad role in classically academic subjects. For example, mathematics students gain expertise at perceiving graphs, classifying the shapes of curves, and knowing what equations might fit a given curve. Science students gain expertise at perceiving laboratory setups. These range widely across grade levels and domains, including the critical features of hydrolyzing water in a primary school general science setting, molecular structures in organic chemistry and genetics, frog dissections in biology, the functional relation of the frequency of waves and diffraction in different media in physics, and the critical features of maps in geology.

The borders separating perceptual learning from conceiving and reasoning often become blurred. And indeed, people perceive in order to understand, and their understanding leads to more and more efficient perception. For example, Herbert A. Simon elaborated on this in 2001 in his discussion of the visual thinking involved in having an expert understanding of the dynamics of a piston in an internal combustion engine. When experts look at a piston or a diagram of a piston or a graph representing the dynamics of a piston, they "see" the higher order, relevant variables, for example, that more work is performed when the combustion explosion moves the piston away from the cylinder's base than when the piston returns toward the base. The ability to "see" such higher-order relations is not just a question of good visual acuity, but it instead depends on content knowledge (about energy, pressure, and work) and on an understanding of how energy acts in the context of an internal combustion engine. In a 2001 article, Daniel Schwartz and John Bransford emphasized that experience with contrasting cases helps students differentiate the critical features when they are working to understand statistics and other academic domains. In a 1993 article, J. Littlefield and John Rieser demonstrated the skill of middle school students at differentiating relevant from irrelevant information when attempting to solve story problems in mathematics.

Classical Issues in Perceptual Learning and Perceptual Development

Perceptual development involves normative age-related changes in basic sensory sensitivities and in perceptual learning. Some of these changes are constrained by the biology of development in well-defined ways. For example, the growth in auditory frequency during the first year of life is mediated in part by changes in the middle ear and inner ear. Growth in visual acuity during the first two years is mediated in several ways: by changes in the migration of retinal cells into a fovea, through increasing control of convergence eye movements so that the two eyes fixate the same object, and through increasing control of the accommodate state of the lens so that fixated objects are in focus. The role of physical changes in the development of other perceptual skills, for example, perceiving different cues for depth, is less clear.

Nativism and empiricism are central to the study of perception and perceptual development. Stemming from philosophy's interest in epistemology, early nativists (such as seventeenth-century French mathematician and philosopher René Descartes and eighteenth-century German philosopher Immanuel Kant) argued that the basic capacities of the human mind were innate, whereas empiricists argued that they were learned, primarily through associations. This issue has long been hotly debated in the field of perceptual learning and development. How is it that the mind and brain come to perceive three-dimensional shapes from two-dimensional retinal projections; perceive distance; segment the speech stream; represent objects that become covered from view? The debate is very lively in the early twenty-first century, with some arguing that perception of some basic properties of the world is innate, and others arguing that it is learned, reflecting the statistical regularities in experience. Given that experience plays a role in some forms of perceptual learning, there is evidence that the timing of the experience can be critical to whether, and to what degree, it is learned effectively.

The "constancy" of perception is a remarkable feat of perceptual development. The issue is that the energy that gives rise to the perception of a particular object or situation varies widely when the perceiver or object moves, the lighting changes, and so forth. Given the flux in the sensory input, how is it that people manage to perceive that the objects and situations remain (more or less) the same? Research about perceptual constancies has reemerged as an important topic as computer scientists work to design artificial systems that can "learn to see."

Intersensory coordination is a major feature of perception and perceptual development. How is it, for example, that infants can imitate adult models who open their mouths wide or stick out their tongues? How is it that infants can identify objects by looking at them or by touching them and can recognize people by seeing them or listening to them?

The increasing control of actions with age is a major result of perceptual learning, as infants become more skillful at perceiving steps and other features of the ground and learn to control their balance when walking up and down slopes.

In 1955 James Gibson and Eleanor Gibson wrote an important paper titled "Perceptual Learning: Differentiation or Enrichment?" By differentiation they meant skill at distinguishing smaller and smaller differences among objects of a given kind. By enrichment they meant knowledge of the ways that objects and events tend to be associated with other objects and events. Their paper was in part a reaction to the predominant view of learning at the time: that learning was the "enrichment" of responses through their association with largely arbitrary stimulus conditions. The authors provided a sharp counterpoint to this view. Instead of conceiving of the world as constructed by add-on processes of association, they viewed perceivers as actively searching for the stimuli they needed to guide their actions and decisions, and in this way coming to differentiate the relevant features situated in a given set of circumstances from the irrelevant ones.

See also: ATTENTION; LEARNING THEORY, ***subentry on*** HISTORICAL OVERVIEW.

