Organizing Knowledge for Tutoring Fire Loss Prevention

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ABSTRACT / The San Bernardino National Forest in southern California has recently developed a systematic approach to wildfire prevention planning. However, a comprehensive document or other mechanism for teaching this process to other prevention personnel does not exist. An *intelligent* tutorial expert system is being constructed to provide a means for learning the process and to assist in the creation of specific prevention plans. An intelligent tutoring system (ITS) contains two types of knowledge—domain and tutoring. The domain knowledge for wildfire prevention is structured around several foci: (1) individual concepts used in prevention planning; (2) explicitly specified interrelationships between concepts; (3) deductive methods that contain subjective judgment normally unavailable to less-experienced users; (4) analytical models of fire behavior used for identification of hazard areas; (5) how-to guidance needed for performance of planning tasks; and (6) expository information that provides a rationale for planning steps and ideas. Combining analytical, procedure, inferential, conceptual, and expositional knowledge into a tutoring environment provides the student and/or user with a multiple perspective of the subject matter. A *concept network* provides a unifying framework for structuring and utilizing these diverse forms of prevention planning knowledge. This network structure borrows from and combines semantic networks and frame-based knowledge representations. The flexibility of this organization facilitates an effective synthesis and organization of multiple knowledge forms.

Wildfire protection programs in the Forest Service, including those dealing with wildland–urban interface fire protection (Gale 1977), are subject to efficiency criteria, i.e., program costs and resource losses must be minimized. Simple frequencies of ignitions are no longer the primary concern. Ignitions that have the greatest potential to become large and/or damaging fires are targeted in a prevention budget (Bradshaw and Johnson 1989). Through the efforts of fire prevention personnel of the San Bernardino National Forest, a new method for prevention planning has evolved; this development is referred to here as the fire loss prevention planning process (FLPPP). The steps contained in this method are described in detail below.

Prevention plans for several of the forest's ranger districts have been developed through the use of this process. The FLPPP was developed and has been used operationally, but no comprehensive document exists for transferring the methods and rationale of the planning process to other prevention personnel. In the FLPPP, location-specific fire problems are analyzed and described in inventory documents and accompanying maps. To a large extent the FLPPP remains a paper-and-pencil exercise for making and recording subjective analyses and judgments. Consequently, new users find it difficult to begin analysis of fire problems—the first, and essential, component of the process.

KEY WORDS: Artificial intelligence; Expert system; Knowledge base; Tutorial

In addition to these analysis and documentation steps, practical application of the FLPPP requires the use of some method for predicting potential wildfire behavior. This means that prevention personnel must have experience with one of several computer-based mathematical models of fire behavior. The full implementation of such a model (for example, Andrews 1986) would add another layer of complexity to the planning steps involved. If these models can be incorporated into operational tools such as a prevention planning system, it simplifies the practitioner's job.

As with many other management tools, the FLPPP is amenable to computer-based application. Through the development of an intelligent tutoring system (ITS) for wildfire prevention program planning it is possible to investigate different functions, forms, and sources of prevention knowledge. However, the few individuals who developed and have subsequently implemented this process bring with them experience and knowledge that has not been formally elucidated. This FLPPP knowledge is composed of: sequences of steps used to accomplish planning tasks, prevention planning concepts and their interrelationships, procedures for performing required steps of the process, intuitive judgement, and explanatory rationale. Any single form of knowledge, e.g., analytical or explanatory, cannot be expected to be applicable to the range of functions required by FLPPP usage. The alternative, using multiple knowledge forms, is not unique to this application, but has been recognized previously by O'Hare and Bell (1985). The requirements of varied knowledge forms and functions mandates a knowledge representation that can support this diversity.

The overall purpose of this research is to determine if a knowledge-based tutorial could facilitate learning about the FLPPP and also provide guidance for developing specific prevention programs. An ancillary objective, aside from tutor development, seeks to formalize the ideas of a process that has been solely operational to date and has not been explicitly recorded anywhere. To accomplish the stated objectives, tutoring needs and knowledge structures were identified and their influence on knowledge content and system design were analyzed. This report details those considerations and introduces a framework for specifying knowledge that results from these wildfire prevention considerations.

