Morrison, R. G., & Holyoak, K. J. (2003). Problem solving. In M. Aminoff & R. Daroff (Eds.), *The encyclopedia of the neurological sciences* (Vol. 1, pp. 60-62). San Diego: Academic Press.

Problem Solving

Encyclopedia of the Neurological Sciences

A PROBLEM ARISES when an organism has a goal (a desired state of affairs) and it is not immediately apparent how the goal can be attained. The range of problems people encounter is enormous: planning a dinner party, tracking deer, diagnosing a disease, winning a game of chess, solving mathematical equations, managing a business, or battling the latest problem with the home computer. Given this diversity, it is not surprising that every cognitive process in the human repertoire, including perception, language, attention, working memory, long-term memory, categorization, judgment, and choice, plays a role in problem solving. The ability to solve problems, along with language, represents the pinnacle of human cognitive evolution.

Not surprisingly, competent problem solving requires functioning of many brain systems. Without intact sensory systems the basic foundational information of the problem is crucially degraded. For example, a lesion to the occipital or parietal cortex could disrupt spatial perception and, hence, impair the ability to play chess. Likewise, the ability to selectively attend to various pieces of perceived sensory information is also crucial to success. Damage to the frontal and/or parietal cortex could disrupt selective attention and make it difficult to focus attention on a running deer amid a bustling landscape. The importance of selective attention extends beyond control of sensory information; problem solving may also depend on the ability to inhibit internally generated stimuli or thought processes. Extensive structured knowledge (semantic memory) is also a necessary prerequisite for expert problem solving. Damage to temporal cortex could result in the loss of access to particular categories in semantic memory necessary for solving a computer problem. Efficient storage and retrieval of event knowledge (declarative memory) is also frequently helpful to solve new problems. For example, it may be helpful for a doctor to recall the complaints of a previous patient in order to diagnose a new patient.

Because of the complex nature of problem solving, it is difficult to isolate the precise roles of these basic processes using the methodology of cognitive neuroscience; however, many studies have been conducted examining these processes in isolation. Our focus is on the function of the dorsolateral prefrontal cortex (DLPFC). This neural region seems to play a particularly general role in problem solving and related forms of thinking and reasoning, especially those that depend on analytical intelligence (the *g* factor) and executive control. Based on an extensive review of the literature on the effects of frontal lesions, Stuss and Benson suggested several classes of deficits related to problem solving. Frontal damage leads to deficits in the ordering or handling of sequential behaviors; impairment in establishing, maintaining, or changing a mental "set"; decreased ability to monitor personal behavior; dissociation of knowledge from the direction of action; and various changes in normal emotional and motivational responses. Each of these classes of deficits is linked to problem solving.

Planning and problem solving depend on the hierarchical organization of action and require coordination of internal goals and knowledge with the constraints of the environment. Systematic investigations of problem solving began with Gestalt psychologists such as Duncker, and the modern formulation of a general theory of problem solving is due to Newell and Simon. In their problem space formulation, problem solving has two fundamental components: forming a representation of a problem space and a search through the space. The representation of a problem consists of four kinds of elements: a description of the initial state in which problem solving begins; a description of the goal state to be reached; a set of operators, or actions that can be taken, that serve to alter the current state of the problem; and path constraints that impose additional conditions on a successful path to solution. The problem space consists of the set of all states that can potentially be reached by applying the available operators. A solution is a sequence of operators that can transform the initial state into the goal state in accord with the path constraints. A problem-solving method is a procedure for finding a solution.

The problem space analysis yields a mathematical result regarding the size of the search space that constrains the possible methods for solving many problems, such as the problem of winning a chess game. A typical game of chess might involve a total of 60 moves, with an average of 30 alternative legal moves available at each step along the way. The number of alternative paths is 30^{60}, a number so astronomical that not even the fastest computer can play chess by exploring every possible move sequence. The exponential increase in the size of the search space with the depth of the search makes many problems impossible to solve by exhaustive search of all possible paths.

