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Problem Solving

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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, entertaining your children at a restaurant before the meal is served, diagnosing a disease, winning a game of chess, solving mathematical equations, deciding which smart phone to buy, managing a business, or even deciding what to write about in an entry on problem solving! 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.

Thus, competent problem solving requires the functioning of many brain areas. 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 on a running child amid a bustling restaurant. 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 writing a chapter on problem solving. 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 remember the complaints of a patient they diagnosed a week ago in order to diagnose a new patient.

While many studies using the methods of cognitive neuroscience have addressed the component processes important for problem solving, it is difficult to isolate single brain regions unique to problem solving. However, much effort has focused on understanding how the prefrontal cortex, particularly the dorsolateral prefrontal cortex (DLPFC) and frontopolar prefrontal cortex contribute. The prefrontal cortex seems to play a particularly general role in problem solving and related forms of thinking and reasoning, especially those that depend on analytic intelligence (the g factor) and cognitive 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. The functions Struss and Benson ascribe to the prefrontal cortex have also been described as the work of working-memory (the contents of our present conscious experience including their maintenance and manipulation).

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. However, modern theories of problem solving grew out of the information processing tradition of the 1960's, particularly the work of 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: 1) a description of the initial state in which problem solving begins; 2) a description of the goal state to be reached; 3) a set of operators, or actions that can be used to alter the current state of the problem; and 4) path constraints that impose additional conditions on a successful path to a 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, implementation of the problem space in the capacity limited working memory system places serious constraints on the methods for human problem solving. 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 the search through the problem space. 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, eliminating the need for extensive search in the problem space. Morrison and colleagues have found that the ability to use analogical reasoning is severely degraded in patients with damage to their prefrontal cortex. Numerous studies using both neuropsychological and neuroimaging methods have now confirmed that prefrontal cortex is critical in analogy for both the comparison process (i.e., analogical mapping) and also inhibiting the semantically similar, but relationally dissimilar contents of long-term memory.

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 using the Internet; thus, you set the subgoal of finding a computer or your smartphone to do the search. 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 discs and three pegs of different lengths. The experimenter places the discs 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 and colleagues 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 and colleagues have confirmed the role of the frontal cortex in problem solving for another task—chess playing—using neuroimaging 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 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. Using functional magnetic resonance imaging (fMRI), Koechlin and colleagues 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. Numerous neuroimaging studies have now implicated frontopolar cortex as being important for relational integration. Evidence also seems to suggest that the more relationally complex a problem the greater the involvement of more anterior areas of prefrontal cortex. Thus, frontopolar prefrontal cortex should become progressively more important as the number of subgoals increases.

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-Cyrl and colleagues 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 after considerable practice. This finding suggests that the basal ganglia (or at least the fronto-striatal circuit) is important for the development of problem-solving skills.

Recently researchers have begun to move beyond simply considering how separate areas of the brain are involved in problem solving to develop an understanding of how brain networks enable problem solving. New analysis techniques for neuroimaging data in cooperation with efforts to build neurally-plausible computational models of problem solving to help analyze these data, will hopefully yield a much clearer picture of how the brain solves problems in the future.

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Further Reading

Anderson, J. R., Albert, M. V., & Fincham, J. M. (2005). Tracing problem solving in real time: FMRI analysis of the subject-paced tower of hanoi. *Journal of Cognitive Neuroscience, 17*(8), 1261-1274. doi:10.1162/0898929055002427

Baddeley, A. D. (2007). *Working Memory, Thought, and Action. Oxford UK:* Oxford Univ. Press.

Bassok, M. & Novick, L. (2012). Problem solving. In Keith J. Holyoak and Robert G. Morrison (eds). *Oxford Handbook of Thinking and Reasoning*. New York: Oxford University Press.

Bunge, S. A., Helskog, E. H., & Wendelken, C. (2009). Left, but not right, rostrolateral prefrontal cortex meets a stringent test of the relational integration hypothesis. *NeuroImage, 46*(1), 338-342. doi:10.1016/j.neuroimage.2009.01.064

Cho, S., Moody, T. D., Fernandino, L., Mumford, J. A., Poldrack, R. A., Cannon, T. D., . . . Holyoak, K. J. (2010). Common and dissociable prefrontal loci associated with component mechanisms of analogical reasoning. *Cerebral Cortex, 20*(3), 524-533. doi:10.1093/cercor/bhp121

Duncker, K. (1945). On problem solving. *Psychol. Monogr.* 58, (Whole No. 270).

