

## **Expertise, Pattern Management, and Decision Making: Challenges in Human Informatics**

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### **Abstract**

*This position paper explores the challenging area of cognition among experts and suggests possible reasons why experts have difficulty explaining how they make decisions in complex and constrained environments. We propose a theory of expertise and decision making that we call the Pattern Management/Mental Reference Frame (PM/MRF) model. The main premise of this theory is that experts use pattern management, including pattern recognition, dynamic pattern matching, and pattern editing to form solutions to complex problems. The theory identifies symmetry, centers of gravity, task reduction, and enhanced mental reference frames as important elements of decision making. The PM/MRF model is compared to other models and frameworks that explain cognition. The paper concludes with a discussion of future challenges in human informatics, including the need for a novel experiment or series of experiments designed to distinguish between various theories and models of cognition, and the challenge to expert systems developers to find novel methods to capture more of experts' decision-making processes in artificial-intelligence systems.*

**Keywords** – Cognition, decision making, expert system, expertise, knowledge acquisition, pattern recognition

### **1. Introduction**

The motivation for this paper is a desire for a better understanding of how experts make decisions in complex and constrained environments, with a view toward better experiments to probe human cognition and better knowledge-acquisition techniques to develop expert systems. (See, for example, [2] and [5]). The paper is organized as follows: Section 2 discusses the role of task reduction in expert decision making. Section 3 describes a cognitive theory of expertise and decision making, including pattern management, symmetry, task reduction, centers of gravity, hyperpatterns, and mental reference frames. This theory is called the Pattern Management/ Mental Reference Frame (PM/MRF) model. In section 4, the PM/MRF model is compared to other decision models and frameworks. Section 5 concludes with future challenges in human informatics and expert systems.

### **2. Factors in expert decision making**

Experts constantly need to make complex decisions rapidly. All experts rely primarily on their cognitive processes to direct information collection, analyze data, make decisions and act on those decisions. The ability to make sound decisions rapidly is easy to recognize and demonstrate. However, to capture and explain how experts make rapid, complex decisions is much more difficult. Metacognition is equally difficult, regardless of the quality of the observed decisions. For example, bad decisions generally are no easier to analyze, explain, and document than are good decisions. When decisions are faulty, explaining the factors that led to a conclusion, and finding the particular factors that led to incorrect decisions, are very difficult for most people. When asked to explain a decision, most people immediately can identify salient features of the information that support their decision. They generally find it very difficult, however, to generate rapidly a very thorough list of salient facts and/or to establish the relationships between them. Experts can solve problems, but they have difficulty explaining exactly how they solved any given problem. Furthermore, a thorough explanation of how one decision was

reached in a specific case, generally, falls short of providing a general solution that will cover all cases. This is a key factor in the knowledge-acquisition bottleneck that knowledge engineers face when they build expert, knowledge-based systems.

Kirlik, et al. have suggested that task-simplification strategies based mainly on perception and pattern recognition are fundamental to the novice-expert shift in dynamic decision making [8]. Task reduction is the process of taking a complex problem and reducing it to a series of less and less complex tasks until a relatively simple problem remains for which we have enough information to reach a conclusion. Each reduced task, which represents a step in the problem-solving method, could involve the application of an algorithm or heuristics [1]. Task reduction is a powerful method of documenting and representing decision-making processes, but the approach has documented weaknesses as well as strengths. Task reduction as a problem-solving methodology is well understood and documented in fields such as systems engineering. Its use in knowledge acquisition is widespread but not dominant. An expert attempting to capture all of the steps and factors in solving a complex technical problem almost never initially generates a complete and accurate list. One of the key challenges of expert-systems research is the collection and representation of this type of decision-making information.

### 3. A cognitive theory of expertise and decision making

The PM/MRF model aims to characterize what experts do when they make decisions, particularly in difficult, time-critical situations. Analyzing, documenting, and checking the finer details of the decision-making process is not natural for experts, even if they also routinely teach their subject area expertise to students. Even then, many experts deemed to be the best and brightest in academia have a very difficult time translating what they know into the words, diagrams and explanations necessary to pass this information on to their students. Whereas teaching a subject may increase the knowledge of the teacher about that subject, it does not necessarily follow that the teacher will be able to find better explanations of the subject matter, particularly for advanced classes. For example, Maestro Andres Segovia's musical ideas seemed incomprehensible even to gifted students in his master guitar classes [10]. Grasping the subtleties of the "Segovia sound" was very difficult for these young players even after his repeated attempts to explain them [10].