Prior to presenting some methods used to organize prevention planning knowledge, the FLPPP is discussed as it relates to this computer implementation, and a brief introduction to intelligent tutoring systems is included. A concept network structure is suggested as one possible mechanism for integrating and representing diverse forms of prevention planning knowledge. Ideas presented here favor methods oriented more toward software engineering (Hayward and others 1986, Oliver 1986, Schmoldt 1987a) rather than the more popular exploratory approach to knowledge system development.

Prevention Planning

To determine whether money spent on prevention reduces wildfire losses, prevention outputs must be balanced against planned goals. These goals are established through systematic analysis of fire problems across entire management areas. The FLPPP includes a detailed inventory of fire problems and precipitating conditions; this inventory consists of documents and maps that specify and illustrate factors that influence fires. On the basis of this inventory, certain areas are targeted for more intensive attention by fire prevention personnel. Prevention program prescriptions (locally developed and implemented) dictate how potential problem areas are addressed. Subsequent program evaluation compares fire losses and prescription implementation. This detailed approach provides for both accountability in program selection and follow-up assessment of success or failure.

Process Components

The FLPPP consists of the sequence of steps shown schematically in Figure 1. A systematic, multivariate analysis of fire problems constitutes the primary advantage of this planning approach. Subsequent planning steps rely on the inventories and maps produced in the analysis phase.

Analysis of wildfire ignition problems involves examination of three independent aspects of wildfire situations: risk[1]—the likelihood that ignitions may occur, hazard—the behavior of wildfires after ignition occurs, and values—the monetary and nonmonetary values at risk from wildfire. The analysis of each aspect of ignition problems, risk, hazard, and value, includes inventory, mapping, and rating of its constituent factors. Each analysis is independent of the others, and no particular order need be followed.

The next step is to aggregate the mapped and rated areas of homogeneous risk, hazard, and values at risk into one map. This consolidation allows identification of *prevention compartments,* each with a risk, a hazard, and a value rating. The consolidated map and companion inventory form the data base for subsequent program planning, implementation, and evaluation. Occasionally, some reworking of the analysis may be necessary to align compartment area boundaries.

From the combined inventory and aggregate map, specific action items are identified for each prevention compartment. Action items are those activities that are performed on a regular basis by fire prevention officers. Prescriptions are written, incorporating each prevention action item; they cover duties to be performed and their priority under the typical range of fire weather conditions used in fire planning. Contingency prescriptions may also be detailed for fire conditions which occur only rarely.

Evaluation of program effectiveness entails examination of the prescriptions in relation to the extent and location of fire losses. Because the goal of prevention is a nonevent (no fire), successful prevention efforts can only be assessed in terms of the numbers and severity of events that do occur, i.e., unacceptable losses. When unacceptable fire losses have not occurred, then assuming average fire conditions, it may be possible to conclude that prevention efforts have been successful. However, faced with losses considered unacceptable by land managers, a careful examination of those specific, damaging fire problems should iden-

[1]In wildfire prevention, the term *risk* is used in a different sense than most readers may be accustomed to. Here, risk denotes an activity or location that have the potential to cause ignitions.

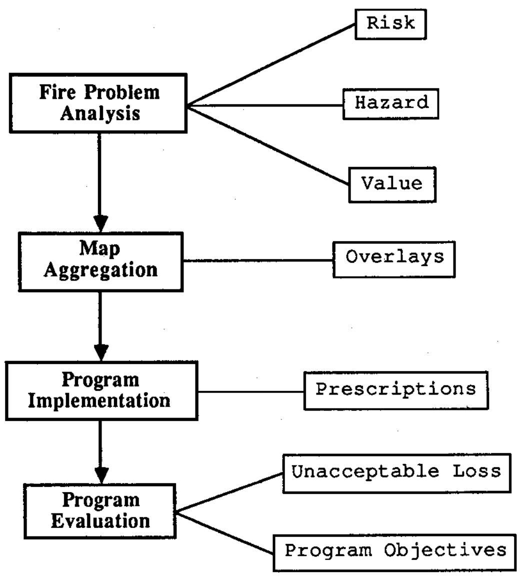

Figure 1. The "bold" components represent stages of the fire loss prevention planning process and the sequence in which they must be performed. Attached components on the right side of the illustration constitute information sources used or documents produced in each respective stage.

tify the most prominent causes. Prevention personnel may refer to documents of program implementation to verify completion of all prescribed tasks; failure to achieve specified tasks indicates a performance problem. Unacceptable losses occurring after tasks have been performed indicates that prescriptions may not be effective and need to be revised. In the course of rewriting prescriptions, it may be necessary to reanalyze the risk, hazard, or value assessments associated with particular areas of losses.