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John J. Rieser

PROBLEM SOLVING

Cognitive processing aimed at figuring out how to achieve a goal is called *problem solving.* In problem solving, the *problem solver* seeks to devise a method for transforming a problem from its current state into a desired state when a solution is not immediately obvious to the problem solver. Thus, the hallmark of problem solving is the invention of a new method for addressing a problem. This definition has three parts: (1) problem solving is *cognitive*—that is, it occurs internally in the mind (or cognitive system) and must be inferred indirectly from behavior; (2) problem solving is a *process*—it involves the manipulation of knowledge representations (or carrying out mental computations); and (3) problem solving is *directed*—it is guided by the goals of the problem solver.

The definition of problem solving covers a broad range of human cognitive activities, including educationally relevant cognition—figuring out how to manage one's time, writing an essay on a selected topic, summarizing the main point of a textbook section, solving an arithmetic word problem, or determining whether a scientific theory is valid by conducting experiments.

A *problem* occurs when a problem solver has a goal but initially does not know how to achieve the goal. This definition has three parts: (1) the *current state*—the problem begins in a given state; (2) the *goal state*—the problem solver wants the problem to be in a different state, and problem solving is required to transform the problem from the current (or given) state into the goal state, and (3) *obstacles*—the problem solver does not know the correct solution and an effective solution method is not obvious to the problem solver.

According to this definition a problem is personal, so that a situation that is a problem for one person might not be a problem for another person. For example, "3 + 5 = ___" might be a problem for a six-year-old child who reasons, "Let's see. I can take one from the 5 and give it to the 3. That makes 4 plus 4, and I know that 4 plus 4 is 8." However, this equation is not a problem for an adult who knows the correct answer.

Types of Problems

Routine and nonroutine problems. It is customary to distinguish between routine and nonroutine problems. In a routine problem, the problem solver knows a solution method and only needs to carry it out. For example, for most adults the problem "589 x 45 = ___" is a routine problem if they know the procedure for multicolumn multiplication. Routine problems are sometimes called exercises, and technically do not fit the definition of *problem* stated above. When the goal of an educational activity is to promote all the aspects of problem solving (including devising a solution plan), then nonroutine problems (or exercises) are appropriate.

In a nonroutine problem, the problem solver does not initially know a method for solving the problem. For example, the following problem (reported by Robert Sternberg and Janet Davidson) is nonroutine for most people: "Water lilies double in area every twenty-four hours. At the beginning of the summer, there is one water lily on the lake. It takes sixty days for the lake to be completely covered with water lilies. On what day is the lake half covered?" In this problem, the problem solver must invent a solution method based on working backwards from the last day. Based on this method, the problem solver can ask what the lake would look like on the day before the last day, and conclude that the lake is half covered on the fifty-ninth day.

Well-defined and ill-defined problems. It is also customary to distinguish between well-defined and ill-defined problems. In a well-defined problem, the given state of the problem, the goal state of the problem, and the allowable operators (or moves) are each clearly specified. For example, the following water-jar problem (adapted from Abrahama Luchins) is an example of a well defined problem: "I will give you three empty water jars; you can fill any jar with water and pour water from one jar into another (until the second jar is full or the first one is empty); you can fill and pour as many times as you like. Given water jars of size 21, 127, and 3 units and an unlimited supply of water, how can you obtain exactly 100 units of water?" This is a well-defined problem because the given state is clearly specified (you have empty jars of size 21, 127, and 3), the goal state is clearly specified (you want to get 100 units of water in one of the jars), and the allowable operators are clearly specified (you can fill and pour according to specific procedures). Well-defined problems may be either routine or nonroutine; if you do not have previous experience with water jar problems, then finding the solution (i.e., fill the 127, pour out 21 once, and pour out 3 twice) is a nonroutine problem.

In an ill-defined problem, the given state, goal state, and/or operations are not clearly specified. For example, in the problem, "Write a persuasive essay in favor of year-round schools," the goal state is not clear because the criteria for what constitutes a "persuasive essay" are vague and the allowable operators, such as how to access sources of information, are not clear. Only the given state is clear—a blank piece of paper. Ill-defined problems can be routine or nonroutine; if one has extensive experience in writing then writing a short essay like this one is a routine problem.

Processes in Problem Solving

The process of problem solving can be broken down into two major phases: *problem representation,* in which the problem solver builds a coherent mental representation of the problem, and *problem solution,* in which the problem solver devises and carries out a solution plan. Problem representation can be broken down further into *problem translation,* in which the problem solver translates each sentence (or picture) into an internal mental representation, and *problem integration,* in which the problem solver integrates the information into a coherent mental representation of the problem (i.e., a mental model of the situation described in the problem). Problem solution can be broken down further into *solution planning,* in which the problem solver devises a plan for how to solve the problem, and *solution execution,* in which the problem solver carries out the plan by engaging in solution behaviors. Although the four processes of problem solving are listed sequentially, they may occur in many different orderings and with many iterations in the course of solving a problem.

