Development of Expertise in Complex Domains

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Abstract

It is necessary to understand how human planners' performance evolves over time with increasing expertise in order to develop effective computer critics, tutors, knowledge acquisition systems, and training strategies. In this paper we present two studies of the development of expertise in complex domains: manufacturing planning and software development planning. We had experts in each domain rank order the plans created by practitioners at various levels of experience from best to worst quality. We did this to assess whether practitioners really did gain skill with increased experience in both of these fields or whether experts were "self proclaimed". Next, we analyzed the spoken statements of the practitioners to identify the knowledge and problem solving strategies they used or lacked. We used these data to model the skill development phases in each domain. These models can be used to develop computer tools and training strategies to help practitioners achieve higher levels of competence.

1. Introduction

In order to develop helpful training strategies and computer tools for assisting planners, it is important to understand what skills they develop as experience increases and in what order they need to develop these skills. In this paper, we will examine the development of planning expertise in two complex domains, the creation of manufacturing plans for the fabrication of parts and the creation of software development plans. Even though many theories have been published on software project management such as Cave and Maymon [2], Baker [1], Pressman [6] and many computer tools have been written to help managers with pieces of the task Simpson [7], managing a large project still remains a daunting task. Parts fabrication is another domain in which practitioners must develop a high degree of expertise in order to be competent. Machinists spend years in apprenticeships developing expertise in all areas of the problem solving, Hayes [4]. We examined practitioners at many levels of experience in both of these domains. Each practitioner solved several problems and we recorded all of their spoken statements as they solved the problems. Next, we had experts in each domain rank order the plans created from best to worst quality so that we could assess whether practitioners really did gain skill with increased experience in both of these fields. Lastly, we examined the spoken statements of the subjects to identify the types of knowledge and the problem solving strategies they each used or lacked. We used this information to create models of the development phases in each domain. By understanding what practitioners do or fail to do, we can develop computer tools and training strategies that can help practitioners to achieve higher levels of competence sooner by filling those knowledge and skill "gaps".

2. Background

In this study, we examine two domains: 1) the development of manufacturing plans for the fabrication of parts and 2) the creation of software development plans.

Software Development Domain: In the software development management domain, the task of the manager is to create a schedule for a new project or update an existing one, which may be behind sched-
ule or over budget. The initial state of the problem consists of all of the information available to a manager, possibly including the current staff assignments, current schedule, budget, requirements, charges to-date, and progress to-date. The manager must develop an updated budget and schedule that shows what steps will need to be taken in order to finish on schedule and within budget. The new plan may include an updated requirements document, an updated customer contract as well as a detailed schedule and budget. In order to accomplish these goals, the manager uses many techniques to understand the situation and determine the proper course of action. Some examples of these techniques include: analysis of charges to-date to determine how money has been spent, requirements analysis to find where the problem occurred and negotiation of the schedule, and budget or requirements changes with the customer. Once the plan is in place, the manager must constantly monitor the project and re-plan when necessary. Figure 1 shows an example of the initial state, goal state and some of the techniques needed for a software development plan.

Part Fabrication Domain: In the domain of part fabrication, the task is to create a manufacturing plan to produce a particular product efficiently. This study examines planning done in small job shops in which only one or a few copies of any given part are made. The machinist is given a piece of metal and a drawing of the part. The machinist must develop a plan consisting of a series of processing steps using available machines and tools to create the part from the given piece of metal. The machinist first needs to understand the specification of the part he or she has been given and the properties of the material to be used. The machinist creates a plan to fabricate the part through a series of machining operations such as drilling, milling, etc. There are two major sub-plans within the overall plan. First, the machinist must "square" the material. This involves making all of the sides perpendicular to the adjacent sides. The other sub-plan involves creating the specified features, such as holes and angles. Figure 2 shows the initial state, goal state, and a partially ordered list of techniques to be used in a plan to machine a given part.

3. Related Work

Two areas that are related to this work include research into project management and project management tools and the research on expertise. Many different project management methodologies have been developed such as the classic project life-cycle described by Cave and Maymon [2], rapid prototyping strategies described by Pressman [6], and case-based development described by Baker [1]. Others have described how new computer tools, such as scheduling systems and spreadsheets, can assist software development management Simpson [7]. These methodologies concentrate on the development and scheduling of technical requirements. It is crucial to understand the technical requirements, but it is impossible to fully understand the technical requirements without knowing how to fully investigate all aspects of the project including the customer and corporate motivations for the project. None of these methodologies directly address the techniques necessary to understand these aspects of the problem.

Several models of expertise have been proposed. One of these models was developed by MacMillan, Entin and Serfaty [5]. They studied the behaviors of military planners with varying levels of experience. They suggest that all of the participants were creating plans by remembering past cases and then modifying the cases. The more experienced participants were able to extract more information from the situation and considered more aspects of the problem in their solutions.