Intelligent Tutoring Systems

Computer-aided instruction began in the 1950s with behavioral psychology's linear program view of instruction (Yazdani 1986). Under this perspective, direction toward some desired behavior is implied; reinforcing stimuli result from a successful response, and direction-correcting stimuli result from an incorrect response. Since this time, many other approaches have been used; most recently, knowledge-based systems have been utilized.

In addition to being effective for problem solving in forestry (Schmoldt 1987b), knowledge systems possess some desirable properties for instructional uses. Expert reasoning and judgment can be represented in the system and conveyed to the student through tutored examples (example-driven problem solving) or declarative explanation (line of reasoning). The student is able to work many examples at varying complexity levels and at a comfortable pace without assistance from an instructor. MYCIN, a diagnostic expert system for infectious diseases (Davis and others 1977), has been transformed into a tutor for medical students (Clancey and Letsinger 1981). Other tutors have been created for teaching: computer programming (Anderson and Reiser 1985, Johnson and Soloway 1985), natural language (Imlah and du Boulay 1985), geometry (Anderson and others 1985), physics (White and Frederiksen 1986), and a pulp and paper process (Woolf and others 1986). Merging computer-aided instruction and knowledge-based systems has resulted in intelligent tutoring systems (ITSs).

Besides the representation of domain knowledge, i.e., knowledge about the subject area, strategies for tutoring the student must also be defined. These strategies may include: (1) organizing the presentation of tutored material, (2) maintaining an actual student history (progress) model, and (3) specifying the intensity of tutor and student interaction (dialog management). To provide a comprehensive learning environment, the student must have access to large amounts of explanation, both for correcting erroneous behavior and promoting desired behavior. Specific implementation of these features depends on the teaching task and the types of students anticipated.

The ITS work described in this study differs from those examples cited above by a need to be multifunctional. Most ITSs contain a method of simulating or hypothesizing specific learning situations (examples) that serve as the focus of the learning environment. This prevention planning tutor will operate with examples provided by individual users, which, presumably, reflect actual planning needs. Two types of users are anticipated: (1) those interested solely in receiving some assistance for developing prevention programs, and (2) prevention personnel who would like to learn and understand the FLPPP, as well as create prevention programs. This knowledge-based tutor must be capable of both aiding the solution of actual ignition management problems and, at the same time, tutoring fire prevention personnel in the techniques of the FLPPP.

Clancey (1987) experienced difficulty with this duality of purpose in the development of GUIDON, a tutoring system which utilized the MYCIN expert system as a problem-solving simulator. Difficulties arose because the diagnostic rules of MYCIN *implicitly* contained much of the diagnostic strategy that a tutor is designed to impart to its students. NEOMYCIN (Clancey and Letsinger 1981) was constructed to emphasize the separation of strategy and domain knowl-

Figure 2. The needs of any particular tutoring environment will depend on the interaction between student and material. Tutoring novel subject matter requires different methods than refining previously learned skills.

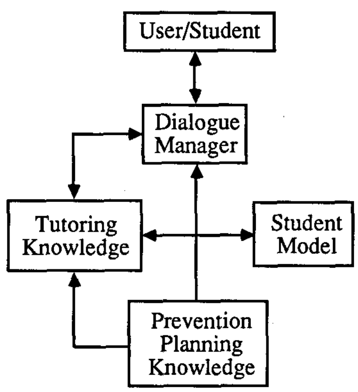

Figure 3. A component diagram of the fire loss prevention planning process tutor depicts the modules and the flow of information between them. The box labeled user/student indicates an exogenous component not constituent to the tutor.

edge in MYCIN and facilitated the development of GUIDON. The ITS described here should not encounter such problems because the intent *ab initio* has been tutoring rather than retooling an existing problem-solving system.

Two basic approaches to tutoring seem to exist in the ITS literature; the approaches differ in the type of material being taught. The types of learning can be categorized along a continuum from new ideas and techniques learning at one end to refinement of thoroughly understood skills on the other. Figure 2 presents some general examples of various points on this learning spectrum. Introductory learning of completely new and unfamiliar material would typify novelty comprehension; here the instructing agent takes a *proactive* role. On the other hand, a review of performance would not require absorbing new ideas, but rather honing current skills (*reactive* tutoring). A blending of the two tutoring methods would most likely occur between these two end points.

