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ABSTRACT

Various aspects of the cognitive model of physics problem solving are discussed in detail including relevant cues, encoding, memory, and input stimuli. The learning process involved in the recognition of familiar and non-familiar sensory stimuli is highlighted. Its four components include selection, acquisition, construction, and integration. The effects of experience, familiarity, cognitive factors, and information processing on problem solving is also discussed. It is concluded that the act of physics problem solving involves many different parts of the human nervous system and it is possible that in the future, the neurochemistry and neurophysics of the brain may explain what actually happens in terms of atoms, molecules, electrons, neurons, and axons in physics problem solving. Contains 12 references. (JRH)

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# ASPECTS OF THE COGNITIVE MODEL OF PHYSICS PROBLEM SOLVING

BY

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The solution of physics problems, in fact any problem in the environment begins in the cognitive system of the solver which begin in childhood. From the studies of memory development in childhood it can be seen that learning abilities steadily increase since memory constantly improves. The more the individual recognizes objects, patterns and concepts, the easier it is to learn new things about the relations and concepts between them or to use in new ways. The more concepts a child has, the more likely he is to comprehend new situations of any one concept and not be confused by other phenomena. The richer and more differentiated the network of the child, the more descriptions the child's brain automatically provides for fitting brand new events into known classifications and categories. This continuing process yields more connecting paths of the new situation into preexisting concepts of memory. Further, in part the child's memory gets better because they acquire not only memorizing skills, but also strategies which yield optimal results (g. Bower & E. Hilgard, 1981). Similarly, the child also learns what strategies and skills to apply to problem solving, recalling the appropriate strategies from the memory that has been built up. Harlow had also shown that building up learning sets in memory resulted in gradual learning of insight in problem solving and that with practice individuals gradually learn to avoid errors and to eliminate extraneous hypotheses (G. Bowers & E. Hilgard, 1981).

Therefore, experience in solving problems in physics, as well as in other subjects such as mathematics, reading and so on is dependent upon what is in long-term memory structures that relate to the physics problem. These structures have been built up as the individual deals with physics problem solving over a period of time.

In solving physics problems the problem solving process starts with a general search for relevant cues. This process is basically the same for expert and novices especially when much knowledge is immediately available for the construction of a model from which to work (Y. Anzai & T. Yokohama, 1984). If the solver is semantically sensitive to the cues in the physics problem to be solved, he will construct an experiential model internally, and then shift to a more scientific model--this is a process that happens if the solver in this situation is an expert. Which kind of model used depends upon the solver's attentional strategies based upon the solver's knowledge in memory. Novices also use this overall approach, but they often find it difficult to focus attention properly in elementary problem situations. Even experts at one time or another will experience difficulty when they encounter problems new to them and search their memories for relevant cues so that they can apply their physics knowledge successfully (Y. Anzai & T. Yokohama, 1984). The search for cues in memory begins with the perceptual process and the encoding of the physics problem content so that it can be brought to the long term memory via the selection process of the short term memory system which filters through and discards information from the problem.

In order to obtain a solution of a complex physics or chemistry problem the problem must be read and converted into a mental representation which is called encoding. After than relevant schemata for organizing and solving the tasks have to be engaged or activated. This is called a search in long term memory. Finally, the activated schemata must be shifted to short term memory, which is called retrieval, to be executed by a central executive. Therefore, the performance on word problems in physics (and chemistry) is a function of the amount and quality of schemata available in long term memory and, is also a function of the ability of short term memory to deal with the amount of data and kind of processes involved. The control and problem solving schemata, assembly and activation is dealt with, by the short term memory processes and is therefore extremely important in dealing with physics and chemistry problem solving (W. Roth, 1990).