*Ex post facto* justifications are easier for experts to provide for their solutions to problems than are reliable descriptions of how they arrived at these solutions [1]. Why can't experts explain what they do and how they make decisions? When experts make decisions, they often deal in a realm characterized by complexity and uncertainty with many interacting variables that are not necessarily independent of each other. The variables all may be connected or correlated in ways not readily apparent to the novice. Many experts evaluate conditions and make decisions based on a great deal of information that is presented to them during a very short time interval. What was appropriate in one context may be inappropriate a few seconds later because of a rapidly changing context.

#### 3.1 Mental reference frames and decision complexity

According to our PM/MRF model, constant exposure to complex problems causes new thought patterns or mental "pathways" to be developed and new concepts to be defined that are not easily verbalized, especially with regard to a complete description. These new pathways lead to new mental reference frames (MRF's) that are, for lack of more precise terminology, "regions" or "configurations" in the mind that are analogous to a change of coordinates in solving some mathematical problems. These MRF's are nonverbal and allow certain complex constructs to be identified, aggregated, used, and manipulated as unit entities rather than as components. The relationships between the components induce and represent additional concepts not contained in the sum of the components. Moreover, the construction of these complex entities goes on subconsciously as a byproduct of learning, and their formation may not come to the direct attention of the expert in training, i.e. they may escape metacognition. (See, for example, [4]).

The complexities of such a learning process and practice do not lend themselves to clear, linear, and verbal explanations. When experts attempt to describe their mental activities, several things happen:

- The expert must shift to a mental paradigm that is conducive to the analysis of concepts as sums of parts. This form of task reduction is unnatural and it puts the expert at a disadvantage, as the relationships between the parts are important. When making decisions, experts must put themselves in a mental state conducive to solving problems in a complex domain. This is not likely to be an entirely verbal mode of cognition.
- Some parts are more easily described than others are. However, some parts never are verbalized and thus are lost to the listener.
- The most intriguing, elegant, and, in some cases, essential aspects of complex concepts are the first to be lost when attempting to describe or demonstrate them verbally, acoustically, or graphically.

These reasons act together as powerful deterrents to experts who attempt to describe the subtle details of what they do. These reasons also explain the observation that we cannot communicate or transfer these skills easily and verbally during training sessions.

The acquisition of expert skills involves the ability to access at will these MRF's as easily as one would open a desk drawer. For accomplished and proficient experts, transition to an enhanced mental reference frames (EMRF) is so effortless and natural they do not notice the transition because they have forgotten how difficult it was to acquire the skill. They have difficulty describing such a state as well as the activities that take place while in that state. When novices ask how they learned their skills, experts frequently will not be able describe much detail and will just say "experience." Moreover, when experts attempt to furnish explanations, they may use terms for which they are unable to give clear definitions [1], especially when explaining their own metacognition.

Being able to understand, study, explain, and use these concepts may lead to better teaching methods for experts and may assist students in understanding what they are doing when they finally "get it." However, knowing it and describing it scientifically will not necessarily make access to the EMRF any easier, just as understanding the acoustics of the singing voice does not enable one to become an accomplished singer. (See, for example, [9] and [11]). In our attempt to understand EMRF's through metacognition, we need to identify a method to recognize when experts are in one of these states. The challenge is to describe EMRF's at the same level of detail comparable to the manner in which the singing voice has been described acoustically. (See, for example, [9] and [11]).

### **3.2 Pattern management, dynamic pattern matching and pattern formulation**

According to our model, *pattern management* is key to higher levels of cognition and at higher and more sophisticated EMRF's. Decision making is associated very closely with pattern recognition and the subsequent manipulation and editing of patterns. We hypothesize that pattern recognition, like creativity, sometimes is best understood and taught through analogy and examples, due to experts' difficulty in offering explanations. Leadership training in decision making requires exposure to and study of many examples. This, according to our hypothesis, is to formulate the pathways to the MRF in which the patterns constitute fundamental building blocks (vs. a collection of components) that contribute to a solution. Many examples are needed to form the complex concepts through repetition and to be sure that rare but important examples are included in the training.