At the novelty end of the continuum, learning is characterized by the desire for a student to assimilate an entirely new or foreign idea or technique. The teacher can assume little prior experience by the student in relation to the new topic. Therefore, the tutor must guide the student through the steps and rationale that lead to understanding of the complete idea (proactive role). Transitions and relationships between ideas and their component ideas must be coached, and supportive reasoning must be available at all stages in the tutoring process. This situation most closely approximates the tutoring duality of ITS development for the FLPPP.

In a slightly different context, a student may need to refine or augment already established skills. Some a priori knowledge of the subject area may be considered normal for a typical student. Often the student is given an example to work, and the tutor follows the progress of the student, only interjecting when an error occurs (reactive tutoring). Consequently, the tutor must be able to distinguish erroneous behavior and/or reasoning by the student and also provide some mechanism for eliciting a more correct response. Relatively passive, reactive methods work better in circumstances that lie near this area of task refinement learning.

Development of a tutor in this study involves the design and construction of the four components illustrated in Figure 3. These are designated as the fire prevention planning knowledge base, actual student model, tutoring strategy knowledge, and dialogue manager. A fully functional tutor with the above components that addresses only a subset of the FLPPP knowledge (e.g., the hazard analysis knowledge) may be prototyped and tested prior to complete system implementation; this is the current stage of development. Consequently, problems in system design can be identified and corrected before there is system-wide dependence on faulty components.

Because the focus of this article centers on the sources, organization, and use of wildfire prevention planning knowledge in a tutoring environment, other aspects of tutor design and construction, such as knowledge acquisition and program implementation, are only discussed as they pertain to the issue of domain knowledge. A prototype of the tutor has been implemented using Allegro[2] Common Lisp on a Macintosh II computer. The modular nature of the

[2] Allegro Common Lisp is a product of Coral Software Corp., P.O. Box 307, Cambridge Massachusetts 02142 USA, and Franz Inc., 1995 University Ave., Berkeley California 94704 USA. Macintosh is a trademark of Apple Computer Inc. Trade names are mentioned solely for information. No endorsement by the US Department of Agriculture is implied.

FLPPP makes it possible to prototype a subsystem that contains only hazard analysis knowledge and will serve to test the functionality of our design.

Knowledge Structure

General

The first step in development of the tutor involves formulating a representation of knowledge about the FLPPP, i.e., the domain knowledge. This representation contains a structured organization of ideas and concepts central to our subject, the FLPPP, and permits the manipulation of these ideas by the computer. Several fire prevention personnel on the San Bernardino National Forest are familiar with the FLPPP and have their own personal insights into the subtleties of fire problem analysis and prevention program implementation. However, no individual within this group was previously highly involved in all aspects of the process. Therefore, it became necessary to combine the knowledge of several experts, and at the same time obtain consensus on the structure and operation of the planning process. A cumulative Delphi technique was used to elicit the experts' community knowledge (Schmoldt and Bradshaw 1988). Emphasis in this article centers on the different forms this knowledge assumes, their representation on the computer using a concept network, and their application in tutoring (functionality).

The demands of proactive tutoring place emphasis on providing a flexible and comprehensive learning environment. Different knowledge functions imply different knowledge representations that are more effectively able to accommodate those functional capabilities. For example, where the desire is to *explain a particular concept,* it may be done most efficiently by storing a textual description of it rather than creating some highly elaborate and complex data structure. On the other hand, when describing the *relationship* between one concept and another, it may be more efficient and flexible to construct a relational description from an internal structural representation of the domain, such as in Figure 4. Clancey (1987) found the MYCIN's unstructured set of production rules was inadequate for articulating strategic, structural, and support relationships. The need to provide tutoring capability and also assistance for specific prevention program planning suggests that multiple forms of domain knowledge be acquired and represented.

Tutoring Functions

Tutoring functions were defined that seemed to support the content of the FLPPP and the perceived needs of end users. The three general functions identified were: (1) planning, (2) coaching, and (3) explicating. Planning requires providing the heuristic and analytical support necessary to assist the user in developing actual prevention programs. Coaching makes how-to knowledge available for completing certain tasks of the FLPPP that may require tutoring assistance. Explication includes rationale and justification for concepts and tasks that are encountered during FLPPP program planning. To realize these functional goals, the tutor should be able to represent and manipulate several forms of FLPPP knowledge.