For example, consider the butter problem described by Mary Hegarty, Richard Mayer, and Christopher Monk: "At Lucky, butter costs 65 cents per stick. This is two cents less per stick than butter at Vons. If you need to buy 4 sticks of butter, how much will you pay at Vons?" In the problem translation phase, the problem solver may mentally represent the first sentence as "Lucky = 0.65," the second sentence as "Lucky = Vons − 0.02," and the third sentence as "4 x Vons = ___." In problem integration, the problem solver may construct a mental number line with Lucky at 0.65 and Vons to the right of Lucky (at 0.67); or the problem solver may mentally integrate the equations as "4 x (Lucky + 0.02) = ____." A key insight in problem integration is to recognize the proper relation between the cost of butter at Lucky and the cost of butter at Vons, namely that butter costs more at Vons (even though the keyword in the problem is "less"). In solution planning, the problem solver may break the problem into parts, such as: "First add 0.02 to 0.65, then multiply the result by 4." In solution executing, the problem solver carries out the plan: 0.02 + 0.65 = 0.67, 0.67 x 4 = 2.68. In addition, the problem solver must monitor the problem-solving process and make adjustments as needed.

Teaching for Problem Solving

A challenge for educators is to teach in ways that foster meaningful learning rather than rote learning. Rote instructional methods promote retention (the ability to solve problems that are identical or highly similar to those presented in instruction), but not problem solving transfer (the ability to apply what was learned to novel problems). For example, in 1929, Alfred Whitehead used the term *inert knowledge* to refer to learning that cannot be used to solve novel problems. In contrast, *meaningful instructional methods* promote both retention and transfer.

In a classic example of the distinction between rote and meaningful learning, the psychologist Max Wertheimer (1959) described two ways of teaching students to compute the area of a parallelogram. In the rote method, students learn to measure the base, measure the height, and then multiply base times height. Students taught by the $A = b \times h$ method are able to find the area of parallelograms shaped like the ones given in instruction (a retention problem) but not unusual parallelograms or other shapes (a transfer problem). Wertheimer used the term *reproductive thinking* to refer to problem solving in which one blindly carries out a previously learned procedure. In contrast, in the meaningful method, students learn by cutting the triangle from one end of a cardboard parallelogram and attaching it to the other end to form a rectangle. Once students have the insight that a parallelogram is just a rectangle in disguise, they can compute the area because they already know the procedure for finding the area of a rectangle. Students taught by the insight method perform well on both retention and transfer problems. Wertheimer used the term *productive thinking* to refer to problem solving in which one invents a new approach to solving a novel problem.

Educationally Relevant Advances in Problem Solving

Recent advances in educational psychology point to the role of domain-specific knowledge in problem solving—such as knowledge of specific strategies or problem types that apply to a particular field. Three important advances have been: (1) the teaching of problem-solving processes, (2) the nature of expert problem solving, and (3) new conceptions of individual differences in problem-solving ability.

Teaching of problem-solving processes. An important advance in educational psychology is cognitive strategy instruction, which includes the teaching of problem-solving processes. For example, in Project Intelligence, elementary school children successfully learned the cognitive processes needed for solving problems similar to those found on intelligence tests. In Instrumental Enrichment, students who had been classified as mentally retarded learned cognitive processes that allowed them to show substantial improvements on intelligence tests.

Expert problem solving. Another important advance in educational psychology concerns differences between what experts and novices know in given fields, such as medicine, physics, and computer programming. For example, expert physicists tend to store their knowledge in large integrated chunks, whereas novices tend to store their knowledge as isolated fragments; expert physicists tend to focus on the underlying structural characteristics of physics word problems, whereas novices focus on the surface features; and expert physicists tend to work forward from the givens to the goal, whereas novices work backwards from the goal to the givens. Research on expertise has implications for professional education because it pinpoints the kinds of domain-specific knowledge that experts need to learn.

Individual differences in problem-solving ability. This third advance concerns new conceptions of intellectual ability based on differences in the way people process information. For example, people may differ in cognitive style—such as their preferences for visual versus verbal representations, or for impulsive versus reflective approaches to problem solving. Alternatively, people may differ in the speed and efficiency with which they carry out specific cognitive processes, such as making a mental comparison or retrieving a piece of information from memory. Instead of characterizing intellectual ability as a single, monolithic ability, recent conceptions of intellectual ability focus on the role of multiple differences in information processing.

See also: CREATIVITY; LEARNING, ***subentry on*** ANALOGICAL REASONING; MATHEMATICS LEARNING, ***subentry on*** COMPLEX PROBLEM SOLVING.

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REASONING

Reasoning is the generation or evaluation of claims in relation to their supporting arguments and evidence. The ability to reason has a fundamental impact on one's ability to learn from new information and experiences because reasoning skills determine how people comprehend, evaluate, and accept claims and arguments. Reasoning skills are also crucial for being able to generate and maintain viewpoints or beliefs that are coherent with, and justified by, relevant knowledge. There are two general kinds of reasoning that involve claims and evidence: formal and informal.