Pattern management plays a key role in decision making. However, strictly and rigidly matching candidate patterns to fixed, static, stored mental patterns is at best an incomplete concept to explain how experts use pattern recognition in making their decisions. This has prompted Cohen, et al. to conclude that straightforward pattern recognition is not the whole story [4]. The concept of pattern matching must be expanded to include the notion of *dynamic pattern matching*, a step in the pattern-management process, which is much more flexible and fluid than classical pattern matching, and which is part of the PM/MRF model. Pattern management is consistent with the idea in [8] that the major difference between novice and expert may not involve only domain rules, but also the ability to extract information rapidly and accurately from the environment that allows experts to use their knowledge in particular situations.

In dynamic pattern matching, the expert may formulate the solution to a problem by combining parts of several patterns, each of which matches a portion of the problem, rather than by finding a single, stored pattern that exactly matches the problem at hand. Dynamic pattern matching is much more suited to making decisions in complex domains that feature many variables, the aggregate of which can give rise to a wide variety of patterns. Here, the human mind can do efficiently what is difficult for computers – the editing and composing of existing patterns to make a new, unique pattern that better fits the unique problem at hand. The expert needs a mental repository that can store many verbal, visual, auditory, non-verbal, non-visual, and non-auditory patterns. These could form the building blocks for complex mental images and patterns that define, for example, an attack strategy, a disease, the modus operandi of a criminal, or a musical idiom. To function in their domains, experts need a way to compare, contrast, categorize and manipulate these complex mental images with respect to the current task. The mechanics of these mental processes are not always evident to the expert.

Part of becoming an expert consists of establishing memory cues to evoke knowledge when it is needed [1]. The concept of memory cues fits well into the framework of pattern management. Memory cues are like indices for retrieving patterns and pattern components. Collections of cues can constitute patterns. A "story" also constitutes a pattern. Expertise is related to recognizing salient dimensions and features, including the symmetry, of a pattern that demand the focus of attention and applying that focus to the stages of pattern management.

Pattern management is consistent with the idea in [8] that the major difference between novice and expert may involve not only domain rules, but also the ability to extract information rapidly and accurately from the environment. Part of this extraction process is pattern recognition, which plays an important part in the insights into decision making in domains such as the military, medicine, manufacturing and law-enforcement. A flash of insight occurs when the correct pattern is recognized, regardless of whether this exact pattern has been observed before. The correct pattern for a unique solution to a problem need not consist of only static components of other patterns, but of modified components from the "library" of patterns, especially tailored to fit the unique problem at hand. Dynamic pattern matching and formulation explain the creativity of experts to deal with new situations. Pattern recognition, dynamic pattern matching, and pattern editing are

integral parts of pattern management. These are similar to the recognitional processes and the situation awareness described in [7]. Experts test a dynamic pattern by mentally applying it as a solution to a problem. They, then critique and correct it in a manner similar to that described in [4] and [7]. If the pattern results in a successful outcome, it is reinforced and enters the pattern “library.”

### 3.3 Hyperpatterns and metacognition

We hypothesize that the process of decision making depends predominantly on pattern management, which includes pattern recall, recognition, manipulation, modification, formation and reassessment. This can be understood in terms of hyperpatterns. A hyperpattern extends the idea of static spatial and temporal patterns to dynamic, editable patterns and partial patterns (with some but not all features present). Experts can use metacognition to examine and evaluate the pattern-editing process to produce new, unique patterns that can be used to respond to novel situations. Experts critique and correct the pattern being edited to match it to the ideal pattern that corresponds to the desired, optimal solution with all or most of its requirements satisfied.

As explained in [4], experts decide whether to think more about a pattern or to act now. This decision will depend on the completeness of the pattern match, the usefulness of further pattern comparison, and the time remaining in which to make a decision.

Dimensions of patterns can have complex interactions. For example, the spatial configuration of a complex, dynamic pattern may be time dependent. We hypothesize that being able to analyze and manipulate patterns along multiple dimensions simultaneously is a critical step in acquiring expert skills in any field. This hypothesis is consistent with the suggestion of Kirlik et al. that pattern recognition plays a fundamental role in becoming an expert decision maker [8]. Individuals in general and experts in particular rely on heuristics [8], which are also patterns. Analytical models consist of patterns, dynamic or otherwise.