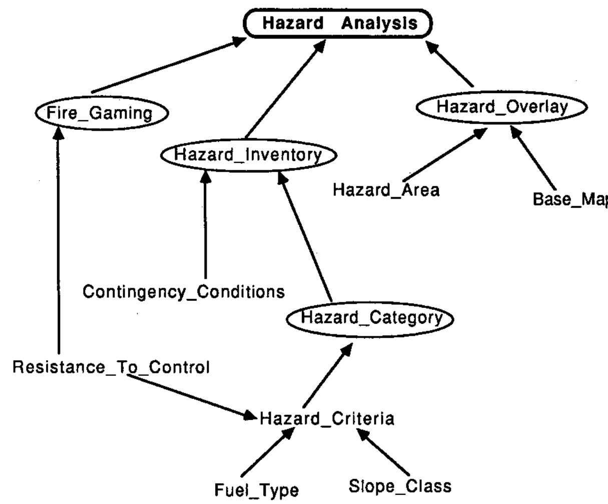

Figure 4. The structured nature of the FLPPP is apparent from the organization of concepts and their links to other concepts.

To formulate a *plan* regarding some activity or process, it becomes necessary to conceptualize a process's constituent steps and to carry out these steps in a manner that leads to a finished product. In the case of the FLPPP, the final product is a set of documents that outlines a wildfire prevention program for the planning area of concern. During the process of generating this plan, analyses must be performed and decisions made based on those analyses. The *structured* nature of the FLPPP (Figure 4) serves as a guide for sequencing the various analysis and decision steps. Each concept or task of the FLPPP can be dissected into simpler and more basic ideas and tasks that can eventually be understood or performed by the student and/or user. *Procedural* knowledge of the FLPPP developers is required at some steps in planning to bridge the gap between experience and user unfamiliarity; these are often represented as rules of thumb. Also, *analytical* capabilities provided by a fire behavior model are essential for providing reasonable estimates of hazard. Incorporation of these three knowledge forms furnishes the user with valuable assistance in creating actual prevention plans.

Coaching the user in the performance of certain tasks required by the FLPPP generally consists of providing extensive guidance. This may mean simply identifying the next step in a task's sequence or carefully walking the user through the construction of some necessary document. Each of these activities involves the use of some *script* knowledge to augment the skill level of the user. Script knowledge is understanding of sequences of events or anticipated characteristics of a familiar scenario, much like the knowledge representation described by Schank and Abelson (1977). Also, extensive use may be made of other, *explanatory* knowledge structures during this how-to instruction; the result would be a more rapid advance in user understanding. After being coached in a particular task, subsequent exposure to the same task should require less tutor assistance and fewer explanations.

Not all of the concepts and relationships of the FLPPP will be understood by the user—some of the terminology may be foreign or ambiguous. There exists a need for some detailed *explicatory* information to describe ideas and their relationships to other ideas. These descriptions may include: *definitions* of each concept or task used; *justifications* for the inclusion of each concept into prevention planning; specific *examples* of each concept to make their meaning more concrete; and *relationships* between each concept and any related ones. Explicating rationale and concepts used for the many ideas inherent in the FLPPP will be of greatest benefit to those users with a desire for in-depth understanding of the process as a general technique, but will also help mitigate confusion experienced by users more oriented toward receiving help with their particular prevention planning task.

Forms and Sources

In the process of outlining tutoring functions, above, several forms of knowledge have been suggested. This section describes in more detail these knowledge forms and how they might be *individually* represented.

The FLPPP contains an inherent structure for the sequence of events that the user must address in creating a wildfire prevention program. Figure 1 displays the general outline of the FLPPP, and Figure 4 presents a more detailed view for one of the analyses. These *structural* descriptions were obtained from interviews with fire prevention experts familiar with the FLPPP. Concepts and activities in Figure 4 are structured in a top-down manner, where subordinate topics must be developed (understood) prior to accepted accomplishment of higher-level ones. Arrows indicate relationships to other concepts and tasks in the hazard analysis phase of the FLPPP; relationships to entities in other subprocesses of Figure 1 are not captured in this diagram but could be included as needs arise.