Formal Reasoning

Formal reasoning is used to evaluate the form of an argument, and to examine the logical relationships between conclusions and their supporting assertions. Arguments are determined to be either *valid* or *invalid* based solely on whether their conclusions necessarily follow from their explicitly stated premises or assertions. That is, if the supporting assertions are true, must the conclusion also be true? If so, then the argument is considered valid and the truth of the conclusion can be directly determined by establishing the truth of the supporting assertions. If not, then the argument is considered invalid, and the truth of the assertions is insufficient (or even irrelevant) for establishing the truth of the conclusion. Formal reasoning is often studied in the context of *categorical syllogisms* or *"if-then" conditional proofs.* Syllogisms contain two assertions and a conclusion.

An example of a logically valid syllogism is: *All dogs are animals; all poodles are dogs; therefore poodles are animals.* A slight change to one of the premises will create the invalid syllogism: *All dogs are animals; some dogs are poodles; therefore all poodles are animals.* This argument form is invalid because it cannot be determined with certainty that the conclusion is true, even if the premises are true. The second premise does not require that all poodles are dogs. Thus, there may be some poodles who are not dogs and, by extension, some poodles who are not animals. This argument is invalid despite the fact that an accurate knowledge of dogs, poodles, and animals confirms that both the premises and the conclusion are true statements. This validity-truth incongruence highlights the important point that the conceptual content of an argument or the real-world truth of the premises and conclusion are irrelevant to the logic of the argument form.

Discussions of formal reasoning may sometimes refer to the rules of logic. It is common for formal reasoning to be described as a set of abstract and prescriptive rules that people must learn and apply in order to determine the validity of an argument. This is the oldest perspective on formal reasoning. Some claim that the term *formal reasoning* refers directly to the application of these formal rules.

However, many theorists consider this perspective misguided. Describing formal reasoning as the evaluation of argument forms conveys a more inclusive and accurate account of the various perspectives in this field. There are at least four competing theories about how people determine whether a conclusion necessarily follows from the premises. These theories are commonly referred to as *rule-based perspectives, mental models, heuristics,* and *domain-sensitive theories.* People outside the rule-based perspective view the rules of logic as descriptive rules that simply give labels to common argument forms and to common errors or fallacies in logical reasoning. These theories are too complex to be detailed here, and there is currently no consensus as to which theory best accounts for how people actually reason. A number of books and review articles provide comprehensive discussions of these theories and their relative merits; one example is *Human Reasoning: The Psychology of Deduction* by Jonathan Evans, Stephen Newstead, and Ruth Byrne.

There is a consensus that human reasoning performance is poor and prone to several systematic errors. Performance on formal reasoning tasks is generally poor, but can be better or worse depending upon the particular aspects of the task. People perform worse on problems that require more cognitive work, due to excessive demands placed on their limited processing capacity or working memory. The required cognitive work can be increased simply by having more information, or by the linguistic form of the argument. Some linguistic forms can affect performance because they violate conventional discourse or must be mentally rephrased in order to be integrated with other information.

In addition, people's existing knowledge about the concepts contained in the problem can affect performance. People have great difficulty evaluating the logical validity of an argument independent of their real-world knowledge. They insert their knowledge as additional premises, which leads them to make more inferences than is warranted. Prior knowledge can also lead people to misinterpret the meaning of premises. Another common source of error is *belief bias,* where people judge an argument's validity based on whether the conclusion is consistent with their beliefs rather than its logical relationship to the given premises.

The systematic errors that have been observed provide some insights about what skills a person might develop to improve performance. Making students explicitly aware of the likely intrusion of their prior knowledge could facilitate their ability to control or correct such intrusions. Students may also benefit from a detailed and explicit discussion of what logical validity refers to, how it differs from real-world truth or personal agreement, and how easy it is to confuse the two. Regardless of whether or not people commonly employ formal rules of logic, an understanding and explicit knowledge of these rules should facilitate efforts to search for violations of logical validity. Theorists of informal reasoning such as James Voss and Mary Means have made a similar argument for the importance of explicit knowledge about the rules of good reasoning. Errors attributed to limited cognitive resources can be addressed by increasing reasoning skill, and practice on formal reasoning tasks should increase proficiency and reduce the amount of cognitive effort required. Also, working memory load should be reduced by external representation techniques, such as Venn diagrams.

Informal Reasoning

Informal reasoning refers to attempts to determine what information is relevant to a question, what conclusions are plausible, and what degree of support the relevant information provides for these various conclusions. In most circumstances, people must evaluate the justification for a claim in a context where the information is ambiguous and incomplete and the criteria for evaluation are complex and poorly specified. Most of what is commonly referred to as "thinking" involves informal reasoning, including making predictions of future events or trying to explain past events. These cognitive processes are involved in answering questions as mundane as "How much food should I prepare for this party?" and as profound as "Did human beings evolve from simple one-celled organisms?" Informal reasoning has a pervasive influence on both the everyday and the monumental decisions that people make, and on the ideas that people come to accept or reject.