### 3.4 Pattern symmetry and centers of gravity

The notion of symmetry pervades all of science and engineering, from molecules to solar systems. An analysis of the symmetry of an object can contribute to the identification of its center of gravity. A problem can be made more straightforward to solve in proportion to the appropriateness of its definition. Calling attention to symmetry in the problem’s definition can be the key to suggesting a solution. For example, if one can identify the center of gravity, the situation is comprehended easily, an additional element of control is gained, and the task is simplified.

Symmetry’s contribution to pattern recognition is evident in the field of chemistry. The identities of many chemical structures, particularly benzene ( $C_6H_6$ ) and buckminsterfullerene,  $C_{60}$ , have been determined by using the power of symmetry. (See, for example, [6]). In the case of benzene, Kekule’s dream was said to have suggested a ring structure. In the case of buckminsterfullerene, only a highly symmetric structure in which each carbon atom has the same chemical environment could explain the single peak in the  $C^{13}$  nuclear magnetic resonance spectrum.

A grasp of the centers of gravity that pertain to various situations can affect an expert’s ability to make correct decisions. For example, in manufacturing, correctly estimating the center of gravity of a new, complex, and heterogeneous object and developing a strategy and procedure to lift, rotate, and transport it safely without damage to the object, personnel or the other objects in its vicinity is the hallmark of skilled crane riggers who have access to their EMRF’s.

Symmetry and centers of gravity also play an important role in battle planning for the military. Information on centers of gravity, whether the center of gravity pertains to a physical object or a battlefield scenario can make the solution to a problem more straightforward. If one can identify the center of gravity, not only in crane rigging but also in military planning, one can take control of the situation with a minimum of effort and expenditure of resources. Objects, as well as less tangible entities such as the course of a battle, revolve most easily about their centers of gravity. The military, especially the Army, uses the concept of a center of gravity in determining courses of action. (See, for example, [3].)

Symmetry is an essential element of pattern recognition. Understanding and recognizing symmetry contributes considerably to an expert’s ability to reduce task complexity. Symmetry recognition is a form of pattern recognition, and the use of symmetry in problem solving is a form of task reduction. A more comprehensive understanding of symmetry and the multiplicity of ways in which it can occur may be a key element of knowledge that distinguishes an expert from a novice.

### 3.5 The relationship between task reduction and pattern management

Task reduction and pattern management have a synergistic relationship. First, pattern management enters the picture before any task is reduced. The expert must understand the whole task, recognize it as a pattern or as a collection of patterns, and identify the parts of the pattern that can “stand alone,” at least temporarily, as reduced tasks. The expert must then divide the complex task into smaller tasks that each can be performed as a unit; have a lesser degree of complexity than the original task, and relate to the total task to preserve the continuity and relationships between task component. This must be done so that the entire task that constitutes a solution to the original problem can be reconstructed from the solutions to the reduced tasks.

Second, task reduction can be seen as the part of the pattern-management that occurs when patterns are edited to form new, unique patterns. Task reduction is an activity that fits into the pattern-manipulation stage of pattern management. Thus, pattern management contributes to task reduction, and task reduction contributes to pattern management. The fact that task reduction is needed at all implies that many complex patterns, the recognition of which could be categorized as “flashes of insight,” are difficult for the novice to capture and master rapidly. This situation implies an insight-acquisition bottleneck.

## 4. Comparison of the PM/MRF model to other decision models and frameworks

The PM/MRF decision model is similar to the Recognition-Primed Decision (RPD) model [7] because both include pattern recognition. RPD and PM/MRF also includes the concept of *situation awareness* because situation awareness involves perception and comprehension of elements in the environment [7] (e.g. pattern recognition) and an understanding of their anticipated status in the near future [7] (e.g. pattern manipulation and editing).

The evidence derived in studies [7], [4] supports the extensive use of pattern management in making decisions. For example, Kaempf et al. conducted a study [7] in which 87 percent of the stages of situation awareness were developed through feature matching (e.g. pattern recognition) and 12 percent through story building, which is a process analogous to the pattern formation and editing. The processes that AEGIS decision makers invoke are consistent with the RPD model in [7]. However, this evidence supports not only RPD model, but the PM/MRF decision model as well.