In solving a problem in physics, the input stimuli obtained by reading the problem is entered through the sensory system and must be identified through a process called pattern recognition (M. Bell-Griedler, 1986). A physics problem is an exercise if the pattern is already in the long term memory. Actually, pattern recognition is thought to occur through feature analysis. The more features recognized by the memory, the more the problem becomes an exercise. One of the processes involved in feature analysis is called top-down processing where the input is matched to expectations so that the perception of the physics problem is fitted to what is previously known, more or less. The other process in feature detection is called data driven processing or bottom-up processing in which a mental structure is found in which to place the inputs as the problem is read (M. Bell-Griedler, 1986). Although some processes require no conscious control and are automatic, other processes are called deliberate because they require conscious control such as recognizing a physics problem. In a physics problem, the more the problem contains unfamiliar patterns, the more deliberate processing is needed. The more the problem is an exercise, the more automatic the processing becomes (M. Bell-Griedler, 1986). The more automatic the pattern recognition, the less attention is needed by the expert, and he is then free to deal with other aspects of the problem. Novices, on the other hand, feel pressed because their lack of fluency of automaturity causes additional strain.

In this process the individual is learning about the nature of the physics of chemistry problem to be solved. Involved in the recognition of familiar and non-familiar sensory stimuli is a learning process of four components according to M. Galle et al., 1990. These are:

1. Selection: The problem solver selects information from the problem that is impinging on the sense receptors and transfers it to short term memory where some of it is discarded.
2. Acquisition: The problem solver actively transfers selected information into long term memory.
3. Construction: The problem solver actively builds connections between the ideas that have reached short term memory and schemes in long term memory that hold specific and general problem solving information together.
4. Integration: The problem solver searches for prior knowledge, condition-action pairs called productions, in long term memory and transfers this knowledge to working memory. The problem solver may then build connections between the incoming information and prior knowledge.

The initial perception of a physics problem is dependent at least upon a person's experience with the problem such as age, previous physics and math background, familiarity solution strategies and familiarity with the problem context and content (R. Charles & F. Lester, 1982). Cognitive factors include the solver's memory, reading ability, analytical ability, logical ability, and spatial skill (R. Charles & F. Lester, 1982). There are also affective factors which include motivation. Many of these elements enter not only the solver's ability to initially deal with the physics problem, but also to find a solution as well.

In expert and novice experiments dealing with physics problem solving it has been found that in the expert's memory physical principles are not stored individually. Rather, physical principles are linked together and stored as "chunks." A chunk is "any stimulus that has become familiar from previous repeated exposure and is (therefore) recognizable as a single unit" (J. Larkin, J. McDermott et al, 1980). A person unfamiliar with the physics problem or relatively unfamiliar with the physics problem as compared to the expert, does not have such tightly linked "chunks." It appears that whenever the expert accesses from memory and applies one principle to the solving of the exercise, he should have all the other principles in the chunk immediately available to solve the physics problem. In the expert's mind, whenever one relation is retrieved from memory, all other principles connected with the chunk become available generated in a small burst or quanta of information. In fact, following a burst or quanta there may be another group of physics relations accessed from the memory as well (J. Larkin, 1979). Since the novice has his physics principles individually, due to lack of experience with physics problem solving and physical principles, and not in chunks or chunks with many other bits of information of various sophistications, the retrieving from memory of one principle does not make the accessing of other principles easier.

Due to experience factors as well as cognitive factors an expert physics problem solver knows many more things than a novice physics problem solver and can rapidly retrieve the necessary information needed to solve a physics problem. The expert's superior performance gives an experimenter a measure of the amount of perceptual knowledge which is measured in chunks or familiar patterns of physics problems held in his long term memory. The large group of perceptual patterns is like an index route, or access path, not only to the knowledge of the expert that is factual, but also to the expert's information about actions and strategies used in solving a problem or exercise in physics. Recognition of a pattern by the expert generates a memory of stored information consisting of actions and strategies that may be of use or pertinent to solving the problem (J. Larkin, J. McDermott et al, 1980). Information processing psychologists define the chunk as "the maximal familiar substructure of the stimulus" (R. Kail and W. Pelligrino, 1985). The capacity of activated human memory appears to be between five and seven chunks. From studies on problem solving in chess and hockey it also appears that while only a small amount of information can be activated at once, individuals with more experience have packed more information on each chunk. Although there are substantial limits on the amount of cognitive processing that can take place there are ways of by-passing these constraints. One way to increase functional capacity of the human processing system is to include more information in each chunk. This process is called recoding (R. Kail and W. Pelligrino, 1985).