Informal and formal reasoning both involve attempts to determine whether a claim has been sufficiently justified by the supporting assertions, but these types of reasoning differ in many respects. The vast majority of arguments are invalid according to formal logic, but informal reasoning must be employed to determine what degree of justification the supporting assertions provide. Also, the supporting assertions themselves must be evaluated as to their validity and accuracy. Formal reasoning involves making a binary decision based only on the given information. Informal reasoning involves making an uncertain judgment about the degree of justification for a claim relative to competing claims—and basing this evaluation on an ill-defined set of assertions whose truth values are uncertain.

Based on the above characterization of informal reasoning, a number of cognitive skills would be expected to affect the quality of such reasoning. The first is the ability to fully comprehend the meaning of the claim being made. Understanding the conceptual content is crucial to being able to consider what other information might bear on the truth or falsehood of a claim. Other cognitive processes involved in reasoning include the retrieval of relevant knowledge from long-term memory, seeking out new relevant information, evaluating the validity and utility of that information, generating alternatives to the claim in question, and evaluating the competing claims in light of the relevant information.

Successful reasoning requires the understanding that evidence must provide information that is independent of the claim or theory, and that evidence must do more than simply rephrase and highlight the assumptions of the theory. For example, the assertion "Some people have extrasensory perception" does not provide any evidence about the claim "ESP is real." These are simply ways of restating the same information. Evidence must be an assertion that is independent of the claim, but that still provides information about the probable truth of the claim. An example of potential evidence for the claim that "ESP is real" would be "Some people know information that they could not have known through any of the normal senses." In other words, evidence constitutes assertions whose truth has implications for, but is not synonymous with, the truth of the claim being supported.

Without an understanding of evidence and counterevidence and how they relate to theories, people would be ineffective at identifying information that could be used to determine whether a claim is justified. Also, lack of a clear distinction between evidence and theory will lead to the assimilation of evidence and the distortion of its meaning and logical implications. This eliminates the potential to consider alternative claims that could better account for the evidence. People will also fail to use counterevidence to make appropriate decreases in the degree of justification for a claim.

Discussions of informal reasoning, argumentation, and critical thinking commonly acknowledge that a prerequisite for effective reasoning is a belief in the utility of reasoning. The cognitive skills described above are necessary, but not sufficient, to produce quality reasoning. The use of these skills is clearly effortful; thus, people must believe in the importance and utility of reasoning in order to consistently put forth the required effort. The epistemology that promotes the use of reasoning skills is the view that knowledge can never be absolutely certain and that valid and useful claims are the product of contemplating possible alternative claims and weighing the evidence and counterevidence. Put simply, people use their reasoning skills consistently when they acknowledge the possibility that a claim may be incorrect and also believe that standards of good reasoning produce more accurate ideas about the world.

Inconsistent, selective, and biased application of reasoning skills provides little or no benefits for learning. Greater reasoning skills are assumed to aid in the ability to acquire new knowledge and revise one's existing ideas accordingly. However, if one contemplates evidence and theory only when it can be used to justify one's prior commitments, then only supportive information will be learned and existing ideas will remain entrenched and unaffected. The development of reasoning skills will confer very little intellectual benefit in the absence of an epistemological commitment to employ those skills consistently.

General Reasoning Performance

Reports from the National Assessment of Educational Progress and the National Academy of Sciences consistently show poor performance on a wide array of tasks that require informal reasoning. These tasks span all of the core curriculum areas of reading, writing, mathematics, science, and history.

Some smaller-scale studies have attempted to paint a more detailed picture of what people are doing, or failing to do, when asked to reason. People demonstrate some use of informal reasoning skills, but these skills are underdeveloped and applied inconsistently. Children and adults have a poor understanding of evidence and its relationship to theories or claims. Only a small minority of people attempt to justify their claims by providing supporting evidence. When explicitly asked for supporting evidence, most people simply restate the claim itself or describe in more detail what the claim means. It is especially rare for people to generate possible counter-evidence or to even consider possible alternative claims.

The inconsistent application of informal reasoning skills could have multiple causes. Some theorists suggest that reasoning skills are domain specific and depend heavily on the amount of domain knowledge a person possesses. Alternatively, underdeveloped or unpracticed skills could lead to their haphazard use. A third possibility is that people's lack of explicit knowledge about what good reasoning entails prevents them from exercising conscious control over their implicit skills.