Fuster, J. M. (2008). *The Prefrontal Cortex, 4th Edition New York NY: Academic Press.*

Goel, V. (2005). *Cognitive neuroscience of deductive reasoning.* In K.J. Holyoak & R.G. Morrison (Eds.), *Cambridge Handbook of Thinking and Reasoning.* New York, NY: Cambridge University Press.

Green, A. E., Kraemer, D. J., Fugelsang, J. A., Gray, J. R., & Dunbar, K. N. (2010). Connecting long distance: Semantic distance in analogical reasoning modulates frontopolar cortex activity. *Cerebral Cortex, 20*(1), 70-76. doi:10.1093/cercor/bhp081

Holyoak, K. J., and Thagard, P. (1995). *Mental Leaps: Analogy in Creative Thought.* MIT Press, Cambridge, MA.

Koechlin, E., Basso, G., Pietrini, P., *et al.* (1999). The role of the anterior prefrontal cortex in human cognition. *Nature* 399, 148–151.

Kroger, J. K., Sabb, F. W., Fales, C. L., *et al.* (2002). Recruitment of anterior dorsolateral prefrontal cortex in human reasoning: A parametric study of relational complexity. *Cerebral Cortex, 12,* 477–485.

Monti, M.M., Osherson, D.N., Martinez, M.J., & Parsons, L.M. (2007). Functional neuroanatomy of deductive inference: A language-independent distributed network. *Neuroimage, 37*, 1005-1016. 10.1016/j.neuroimage.2007.04.069

Morrison, R.G. (2005). Thinking in working memory. In K.J. Holyoak & R.G. Morrison (Eds.), *Cambridge Handbook of Thinking and Reasoning* (pp. 457-473). New York, NY: Cambridge University Press.

Morrison, R.G., & Knowlton, B.J. (2012). Cognitive neuroscience of higher cognition. In K.J. Holyoak & R.G. Morrison (Eds.), *Oxford Handbook of Thinking and Reasoning.* New York: Oxford University Press.

Morrison, R.G., Krawczyk, D., Holyoak, K.J., Hummel, J.E., Chow, T., Miller, B., & Knowlton, B.J. (2004). A neurocomputational model of analogical reasoning and its breakdown in frontotemporal lobar degeneration. *Journal of Cognitive Neuroscience, 16,* 260-271. doi:10.1162/089892904322984553

Newell, A., and Simon, H. A. (1972). *Human Problem Solving.* Prentice-Hall, Englewood Cliffs, NJ.

Nichelli, P., Grafman, J., Pietrini, P., *et al.* (1994). Brain activity in chess playing. *Nature* 369, 191.

Owen, A. M., Downes, J. J., Sahakian, B. J., *et al.* (1990). Planning and spatial working memory following frontal lobe lesions in man. *Neuropsychologia* 28, 1021–1034.

Robin, N., and Holyoak, K. J. (1995). Relational complexity and the functions of prefrontal cortex. In *The Cognitive Neurosäences* (M. S. Gazzaniga, Ed.), pp. 987–997. MIT Press, Cambridge, MA.

Saint-Cyr, J. A., Taylor, A. E., and Nicholson, K. (1995). Behavior and the basal ganglia. In *Behavioral Neurology of Movement Disorders* (W J. Weiner, and A. E. Lang, Eds.), Vol. 65, pp. 1–28. Raven Press, New York.

Shallice, T (1988). *From Neuropsychology to Mental Structure.* Cambridge Univ. Press, Cambridge, UK.

Stuss, D. T, and Benson, D. F. (1986). *The Frontal Lobes.* Raven Press, New York.

Wharton, C. M., Grafman, J., Flitman, S. S., *et al.* (2000). Toward neuroanatomical models of analogy: A positron emission tomography study of analogical mapping. *Cogn. Psychol.* 40, 173–197.