In addition, neural implementation of the problem space places serious constraints on the methods for human problem solving. One of the most robust findings in all experimental psychology is that humans have a limited-capacity working memory. Although there has been considerable debate about the exact size of working memory, there is general agreement that its capacity is small compared to the amount of information humans store in their long-term memory. Given this limited capacity, successful problem solving requires efficient management of search. Expert problem solving depends on extensive knowledge stored in long-term memory, which can be brought to bear on familiar types of problems. Knowledge makes it possible to form a useful problem representation and may suggest appropriate actions. Problem solving then becomes a form of recognition with implications for action, obviating the need for extensive search. Until 1997, when world-champion grandmaster Gary Kasparov was defeated in a chess match by the computer program Deep Blue II, the human ability to recognize familiar patterns and their action implications allowed human experts to hold their own against the chess-playing prowess of programs based on massive search. In less constrained problem domains, such as managing a business or negotiating international treaties, no search-based computer program can rival human expertise.

Even in domains in which they are not expert, people typically use intelligent search strategies. One strategy is based on analogical reasoning. If the reasoner recognizes parallels between a novel problem and a familiar solved one, then the previous solution may be adapted to fit the new problem, obviating the need for extensive search in the problem space. Morrison *et al.* have found that the ability to use analogical reasoning is severely degraded in patients with damage to their prefrontal cortex. Using positron emission tomography (PET), Wharton *et al.* found that left prefrontal cortex was selectively activated during a visual analogy task.

Central to the ability to reason by analogy is the ability to form and manipulate mental representations of relations between objects and events, which involves several functions that have been ascribed to prefrontal cortex. First, analogy requires that the objects in the situations being compared be bound to their relational roles. Prefrontal cortex has been shown to be important for binding in numerous studies involving monkeys and humans. Second, the central executive of working memory, for which DLPFC is critical, appears to be the critical component of working memory necessary for the manipulation of material and is thus critical for successful analogy performance.

If neither direct prior knowledge nor an analogy is available, heuristic search methods may be used. One of the most basic of these, means–ends analysis, depends on a combination of forward and backward search, where forward search involves applying operators to the current state to generate new states and backward search involves finding possible precursor states to the goal state. The key idea underlying means–ends analysis is that search is guided by detection of differences between the current state and the goal state. Suppose you have the goal of trying to get your car washed. The obvious difference between the current state and the goal state is that the car is unwashed. The operator "send car through car wash" could reduce this difference. However, to apply this operator you first need to get your car to a car wash. If it is not already at a car wash, you now set the subgoal of getting your car to an appropriate location. Before you can do this, you need to locate a car wash to which you can drive. You might be able to locate one in the yellow pages of a telephone directory; thus, you set the subgoal of finding a telephone directory. Subgoaling continues until the conditions for applying the operator are met, and you can finally reduce the difference in the original problem. Means–ends analysis illustrates several important points about intelligent heuristic search. First, it is explicitly guided by knowledge of the goal. Second, an initial goal can lead to subsequent subgoals that effectively decompose the problem into smaller parts. Third, methods can be applied recursively; that is, in the course of applying a method to achieve a goal, the entire method may be applied to achieve a subgoal.

Shallice conducted a study that specifically examined the manner in which frontal lobe patients approach novel problems requiring planning and organized sequential action. He tested patients with various forms of brain damage, as well as control subjects, on their ability to solve various versions of the Tower of London puzzle. This puzzle consists of three differently colored beads and three pegs of different lengths. The experimenter places the beads in a starting configuration, and the subject must then move them into a new configuration defined by the experimenter in a minimum number of moves. The number of moves required to achieve the goal defines the level of difficulty. Although all of the groups of brain-damaged subjects in Shallice's study were impaired in their performance relative to the control subjects, those with damage to the left frontal lobe showed the greatest decrement, particularly for the more difficult versions of the puzzle. The nature of the errors made by the frontal lobe subjects indicated that they had difficulty in planning: They could not establish an appropriate order of subgoals. The deficit was not due to a general limitation of short-term memory because variations in the patients' performance on a digit-span test could not account for the differences in problem-solving success.

Recent evidence suggests that the previously mentioned findings should be interpreted cautiously. In particular, although Owen *et al.* have replicated the effect of an overall frontal deficit on performance in the Tower of London task, the selective effect of left hemisphere damage has not been found in other experiments. However, Nicelli *et al.* have confirmed the role of the frontal cortex in problem solving for another task—chess playing—using PET activation measures. When chess players were asked to decide whether it is possible to achieve a checkmate in one move (a task requiring planning), brain activity was selectively increased in regions of both the left and the right frontal cortex. The same study found that several posterior regions of the brain, especially those associated with generation of visual images, also play significant roles in chess playing.