During implementation of the FLPPP by its originators, some implicit techniques for performing various steps of the process were incorporated into operational versions. These *subjective* judgments include shortcuts and experience-based methods that have been found beneficial. For example, the two factors that generally influence fire hazard are slope and fuel. By using some mathematical fire behavior model (e.g., Andrews 1986), different combinations of fuel types and slope classes will produce different estimates for *resistance to control,* an index of predicted fire behavior. However, estimates for particular combinations of fuel and slope factors may not be substantially different for purposes of eventually assigning hazard levels to geographical compartments. Heuristics like the one below, which incorporate subjective judgments may help the user obtain a more realistic number of hazard levels and associated fuel and slope conditions.

```
IF (Resistance_To_Control [Slope_Class X]
    [Fuel_Type Z]) ≤ 1.1 * (Resistance_To_Control
    [Slope_Class Y] [Fuel_Type Z])
  AND (Abs(Value(Slope_Class X))
    (Value (Slope_Class Y))) ≤ 10
THEN (Average (Slope_Class X) (Slope_Class Y))
  AND (Remove [Slope_Class Y])
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Here, if Resistance_To_Control for two combinations of fuel and slope factors does not differ by more than 10%, and the slopes differ only slightly (≤10°), then combine the two slope classes into one. Rules of thumb like this would be unknown to someone unfamiliar with the FLPPP.

It is also possible to use heuristics (these are included in the initial prototype) in the place of fire behavior model estimates of resistance to control; resistance could be inferred from fuel and slope descriptions in a qualitative rather than quantitative (analytical) manner. From what is known about resistance to control and its precipitating conditions in the San Bernardino National Forest, several decision rules are being added to the initial system to estimate this parameter from fuel and slope information. However, physical science research has produced mathematical models of fire spread and intensity, and it seems advisable to take advantage of state-of-the-art *analytical* knowledge. Subsequent versions of the tutor will incorporate these more sophisticated mathematical relationships.

Substantial detail needs to be included in the tutor to answer the "what" and "why" questions (explication). It resides in the form of textual descriptions of definitions and justifications. For example, there may be some vague understanding of what a *fuel type* is (Figure 4), but expositional material such as an explicitly stored definition and several examples would help alleviate possible ambiguities. Also, a justification for the concept fuel type and some relationships to other concepts should indicate how and why the idea is useful in the FLPPP. Relationships between concepts *not directly* connected structurally or logically (e.g., Resistance_To_Control and Hazard_Inventory in Figure 4) can be constructed by synthesizing explanations. Connections between intermediate concepts that are stored in the structural representation could be combined to produce such an explanation. The indispensable nature of expositional knowledge means that it must be available to the user at all times, especially during planning and coaching activities.

Script knowledge is akin to the step-by-step format of a recipe, except that at any stage in this recipe it may be necessary to provide another level of detail for some poorly understood topic. In reference to Figure 4, there may be a detailed description of some method that works well for delineating fire hazard areas. A specific procedure (program code) or subordinate sequence of steps could be invoked to provide guidance in this task. This knowledge would only be accessed during the utilization of that script.

Subordinate levels of detail within a script are local knowledge to that particular script. They can only be utilized in the specific situation for which they were designed, and they are not directly accessible by other parts of the knowledge structure. In contrast, other aspects of the FLPPP knowledge structure may act as global knowledge and may be utilized from within procedures and script sequences. For example, expositional information could be made available during the fire hazard area delineation task mentioned above. This does not present any limitations because each knowledge form only requires access to certain other forms for performing various functions. The dialogue manager still provides the user with general availability to the entire knowledge base.