The military planning domain is similar in complexity to software development management and parts fabrication. Therefore, it is not surprising that similar types of plan weaknesses were found in this study. The more experienced the software development manager, the more critical parts of the problem were identified. MacMillan, Entin and Serfaty did not consider...
Another model of expertise, proposed by Dreyfus and Dreyfus [3], described a five stage development model of expertise. They suggest that these stages hold for both routine and non-routine tasks. In the first phase, the novice learns rules and facts about the domain. In the second stage, the subject learns that situations can be identified by combinations of facts. In the third stage, the subject develops his or her own rules for deciding on the proper course of action. In the fourth and fifth stages, subjects remember many past situations and intuitively choose an appropriate course of action with increasing ease.

Our multi-step models of expert development can be contrasted with the model proposed by Dreyfus and Dreyfus [3] in that experts in the domains of parts fabrication and software development manage to create plans in a generative fashion while the approach suggested by Dreyfus and Dreyfus suggests a case-based approach. Although a case-based approach may be appropriate for some domains, experienced managers and machinists used past experiences to help them choose individual technique to solve small pieces of the problem, but did not try to apply a plan for a past task to the new problem.

4. Methods

In each of the domains, two groups of subjects were used: problem solvers and judges. The group of problem solvers in each domain was made up of volunteer practitioners having various levels of experience. Two judges were identified in each domain. Each of the judges had more experience than any of the subjects (15 plus years). Each group of problem solvers were given a set of problems and were asked to speak aloud as they solved them. Each of the problem solving sessions was recorded and transcribed. The two expert judges were asked to review each of the plans created, comment on their relative strengths and weaknesses, and rank order them from highest to lowest quality. The transcriptions were analyzed to identify the knowledge sources and skills used by each problem solver and to identify how these skills changed with increasing experience.

Software Development Domain

**Problem Solvers:** In the domain of software development management, eight subjects were used with experience ranging from two years (as a team lead) to sixteen years in management. The managers came from four different large companies. All four of these companies specialize in software development.

**Judges:** Two different expert software development managers served as judges for this project. Each had more than twenty years of experience.

**Software Development Tasks:** The problem solvers were each given two problems. The first involved a new contract the second involved taking over a project in progress that was behind schedule.

**Procedure** Because the problems solvers come from four different companies at five different locations, all of the protocol analysis sessions were held over the phone. The problem statements were sent to them by mail in advance with instructions not to read the actual problem before the “talk aloud” sessions. The sessions were recorded and analyzed in the manner described above.

Parts Fabrication Domain

**Problem Solvers:** Seven subjects (machinists) with experience levels ranging from two to ten years were used in this study. They came from a variety of industries and machine shops.

**Judges:** Two expert machinists judged the plans. They had fifteen and eighteen years of experience respectively.

**Tasks:** The problem solvers were asked to create manufacturing plans for three different machined parts. The plans were to be executed on a 3-axis machining center. Machinists were given a drawing of each part, the stock material from which the part would be made, and a list of the tools.

**Parts Fabrication Procedures:** The machinists were each given three problems and asked to “think aloud” as they created manufacturing plans to fabricate each part. Each session was recorded and transcribed, the plans ranked, and the transcriptions analyzed to determine skills used, as above.
5. Results

Changes in Plan Quality with Experience

The results for the software development managers are shown in Figure 3 and for the machinists in Figure 4. Both graphs show the average quality of the plans created versus the years of experience of the practitioner. The average quality of the plans was computed by averaging the rankings given to each of a practitioner’s plans by the judges.

Software Development Management: There is a non-linear relationship between plan quality and experience which is statistically significant at the 1 percent significance level. The graph showing the data points and the fitted curve is shown in Figure 3. The correlation between the years of experience and the average plan quality is 0.89.

Parts Fabrication: There is a linear relationship between plan quality and experience for machinists which is statistically significant at the 1 percent significance level. The line representing this relationship and the data points are shown in Figure 4. The correlation between the years of experience and the average plan quality is 0.91.

A non-linear function was found for the manager data while a linear function was found for the machinist data. However, this does not necessarily indicate that the development of expertise follows fundamentally different functions in the two domains. It may simply be a reflection of the fact that the machinists examined had a narrower range of experience (2-10 years) and the function may appear linear in this range.

Figure 3 shows that new managers improve very rapidly initially. This may be because software development managers are often given a great deal of responsibility immediately. If they do not learn quickly, they are removed from management. One of the less experienced managers performed much better than expected for his level of experience. It is possible that he is exceptionally talented, however it is also the case that one of the test problems was very similar to the project on which he worked.

Development Stages in Planning Expertise

The structure and characteristics of the plans created and the recorded statements of the planners were examined in order to develop a model of the development of planning expertise in each domain. The stages of development in the two domains were similar, but not identical. We identified four phases for software development managers and five for machinists. One possible reason for the difference in the number of stages of development in the two domains is that because managers are given more responsibility earlier, they pass through the early skill phases faster than machinists. It is possible that if managers spend less time in that phase, we simply did not observe a
manager in the basic skills phase.

Software Development Management

We have identified four phases of development including the rote, experimental, competent, and master phases. The behaviors and skills possessed by practitioners in each phase are discussed below.