Means–ends analysis requires extensive use of working memory to maintain and operate on information related to goals and subgoals. In a recent study utilizing functional magnetic resonance imaging (fMRI), Koechlin *et al.* employed a task that could be modified to manipulate working memory load as well as goal use. They found that when the task required participants to use working memory to perform a dual task, DLPFC was active. However, when participants were required to maintain a main goal while concurrently using subgoals, frontopolar prefrontal cortex was also recruited. It is not clear, however, if manipulating interrelated goals per se is different from manipulation of any other form of higher order relational information because adding a branching goal necessarily increases the relational complexity of the task. Robin and Holyoak argued that a major function of prefrontal cortex is the maintenance and manipulation of relational information. Several studies utilizing fMRI have found that regions in the DLPFC and frontopolar cortex become more active as relational complexity is increased. Waltz *et al.* found that patients with frontal-variant frontotemporal dementia had great difficulty in several tasks when relational complexity exceeded one relation. Thus, it appears that prefrontal cortex is critical for complex problem solving at higher levels of relational complexity.

Although laboratory studies usually focus on problems that are novel for the participant, expert real-world problem solving frequently involves evoking a relevant problem schema and using specialized problem-solving methods. There is increasing evidence that the development of problem-solving skill involves other brain areas in addition to prefrontal cortex. Saint-Cyr *et al.* have found that Parkinson's disease and early stage Huntington's disease patients who have significant damage to the basal ganglia, unlike normal learners, typically show little improvement in a modified version of the Tower of Hanoi (Tower of Toronto) performance after considerable practice. This finding suggests that the basal ganglia (or at least the basal ganglia–prefrontal cortex circuit) is necessary for development of problem-solving skills.

With the development of more precise brain imaging techniques and a better understanding of the core cognitive abilities underlying complex problem solving, a much clearer picture of how the brain solves problems should emerge in the near future.

—Robert G. Morrison and Keith J. Holyoak

***See also*–Behavior, Neural Basis of; Intelligence; Learning, Motor; Learning, Overview; Memory, Working**

Acknowledgments

Preparation of this entry was supported by National Science Foundation Grant SBR-9729023 and National Institute of Mental Health Training Grant MH-1992605.

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Procháska, Georg (Jiří)

Encyclopedia of the Neurological Sciences

Georg Jiří Procháska, circa 1788 (from a painting by G. Kneipa in the gallery of the Dean and Professors of the Medical Faculty of Prague).

GEORG (JIŘÍ) PROCHÁSKA (1749–1820) was born in Moravia, which is now in the Czech Republic. The support of friends allowed him to study at the Jesuit Gymansium in Znojmo. The future anatomist, physiologist, embryologist, and ophthalmologist studied philosophy in Olomouc from 1765 to 1767. He began his study of medicine in Vienna in 1770 working with Anton de Haen, who recognized his skill in anatomical drawing. Joseph Barth, professor of anatomy, became his supporter after the death of de Haen. Procháska became professor of anatomy and ophthalmology at the University of Prague, performing some 3000 operations for cataracts in his lifetime. In 1791, he went to Vienna, where he remained until 1819 as professor of anatomy and ophthalmology.

His interests and publications covered the areas of blood movement, muscle and nerve structure, the generation and origin of monsters from epigenesis, and the abrasion of human teeth. His most important work was on reflex action as an example of nervous activity. His evaluation and systematic presentation of the work of his contemporaries on nerve function were vital to future researchers.

In 1779, Procháska determined that the fundamental structures of nervous tissue were globules by using the microscope. His most significant work was *Commentatio de Functionibus Systematis Nervosi (*1784). He endeavored to explain the workings of the nerves from observation rather than theory alone. This publication made him one of the outstanding physiologists of the nervous system of the 18th century and advanced Descartes' concept of the reflex as an entity for study. In this work, Procháska went beyond Whytt and other 18th-century scientists in the detail and precision with which he described how the nervous system is acted on by stimuli. The nerve force, the vis nervosa, coordinates all impressions passing to the individual nerve centers. He observed that this force is divisible. Severed parts containing these nerves would still display reflex reactions. He was a contemporary of Johann August Unzer and both men studied the concept of reflexes.

Procháska postulated the existence of two types of nerve fibers. One type conducts sensory impulses from the periphery of the body to sensortium commune—through the spinal cord, medulla oblongata, and crura cerebri to the thalamus—and is called gray matter. The other type of nerve conducts reflected impulses from the nerve centers to the muscles and other effector organs. These actions are independent of both the will and the soul. He drew a