Inconsistent use of informal reasoning skills may also arise because people lack a principled belief in the utility of reasoning that would foster a consistent application of sound reasoning. People have extreme levels of certainty in their ideas, and they take this certainty for granted. In addition, the application of reasoning skills is not random, but is selective and biased such that prior beliefs are protected from scrutiny. This systematic inconsistency cannot be accounted for by underdeveloped skills, but can be accounted for by assuming a biased motivation to use these skills selectively. Regardless of whether or not people have the capacity for sound reasoning, they have no philosophical basis that could provide the motivation to override the selective and biased use of these skills.

Development of Reasoning Skills

There is only preliminary data about how and when informal reasoning skills develop. There is preliminary support that the development of reasoning takes a leap forward during the preadolescent years. These findings are consistent with Piagetian assumptions about the development of *concrete operational thinking,* in other words, thinking that involves the mental manipulation (e.g., combination, transformation) of objects represented in memory. However, younger children are capable of some key aspects of reasoning. Thus, the improvement during early adolescence could result from improvements in other subsidiary skills of information processing, from meta-cognitive awareness, or from an increase in relevant knowledge.

A somewhat striking finding is the lack of development in informal reasoning that occurs from early adolescence through adulthood. Some evidence suggests that college can improve reasoning, but the overall relationship between the amount of postsecondary education and reasoning skill is weak at best. The weak and inconsistent relationship that does exist between level of education and reasoning is likely due to indirect effects. Students are rarely required to engage in complex reasoning tasks. However, the spontaneous disagreements that arise in the classroom could expose them to the practice of justifying one's claim. Also, engagement in inquiry activities, such as classroom experiments, could provide implicit exposure to the principles of scientific reasoning.

There are relatively few programs aimed at developing informal reasoning skills; hence, there is little information about effective pedagogical strategies. Where they do exist, curricula are often aimed at developing general reasoning skills. Yet, many believe that effective reasoning skills are domain- or discipline-specific. Nevertheless, given the pervasive impact of reasoning skills on learning in general, it is clear that more systematic efforts are needed to foster reasoning skills at even the earliest grade levels. Of the approaches that have been attempted, there is some evidence for the success of *scaffolding,* which involves a teacher interacting with a student who is attempting to reason, and prompting the student to develop more adequate arguments. Another approach is to explicitly teach what *good reasoning* means, what *evidence* is, and how evidence relates to theories. This approach could be especially effective if classroom experiments are conducted within the context of explicit discussions about the principles of scientific reasoning. Also, if reasoning skills are discussed in conjunction with the content of the core subject areas, then students may develop an appreciation for the pervasive utility and importance of reasoning for the progress of ideas.

A number of theorists have suggested that debate between students with opposing views could foster the basic skills needed for informal reasoning. Debates could give students practice in having to consider opposing viewpoints and having to coordinate evidence and counterevidence in support of a claim. Also, providing justification for one's positions requires some cognitive effort, and the norms of social dialogue could provide the needed motivation. However, interpersonal debates are most commonly construed as situations in which individuals are committed to a position ahead of time, and in which their goal is to frame the issue and any evidence in a manner that will persuade their opponent or the audience that their own position is correct. Students' reasoning is already greatly impaired by their tendency to adopt a biased, defensive, or noncontemplative stance. Debate activities that reinforce this stance and blur the difference between defending a claim and contemplating a claim's justification may do more harm than good. To date, there is no empirical data that compare the relative costs and benefits of using interpersonal debate exercises to foster critical reasoning skills.

See also: LEARNING, ***subentry on*** CAUSAL REASONING; LEARNING THEORY, ***subentry on*** HISTORICAL OVERVIEW.

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THOMAS D. GRIFFIN

TRANSFER OF LEARNING

Imagine that every time that people entered a new environment they had to learn how to behave without the guidance of prior experiences. Slightly novel tasks, like shopping online, would be disorienting and dependant on trial-and-error tactics. Fortunately, people use aspects of their prior experiences, such as the selection of goods and subsequent payment, to guide their behavior in new settings. The ability to use learning gained in one situation to help with another is called *transfer.*

Transfer has a direct bearing on education. Educators hope that students transfer what they learn from one class to another—and to the outside world. Educators also hope students transfer experiences from home to help make sense of lessons at school. There are two major approaches to the study of transfer. One approach characterizes the knowledge and conditions of acquisition that optimize the chances of transfer. The other approach inquires into the nature of individuals and the cultural contexts that transform them into more adaptive participants.

Knowledge-Based Approaches to Transfer

There are several knowledge-based approaches to transfer.

Transferring out from instruction. Ideally, the knowledge students learn in school will be applied outside of school. For some topics, it is possible to train students for the specific situations they will subsequently encounter, such as typing at a keyboard. For other topics, educators cannot anticipate all the out-of-school applications. When school-based lessons do not have a direct mapping to out-of-school contexts, memorization without understanding can lead to inert knowledge. Inert knowledge occurs when people acquire an idea without also learning the conditions of its subsequent application, and thus they fail to apply that idea appropriately. Memorizing the Pythagorean formula, for example, does not guarantee students know to use the formula to find the distance of a shortcut.