Rote Phase: Managers in the rote phase understood the need to develop the technical requirements for the project. However, they only included a few sub-problem areas in their plans and used only a couple of techniques to address all of the goals that they did recognize. They used these few techniques to address all of the problems whether or not the techniques would actually solve the problems. They had no overall strategy and did not do any evaluation of their plans.

Experimental (Techniques) Phase: The managers in the experimental phase understood the overall objectives that had to be achieved in order to create a workable plan, but they were lacking in many types of knowledge. Although they recognized more of the domain sub-problems than in the rote phase, they still skipped many sub-problems, such as understanding customer requirements. They also did not know many techniques, conditions under which these techniques could be applied, or their cost. Consequently, they missed important goals and possible ways of accomplishing those goals.

Competent Phase: Managers in the competent phase produced high quality plans. The judges commented on the high quality of plans created in this phase. The managers consistently covered all of the areas that were critical in a good management plan and developed contingency plans to reduce project risk.

Master Phase: Managers in this phase have a wealth of experience and knowledge that they can draw upon. They are confident in their decisions and sometimes will step beyond the boundaries of their job for the good of the project in ways that the competent managers would not. For instance, one manager in the master phase planned to help the customer change his or her internal business procedures in order to get the project out of trouble.

Parts Fabrication

We have identified four phases of development including the rote, basic skills, experimental, competent, master phases. The behaviors and skills possessed by practitioners in each phase are discussed below.

Rote Phase: Machinists in the rote phase tended to apply one or two basic plans, which they would modify for any problem whether or not either of these plans was appropriate for the problem. There was no consideration given to interactions between the steps of the plan. The machinist at this level tried to develop efficient plans, but they failed due to lack of knowledge. They did no evaluation of the plans that they created and seemed oblivious to the fact that their plans were infeasible.

Basic Skills Phase: Machinists in this phase have started to understand the pre-conditions necessary to use many techniques. Most of the techniques are applied correctly and do not interfere with other plan steps. They also seem to understand that they do not know enough to try to combine the goals. There are a completely separate set of steps for squaring and feature creation.

Experimental (Efficiency) Phase: The plans created by machinists in the experimental phase were marked by attempts at developing more efficient plans. Their plans were shorter, but slightly less likely to be feasible than machinists in the basic skills phase. This may because they are learning both more techniques and how to use them to accomplish more than one goal in order to create efficient plans.

Competent Phase: Machinists in the competent phase produce feasible and efficient plans. They know many techniques, when to apply them, and how they can be combined successfully. The machinists evaluated the plans that they were creating often and considered many alternative strategies.

Master Phase: Master machinists produce consistently high quality plans. They differ from the competent machinists in that they understand the boundaries of their knowledge and skills very well. They are able to identify situations in which they do not know how the tools and materials will behave. Consequently, they are rarely surprised by unexpected failures. This allows them to choose effective techniques and to seek information when needed.

Needs in Education of Planners

Observing changes in knowledge and skills over time makes it possible to identify what novice planners
are lacking, and in what areas education or computer tools could assist them by filling in these knowledge gaps. The less than competent practitioners in both of these studies had problems in two areas: they lacked knowledge of the techniques available to them and when these techniques could be used and they did not visualize the current state of the problem well. We feel that development of an overall framework of tools can help less experienced practitioners to plan at a higher level of competence.

**Software Development Management:** There are many tools available to help software development managers with pieces of the planning problem, such as scheduling tools and spreadsheets. However, there is a need for tools that helps the manager to see the “big picture”. They need to be able to understand all of the areas that must be explored in order to understand all of the project goals that need to be fulfilled in order to be successful. In this study, we found that managers in the rote and experimental phases missed whole portions of the problem. They failed to consider all of the requirements. For instance, many of them did not even consider exploring the customer's priorities before scheduling work. New managers seem to need help identifying all sources of goals and constraints that must be considered to produce a successful plan, such as the customer's motivations, the goals of the company, as well as its strengths and weaknesses. After recognizing what needs to be accomplished, the new manager needs suggestions of techniques for addressing these problems. These techniques could include anything from meeting with different groups such as marketing or customers to using a commercial scheduling tool to create the schedule once all the requirements have been understood.

**Parts Fabrication:** The machinists in the early stages of expertise development had three main problems. They lacked knowledge of possible techniques, when to use them, and how to optimize plans. Additionally, they did not seem to visualize how each plan step were changed the shape of the part. For instance, the machinists in the rote phase often planned to machine both ends of a part that was shorter than the clamping device holding it. In this situation it is impossible for the machining tool to cut both ends of the part without also cutting the clamp. Computer tools that simulate actions and display the current state of the material to the novice machinists would help them to see what plan steps were even possible. Additionally, it seems they need to be taught the basic skills of recognizing the techniques to use and when to use them in order to produce feasible plans before they can start to handle optimization issues.

6. Conclusion

In this paper, we have reported the results of two studies of plan quality in two complex domains, software development management and parts fabrication. In both domains, planners’ average plan quality clearly increased as the planner gained experience, although at different rates. We have described briefly the skills and knowledge that are present or lacking in planners at each phase of development. This model can provide important guidance in designing both training programs and computer tools for filling in missing knowledge, and helping planners to achieve higher levels of competence.

**References**