Research has indicated that it takes approximately 40 milliseconds per chunk times five to seven chunks which is approximately a quarter of a second. If a person such as an inexperienced physics exercise solver were to scan memory inefficiently as is the case because much of exercise solving information is in small sized chunks or in individual units, the extra time needed would increase rapidly. This is why novice physics problem solvers take more time to solve the exercise correctly if at all, than do experts provided proper problem solving is available in the memory of the novice (R. Kail and W. Pelligrino, 1985).

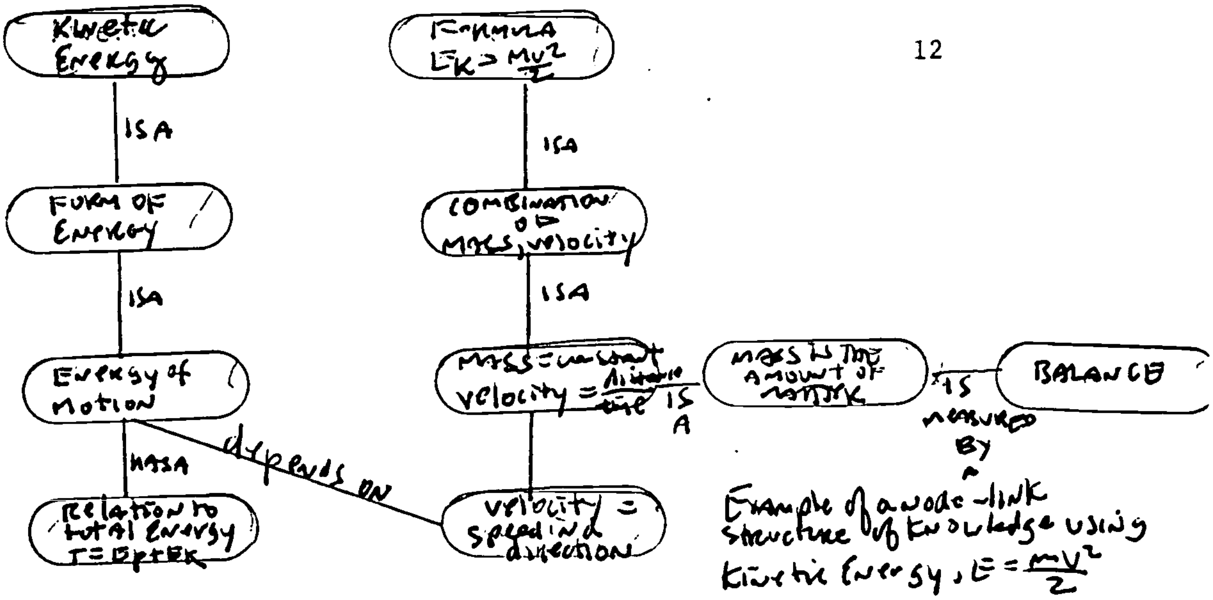
An expert in chess problem solving (called master or grand master) can recognize approximately 50,000 patterns on a chess board. Similarly, a physics problem solver knows many more things than a novice physics exercise solver and can rapidly retrieve the necessary information needed to solve a physics exercise or problem. The expert's superior performance gives the observer a measure of the amount of perceptual knowledge which is measured in chunks or familiar patterns held in his long term memory. This large group of perceptual patterns is like an index, or access route, not only to the expert's factual knowledge, but also to the expert's information about actions and strategies used in solving an exercise or problem in physics or chemistry. Recognition of a pattern by the expert generates a memory of stored information consisting of actions and strategies that may be germane to solving the problem or exercise at hand (J. Larkin, J. McDermott et al, 1980).