Knowing when to use an idea depends on knowing the contexts in which the idea is useful. The ideas that people learn are always parts of a larger context, and people must determine which aspects of that context are relevant. Imagine, for example, a young child who is learning to use the hook of a candy cane to pull a toy closer. As the child learns the action, there are a number of contextual features she might also learn. There are incidental features—it is Christmas; there are surface features—the candy is small and striped; and there are deep features—the candy cane is rigid and hooked. Instruction for transfer must help the child discern the deep features. This way the child might subsequently use an umbrella handle to gather a stuffed animal instead of trying a candy-striped rope.

When people learn, they not only encode the target idea, they also encode the context in which it occurs, even if that context is incidental. For a study published in 1975, Gooden and Baddeley asked adults to learn a list of words on land or underwater (while scuba diving). Afterwards, the adults were subdivided; half tried to remember the words underwater and half on land. Those people who learned the words underwater remembered them better underwater than on land, and those people who learned the words on land remembered them better on land than underwater. This result reveals the context dependency of memory. Context dependency is useful because it constrains ideas to appear in appropriate contexts, rather than cluttering people's thoughts at odd times. But context dependency can be a problem for transfer, because transfer, by definition, has to occur when the original context of learning is not reinstated—when one is no longer in school, for example.

Surface features, which are readily apparent to the learner, differ from incidental features, because surface features are attached to the idea rather than the context in which the idea occurs. Surface features can be useful. A child might learn that fish have fins and lay eggs. When he sees a new creature with fins, he may decide it is a fish and infer that it too lays eggs. Surface features, however, can be imperfect cues. People may overgeneralize and exhibit *negative transfer.* For example, the child may have seen a dolphin instead of a fish. People may also undergeneralize and fail to transfer. A child might see an eel and assume it does not lay eggs. Good instruction helps students see beneath the surface to find the deep features of an idea.

Deep features are based on structures integral to an idea, which may not be readily apparent. To a physicist, an inclined plane and scissors share the same deep structure of leverage, but novices cannot see this similarity and they fail to use a formula learned for inclined planes to reason about scissors.

Analogies are built on deep features. For example, color is to picture as sound is to song. On the surface, color and sound differ, as do pictures and song. Nonetheless, the relation of *used to create* makes it possible to compare the common structure between the two. Analogy is an important way people discover deep features. In the 1990s, Kevin Dunbar studied the laboratory meetings of cell biologists. He found that the scientists often used analogies to understand a new discovery. They typically made transfers of *near* analogies rather than *far* ones. A far analogy transfers an idea from a remote body of knowledge that shares few surface features, as might be the case when using the structure of the solar system to explain the structure of an atom. A near analogy draws on a structure that comes from a similar body of knowledge. The scientists in Dunbar's study used near analogies from biology because they had precise knowledge of biology, which made for a more productive transfer.

Instruction can help students determine deep features by using analogous examples rather than single examples. In a 1983 study, Mary Gick and Keith Holyoak asked students how to kill a tumor with a burst of radiation, given that a strong burst kills nearby tissue and a weak burst does not kill the tumor. Students learned that the solution uses multiple weak radiation beams that converge on the tumor. Sometime later, the students tried to solve the problem of how a general could attack a fortress: If the general brought enough troops to attack the fortress, they would collapse the main bridge. Students did not propose that the general could split his forces over multiple bridges and then converge on the fortress. The students' knowledge of the convergence solution was inert, because it was only associated with the radiation problem. Gick and Holyoak found they could improve transfer by providing two analogous examples instead of one. For example, students worked with the radiation problem and an analogous traffic congestion problem. This helped students abstract the convergence schema from the radiation context, and they were able to transfer their knowledge to the fortress problem.

Transferring in to instruction. In school, transfer can help students learn. If students can *transfer in* prior knowledge, it will help them understand the content of a new lesson. A lesson on the Pythagorean theorem becomes more comprehensible if students can transfer in prior knowledge of right triangles. Otherwise, the lesson simply involves pushing algebraic symbols.

Unlike transfer to out-of-school settings, which depends on the spontaneous retrieval of relevant prior knowledge, transfer to in-school settings can be directly supported by teachers. A common approach to help students recruit prior knowledge uses *cover stories* that help students see the relevance of what they are about to learn. A teacher might discuss the challenge of finding the distance of the moon from the earth to motivate a lesson on trigonometry. This example includes two ways that transferring in prior knowledge can support learning. Prior knowledge helps students understand the problems that a particular body of knowledge is intended to solve—in this case, problems about distance. Prior knowledge also enables learners to construct a mental model of the situation that helps them understand what the components of the trigonometric formulas refer to.