The PM/MRF model also can be compared to the model described by Cohen, et al. [4] where they define metacognitive skills as “verifying and improving the results of pattern recognition in support of decision making in novel and uncertain situations.” In a similar vein but with a more comprehensive concept of patterns, we propose that experts use metacognitive skills to manipulate, modify, and edit patterns (after they recall and recognize these patterns) to produce a new and unique pattern designed to fit a novel situation. These two views, while not diametrically opposed, are based on fundamentally different assumptions about the nature of patterns.

Whereas both agree that pattern recognition and metacognition play central roles in the design of new solutions for novel problems, our view of patterns covers all of the elements of Cohen, et al.’s [4] framework that they call the “recognition/metacognition (R/M) model” and covers additional ground. For example, [4] describes going beyond pattern matching to create plausible stories for novel situations. We maintain that the creation of plausible stories for novel situations is simply the next step in pattern management. In the PM/MRF model, this step constitutes a shift from pattern matching to pattern editing and the composition of new patterns from elements of old ones that were recalled and recognized as being relevant to the situation at hand. The R/M model explains how experts exploit their domain experience while dealing with uncertainty and novelty [4]. However, it is by no means the only explanation of these phenomena. Whereas we generally agree with the conclusions of Cohen, et al. [4], we think that the time has come to take the next step in the characterization of pattern management by experts and to offer an alternate explanation of how to arrive at these conclusions.

We hypothesize that the ability to edit new patterns partly depends on the number of ways to divide existing patterns into components, i.e. the number of dimensions and aspects of patterns that can be analyzed. For example, an expert may be able to divide patterns along a multiplicity of dimensions according to the pattern’s attributes and characteristics, whereas a novice may not be readily aware of the many variables that pertain to patterns. Selecting the correct dimensions is as important as selecting the correct components after performing the divisions. It relates to the selection of the correct reference frame (e.g. coordinate system) that makes the solution to the problem more straightforward.

Noticing conflicts between observations and a conclusion [4] just amounts to comparing the pattern of observed events and cues to the pattern created mentally that summarizes the expert’s conclusion. We observe that all metacognitive skills described by Cohen, et al. [4] that are present in proficient decision making can be reduced to patterns – recognizing, comparing, editing, dividing them into components and producing new patterns.

Whereas the PM/MRF model is more comprehensive in its explanations of the decision making process than are some other models and frameworks, the experimental evidence to date supports multiple theories, models, frameworks, and explanations. For example, the R/M framework [4] explains some of the same observed behaviors as the PM/MRF model. This evidence is insufficient to favor the PM/MRF model presented here over previously described models, frameworks, and

theories. Therefore, a major challenge in the area of cognition theory is to design research that can distinguish between the various proposed models, frameworks, and theories of decision making (e.g. RPD, R/M, PM/MRF, etc.). This research should be designed to show whether one of these models is more correct than are the others.

## 5. Future challenges

Several challenges remain in the areas of expert cognition, human informatics, and expert systems. One challenge to cognitive psychologists is to formalize the inquiry into the comparison between the various models and frameworks that offer explanations of cognition. The main problem here is to develop experiments and other studies to probe the differences between models to attempt to identify the model that is the most comprehensive and accurate. If this cannot be done, the alternate challenge is to show how models are equivalent, i.e. to demonstrate that the models actually are different ways to describe the same phenomena, as opposed to the models addressing different phenomena, per se.

A challenge to expert-system developers is to construct expert systems that can simulate the manipulation of patterns dynamically using similar techniques that experts use mentally. A major challenge to knowledge-base developers is to devise a novel method to capture the kind of expertise that is difficult for experts to describe, such as dynamic pattern manipulation, in a knowledge base. This will require more expressive knowledge bases, inference engines, and human-machine interfaces than those available today. Perhaps more importantly, it also will require a paradigm shift in the way humans interact with computers. Part of that challenge consists of improving artificial-intelligence systems to the point where they can acquire, represent, store, categorize, index, retrieve, and manipulate large numbers of patterns and pattern fragments in an efficient manner that will enable the rapid management of patterns that is necessary for expert decision making. This is especially challenging when one considers that a complex pattern could consist of a visual part, an auditory part, and a non-physical part. Advances in parallel processing may contribute to an extent in this area.

Clearly, it will be necessary to look across broad fields of science, engineering, and technology to find solutions to these problems. Whereas some will argue that we will never get to this point, others call attention to the impossibility of the World Wide Web 100 years ago.

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