Although the construction of an expert's memory is not definitely known, it is though that the indexed memory is organized as a vast collection of productions. Each production consists of a condition and an action. In this model a stimulus satisfies the conditions of a person's production -- in other words, the brain contains a recognizable pattern. Once the condition evokes a recognizable pattern, appropriate action is immediately generated. The actions are stored in memory and the conditions are the index by means of which memory is accessed. Thus, condition-action pairs forming productions are really higher level counterparts of the classical behaviorist psychology concept of stimulus-response pairs (J. Larkin, J. McDermott et al, 1980). A model of physics exercise and problem solving considers exercise and problem solving as a production system in which a recognizable pattern in a physics exercise or problem elicits an action which it stores in memory. An expert has more of these condition-action pairs available in memory than does a novice.

In another model of human memory it is though that the memory consists of a complex organization of nodes connected by links. This combination of nodes and links is called a "list structure." According to this view, objects and components of objects correspond to nodes and relations of objects correspond to links. This model is based on the fact that "almost all computer simulations of cognition use list structures together with productions that can act on these list structures as their fundamental means for representing memory (J. Larkin, J. McDermott et al, 1980)."

The node and link structure concerning exercise and problem solving is vast in the expert and less so in the novice. Not only does the expert have a greater number of nodes or representation of physics problems, but also many more links or relations between physics facts and problems. The patterns or chunks the expert recognizes serve as an index to relevant portions of the knowledge store. This knowledge store consists of a vast set of schemata that allow the expert to interpret and analyze a physics problem or exercise, or make what is a problem for the novice and exercise for the expert.

The information processing approach to human knowledge is represented as a network in which conceptually similar entries are associated with each other. The network is basically associative and the entries are nodes linked together. There are different types of associations (links). For example: is a links can be used to denote category membership; can and has are used to denote properties of the node; further, shorter links denote more strength and longer links denote weaker strength. An example in physics could be the concept of kinetic energy and a portion of this network of nodes and links in human memory could look like the following:



Example of a node-link structure of knowledge using kinetic energy, $E = \frac{mv^2}{2}$

In the node-link representation a node could be a concept such as speed or velocity and another node could be the formula for velocity with the link between the two nodes a relationship that is the quantitative description. Also, another link could be factor analysis relationships such as looking for the value for distance and time elapsed. Another link between the two nodes could be the direction of the motion. These node-link relations are thought to be in long term memory in some form.

An aspect of the memory state of the expert as compared to the memory of the novice is the hierarchical organization of the knowledge structures and problem or exercise solving structures of the two differing memories. An expert has a knowledge block which describes the knowledge about the entire domain at the grossest level of description. The lower level knowledge blocks, obtained by successive elaboration, contain increasingly detailed descriptions of various aspects of knowledge described at higher levels. In this organization of memory, the higher level knowledge blocks are described in terms of abstract concepts. The lower level knowledge blocks are described in terms of more exactly defined concepts (F. Reif and J. Heller, 1982). Combining the node-link theory with the hierarchical model, the nodes in the expert are factual sites of a higher level and the links are relations between the higher level nodes. The relations are also at a higher level than in the novice whose nodes are at a lower level and the relations between the nodes are also not as all encompassing nor sophisticated.

The node-link and hierarchical models combined are together considered a cognitive structure called a problem schemata. That is, a problem schemata is a set of elements of knowledge that are closely linked with each other within the knowledge base of the problem solver. Each schemata concerns a particular type of problem or exercise. Chi et al, (1981) has found that experts tend to sort physics problems according to the underlying physics principle. Novices were found to concern themselves with the surface characteristics of problem situations. Experts would characterize a problem as a Newton's 2nd Law problem while novices would say that this is a pulley problem," for example.