Sometimes students cannot transfer knowledge to school settings because they do not have the relevant knowledge. One way to help overcome a lack of prior knowledge is to use contrasting cases. Whereas pairs of analogies help students abstract deep features from surface features, pairs of contrasting cases help students notice deep features in the first place. Contrasting cases juxtapose examples that only differ by one or two features. For example, a teacher might ask students to compare examples of acute, right, and obtuse triangles. Given the contrasts, students can notice what makes a right triangle distinctive, which in turn, helps them construct precise mental models to understand a lesson on the Pythagorean theorem.

Person-Based Approaches to Transfer

The second approach to transfer asks whether person-level variables affect transfer. For example, do IQ tests or persistence predict the ability to transfer? Person-based research relevant to instruction asks whether some experiences can transform people in general ways.

Transferring out from instruction. An enduring issue has been whether instruction can transform people into better thinkers. People often believe that mastering a formal discipline, like Latin or programming, improves the rigor of thought. Research has shown that it is very difficult to improve people's reasoning, with instruction in logical reasoning being notoriously difficult. Although people may learn to reason appropriately for one situation, they do not necessarily apply that reasoning to novel situations. More protracted experiences, however, may broadly transform individuals to the extent that they apply a certain method of reasoning in general, regardless of situational context. For example, the cultural experiences of American and Chinese adults lead them to approach contradictions differently.

There have also been attempts to improve learning abilities by improving people's ability to transfer. Ann Brown and Mary Jo Kane showed young children how to use a sample solution to help solve an analogous problem. After several lessons on transferring knowledge from samples to problems, the children spontaneously began to transfer knowledge from one example to another. Whether this type of instruction has broad effects—for example, when the child leaves the psychologist's laboratory—remains an open question. Most likely, it is the accumulation of many experiences, not isolated, short-term lessons, that has broad implications for personal development.

Transferring in to instruction. When children enter school, they come with identities and dispositions that have been informed by the practices and roles available in their homes and neighborhoods. Schools also have practices and roles, but these can seem foreign and inhospitable to out-of-school identities. Na'ilah Nasir, for example, found that students did not transfer their basketball "street statistics" to make sense of statistics lessons in their classrooms (nor did they use school-learned procedures to solve statistics problems in basketball). From a knowledge approach to transfer, one might argue that the school and basketball statistics were analogous, and that the children failed to see the common deep features. From a person approach to transfer, the cultural contexts of the two settings were so different that they supported different identities, roles, and interpretations of social demands. People can view and express themselves quite differently in school and nonschool contexts, and there will therefore be little transfer.

One way to bridge home and school is to alter instructional contexts so children can build identities and practices that are consistent with their out-of-school personae. Educators, for example, can bring elements of surrounding cultures into the classroom. In one intervention, African-American students learned literary analysis by building on their linguistic practice of signifying. These children brought their cultural heritage to bear on school subjects, and this fostered a school-based identity in which students viewed themselves as competent and engaged in school.

Conclusion

The frequent disconnect between in-school and out-of-school contexts has led some researchers to argue that transfer is unimportant. In 1988, Jean Lave compared how people solved school math problems and best-buy shopping problems. The adults rarely used their school algorithms when shopping. Because they were competent shoppers and viewed themselves as such, one might conclude that school-based learning does not need to transfer. This conclusion, however, is predicated on a narrow view of transfer that is limited to identical uses of what one has learned or to identical expressions of identity.

From an educational perspective, the primary function of transfer should be to prepare people to learn something new. So, even though shoppers did not use the exact algorithms they had learned in school, the school-based instruction prepared them to learn to solve best-buy problems when they did not have paper and pencil at hand. This is the central relevance of transfer for education. Educators cannot create experts who spontaneously transfer their knowledge or identities to handle every problem or context that might arise. Instead, educators can only put students on a trajectory to expertise by preparing them to transfer for future learning.

See also: LEARNING, ***subentries on*** ANALOGICAL REASONING, CAUSAL REASONING, CONCEPTUAL CHANGE.

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LEARNING COMMUNITIES AND THE UNDERGRADUATE CURRICULUM

Educational observers have long argued that student involvement is important to student education. Indeed a wide range of studies, in a variety of settings and of a range of students, have confirmed that academic and social involvement, sometimes referred to as academic and social integration, enhances student development, improves student learning, and increases student persistence. Simply put, involvement matters. But getting students involved can be difficult. This is especially true for the majority of college students who commute to college, who work while in college, or have substantial family responsibilities beyond college. Unlike students who reside on campus, these students have few, if any, opportunities to engage others beyond the classroom.

For that reason an increasing number of universities and colleges, both two- and four-year, have turned their attention to the classroom—the one place, perhaps the only place, where students meet each other and the faculty. Researchers have asked how that setting can be altered to better promote student involvement and in turn improve student education. In response, schools have begun to institute a variety of curricular and pedagogical reforms ranging from the use of cooperative and problem-based learning to the inclusion of service learning in the college curriculum. One reform that is gaining attention, that addresses both the need for student involvement and the demands for curricular coherence, is the use of learning communities.