Systematic Implementation

The system design presented above describes a top-down approach that addresses system functions and requirements at the outset. Subsequent construction of subordinate components builds supportive structures to effect these top-level specification. Forms and representations of the domain knowledge have been identified and linked to tutoring system goals. Necessary capabilities of the dialogue manager and the tutoring strategy are not detailed here, but were determined by the tutoring functions. Consequently, to support the tutoring functions, domain knowledge must be compatible with those components.

Exploratory development (trial and error) of a knowledge system must occur at the prototype stage because of the artistic nature of AI. However, this prototyping should be performed within the restrictions of a well-conceived design. Initial testing of a prototype on a subset of the FLPPP domain (hazard analysis) should illuminate those implementation characteristics that may require later revision. It may also be necessary to conform a prototype to the a priori requirements of higher-level components, e.g., the dialogue manager.

Development of the FLPPP tutor relies on a guiding framework for tutoring. Within this design framework effective implementation methods (knowledge representation and algorithms) are explored to accomplish these preset goals.

The Concept Network

To maximize the cohesiveness of these diverse representations of distinct knowledge forms, a single unifying knowledge representation was sought. It was reasoned that a knowledge representation scheme that acted as an umbrella for all knowledge forms would simplify implementation and permit knowledge sharing between tutoring functions by enhancing connectedness. A blend of the semantic network and frame-based representations was selected and is given the label *concept network.* Quite independently, Kolbe and others (1987) used a semantic network of frames (apparently equivalent to a concept network) to represent knowledge in their ITS. This approach combines the link-and-node structure of a semantic net with the autonomous, object-oriented storage used by frames.

Semantic networks were first suggested and used by Quillian (1968). One of the most notable implementations of this approach occurred in the PROSPECTOR mineral exploration system of Duda and others (1978). Essentially, the method uses nodes to represent objects, concepts, or situations in the subject area, and connects them by means of relationship links. The effect is a representation similar to the concept diagram in Figure 4 with the addition of labels on the arrows. This node-and-link structure permits great generality and flexibility in the description of highly complex and interrelated domain entities. However, all of the knowledge resides in the nodes and links; this may be

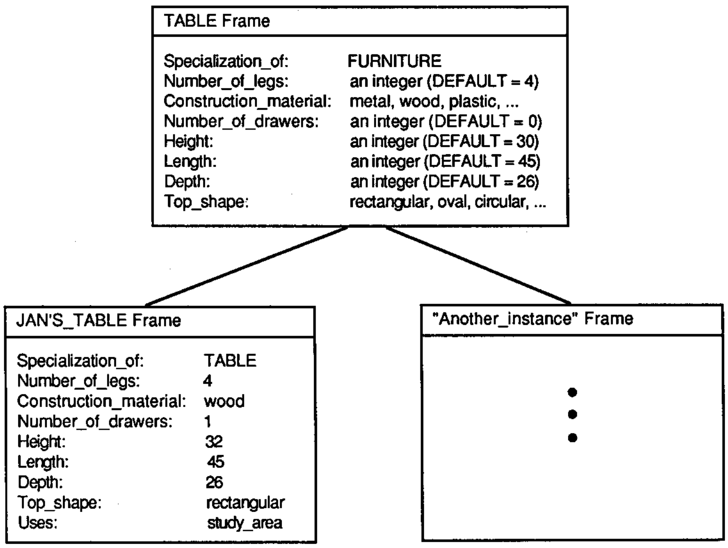

Figure 5. A class frame is illustrated with its relationship to an instance frame of the class.

inefficient or needlessly complex for some knowledge forms.

Frame representations were initially proposed by Minsky (1975). Since their introduction, they have been utilized in many expert systems (Barr and Feigenbaum, 1981) for organizing knowledge into discrete units. A contemporary, fire-management example of frame-based knowledge representation appears in Reinhardt (1987). A frame can be viewed as a box containing many separate compartments. Each compartment holds some relevant information (usually attributes and their values) about the object being represented. Frames usually appear in hierarchies, where certain frames may inherit attributes and values from other frames. In Figure 5, the *class* of TABLE objects contains several compartments, each with an attribute and its value. Particular *instances* of TABLE (e.g., JAN'S_TABLE) are linked to the class TABLE via an inheritance relationship. JAN'S_TABLE may inherit particular attributes and values (e.g., Length and Depth) from the class TABLE and may include additional attributes (e.g., Uses) not general to the class. Barr and Feigenbaum (1981) note that frames' main advantage lies in their ability to "direct attention and facilitate recall and inference." Their main limitation has been a restriction to inheritance links, rather than more general relationship links.