The content of an adequate problem schemata in long term memory is not simply composed of solution principles. Besides declarative knowledge exemplified by principles, formulae and concepts, a typical problem schemata would also contain characteristics of problem situations so that there is a link between an actual physics problem and the problem schemata. A good problem schemata would also contain procedural knowledge which is knowledge about actions that are necessary for solving that particular type of problem. Finally, a completely adequate problem schemata tells the problem solver the stages the problem solver must follow which is like a plan to work the problem out -- a strategic type of knowledge. These strategies are general and their applicability is not limited to one type of problem or exercise. Thus, an expert who has a knowledge base organized with problem schemata can quickly select the proper declarative, procedural, connective and strategic knowledge from long term memory to solve a particular physics problem or exercise (T. De Jong and M. Fergusson-Hessler, 1986).

The nodes in an associate network refer to generic versions of concepts such as formulae, principles and concepts in a physics problem schema. The declarative knowledge, as this is called, can consist of prototypes which deal with general properties of physics problems. However, besides prototypes which are a means by which an individual can abstract the common elements of experiences that occur over time, there are scripts in the declarative knowledge memory bank. The activities involved in solving a physics problem or exercise which are temporarily organized events in a complex collection. An example of a script in solving a physics problem or exercise would be using the factor analysis method: 1) write down what is known; 2) remember the proper formula; 3) use a method to solve for the unknown quantity that is desired; 4) substitute the values known for the symbols in the problem or exercise; 5) calculate the answer (this could be done by calculator or by hand). A sixth step could be check answer if available. In solving a physics problem or exercise the situation of the problem would be completely unintelligible if the memory consisted only of specific experiences.

In procedural knowledge, production systems come into play. These productions include algorithms which will always result in the correct answer and heuristics which are general problem solving strategies.

Chi et al (1981) had determined that expert problem solvers in physics had differently organized knowledge bases than novices. It appears that experts tend to sort problems according to the underlying physics principles and novices in contrast attended to the surface characteristics of the problem situations. From this information and other studies, they inferred that the knowledge of an expert is structured differently than novices. The experts possess more complete and adequate problem schemata. Chi *et al* (1982) contended that a cognitive structure adequate for problem solving is composed of *problem schemata*. They defined a problem schemata as a "set of elements of knowledge that are closely linked with each other within the knowledge base of the problem solver and that concern a particular type of problem" (De Jong and Ferguson-Hessler, 1986). De Jong and Ferguson-Hessler (1986) have gone further, however, and maintain that the content of an adequate problem schema in memory is not limited to solution principles.

There must be declarative knowledge in long term memory such as principles, formulae and concepts, but also a problem schema should contain characteristics of problem situations so that a connection between an actual problem and the problem schema is possible as suggested by Schoenfeld and Hermann (1982). It should also be pointed out that Reif and Heller (1982) have taken another approach and suggest that the knowledge of experts is organized in hierarchical fashion, and this means that their knowledge is arranged on different levels of detail so that the higher levels give abstract and general laws and definitions which are manifested and specified at the lower levels. De Jong and Ferguson-Hessler (1986) tested novice and expert problem solvers and found there is support for the hypothesis that novice problem solvers have their knowledge organized in a more problem-type centered way than poor problem solvers. Once a student recognizes the relevant characteristics in the description of the problem. the declarative and procedural knowledge needed for the solution become available assuming the student has knowledge of the physics and required mathematics.

# CONCLUSION

In conclusion, the act of physics problem solving involves many different parts of the human nervous system. On one level is the flow chart and informational processing level. This view contends that the educational psychology of physics problem solving should stress the importance of a logical system of interacting parts, not the specific details of the neurological aspects of the physics solving. They contend that the main question is a description that gives an adequate explanation and has predictive properties of the physics problem solving process. It is possible, however, in the future, that the neurochemistry and neurophysics of the brain may explain what actually happens in terms of atoms, molecules, electrons, neurons and axons in physics problem solving. From contemporary experimentations and theory it is clear that physics problem solving is rapidly being understood at least at the information processing level.

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