The idea of a concept network attempts to combine the benefits of these two approaches. The object-oriented nature of frames is combined with the flexible structuring of semantic nets. Concepts in the FLPPP become nodes and are represented as frames. Internode connections are links (also represented as frames in our system), which are not restricted to inheritance relationships. Several example concept network nodes are presented in Figure 6. Each node contains a number of attributes of the entity being represented and values of those attributes. Expository knowledge is stored as text between double quote marks, as in the definition or the justification of ignition-potential-activity. Structural knowledge can be stored as a list of relationships and their related concepts or related tasks, e.g., ignition-potential-activity "is a component of" risk-ranking. Detailed examples of concepts may be included in a list of "examples"-attribute values, which may name other concept nodes, e.g., water-use-campgrounds. Where expert judgment is useful at particular decision points in the planning process, it would also be desirable to attach if–then decision rules to another attribute of a node; this optional mechanism is not represented in the illustration. Such rules could be invoked to make decisions that the inexperienced user may be unable to make.

The ignition-potential-activity frame represents a *concept* of the FLPPP. Other nodes, which might represent *tasks* in the planning process, e.g. risk-inventory, might contain an additional attribute in the place of an "examples" attribute. This attribute compartment might contain "how-to" knowledge (executable code or script sequences) to guide the user in completing a particular task. Concept networks allow the system developer to collect, store, and catalog knowledge regarding individual objects in separate, data structure localities and yet relate them to many other objects in the knowledge base.

Discussion

A knowledge-based intelligent tutoring system has

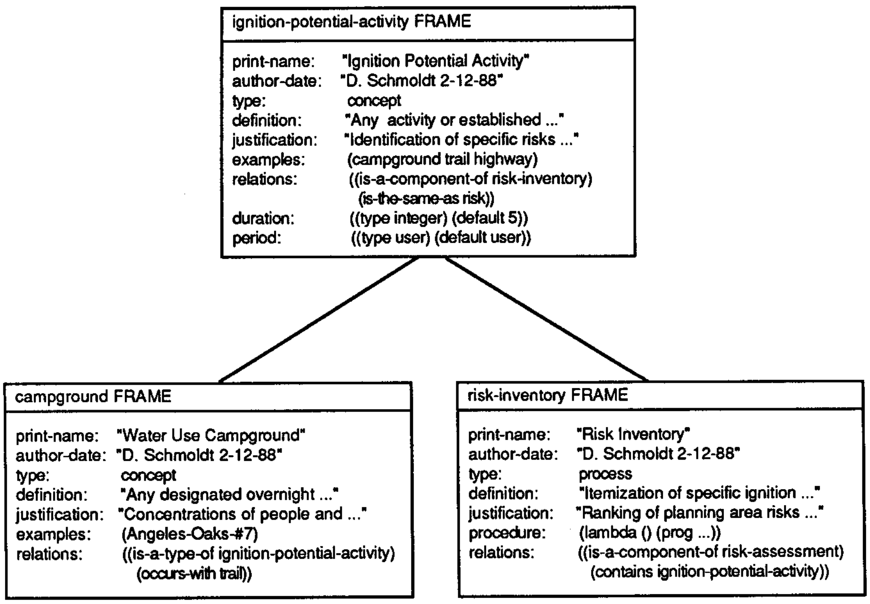

Figure 6. Several nodes of the FLPPP concept network depict typical attributes and their values. Ignition-potential-activity is a class frame and campground is a subclass frame. The task of inventorying risks is related to the other two concepts.

been suggested as a viable alternative to more passive learning aids, such as documentation in the form of manuals. The dialogue aspect of an on-line tutor may substantially increase the utility of such teaching mechanism. Mixed-initiative interaction (i.e., both tutor and student may direct the flow of the tutoring session) between tutor and student should allow the student some measure of control over topics covered and learning rate. The dual nature of tutor *and* planning aid represents a functionality that would be difficult to match with conventional hard-copy materials.

Development of a concept network representation was prompted by the need for a formal structure that would permit the storing and sharing of disparate knowledge forms and their internal representations. It seems particularly well suited for these purposes—due in part to its natural mirroring of the FLPPP structure. Although specification of knowledge forms and representation in a concept network in this particular study resulted from a careful analysis of FLPPP tutoring requirements, there does not appear to be any design limitation that would restrict the use of this framework in a more general sense. That is, other tutoring applications could be expected to benefit from the knowledge organization outlined here.

A deliberate and orderly approach to knowledge system implementation *can* be reconciled with the traditional urgency to begin prototyping. However, hasty prototyping should not preclude careful system design. Rather, it should follow design and address specific system components and models. Prudent design considerations and the resulting system morphology should be relatively unaffected by subsequent computer implementation. Prototypic modifications should arise from changes in implementation methods, as opposed to a poor, or lacking, initial design phase.

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