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A Technical Description of the ADVISE.1 Meta-expert System

BY

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CHAPTER 1

The ADVISE System: A General Overview

We are currently witnessing a rapid increase of interest in building expert systems for a wide variety of practical problems. Among the many application domains where expert systems have been already tried are medicine, geology, chemistry, agriculture, accountancy, computer system configuration, accountancy, engineering design and VLSI circuit design. Current systems, however, suffer from a number of limitations that restrict their utility. They typically employ a single form of knowledge representation (production rules), no learning ability, only one type of inference mechanism and control strategy and poor user interaction facilities.

The research described here represents our attempts to overcome some of these limitations. We have developed a general purpose inference system, called ADVISE, which consists of a set of modules for the development of and experimentation with expert systems in a variety of application domains. Among the important and novel ideas in ADVISE are the incorporation of three different types of knowledge representation, inductive learning capabilities and several inference control strategies. We feel that ADVISE represents a substantial advance in expert system design and functionality and can be viewed as a "second generation" general purpose expert system.

Before going any further let us start by examining the notion of an expert system. Usually, an expert system is defined as a computer system that exhibits high performance in a specific problem domain due to a large amount of formally encoded domain knowledge and the ability to conduct formal reasoning on this knowledge. An expert system is designed to perform a host of tasks that a human expert would typically perform: diagnose, interpet, consult, classify, identify, search through a space of possible solutions, explain and analyze [Buchanan83].

The domain knowledge is represented in an expert system as a set of production rules. These rules take the form of:

> IF <condition> THEN <action>
>
> where
>
> > <condition> is a logic expression which must be satisfied to a certain preset degree, and
> >
> > <action> is a set of actions to be performed if the <condition> part of the rule is satisfied. The <condition> may include both the context within which the rule is applicable, and the specific conditions to be satisfied by the situation in order to apply to it the <action>.

The set of production rules that characterize a given application area is termed the knowledge base. The knowledge base is one of the three major components of an expert system.

The second major component is the inference mechanism by which the knowledge base is used to perform given tasks. The inference mechanism is divided into two parts:

- a *rule evaluator/executer* that does inference *within* a rule, and
- a *control scheme* that does inference *among* rules.

In many expert systems, some form of *probable* or *plausible* reasoning is used in the inference procedure to handle uncertainties. Data are often represented as *object/value/confidence* triples.

The third major component of an expert system is the memory needed to store intermediate results of rules when they are actuated or *fired.* Some architectures term this component the *blackboard.*

A favorite starting point for expert system architecture is to organize these three components as a production system. This production system organization contains a *recognize-act* cycle in which a control scheme decides which rules to evaluate and, if any fire, executes their right-hand sides. For more details on production systems see [Nilsson80] , [Davis76] and [Michie80]. Many expert systems are not pure production systems, however. Many are more like Markov algorithms in that the productions are ordered.

There is another way to view the architecture of an expert system that turns out to be isomorphic in many respects to the view of an expert system as a production system. In this view, the expert knowledge is in the form of a network. The control scheme becomes a network traverser/updater. This is the view incorporated in PROSPECTOR [Duda78]. See [Gevarter82], [Michie80], and [Stefik82] for more detailed overviews of expert systems. The next chapter shows how the general purpose inference system ADVISE goes beyond the simple expert system architecture described above.

1.1. Novel Features of ADVISE

ADVISE has been designed to provide the knowledge base engineer with an expert system workbench. It provides a number of facilities not commonly found in existing expert systems. These features include:

- representation of knowledge in three different forms: a rule base, a network base, and a relational data base,
- use of a very flexible representation for inference rules,
- modular design,
- freedom to choose and design a host of inference control strategies,
- inductive learning capabilities,
- implementation of the system in Pascal (a popular language widely available on many computer systems),
- common virtual memory representation for data,
- selection of rule evaluation schemes,
- philosophy of separating control of flow specification *(strategic information)* from non-procedural information *(tactical information)* in the system, and
- emphasis on simplifying man-machine interaction.

Many of these features will be discussed in the next section. As this list shows, there is an emphasis on user and developer flexibility and convenience in ADVISE. The user interface is designed as an independent module and supports the idea of *friendly* user interaction. This interaction can be developed almost independently of the rest of the system and supports multiple terminal types.

There is the design goal of getting ADVISE *out to the public*. This is a major reason why Pascal was chosen as the implementation language. Good versions of Pascal are available on many microcomputer systems. A micro-based version of ADVISE has not been implemented yet but there are two methods to support them. One method is hand tailoring ADVISE to the microcomputer environment. The other more attractive option is automatic tailoring. ADVISE would eventually have a tool for doing this.

There is a goal of a *clean design* in ADVISE. In many expert systems the tactical and strategic knowledge is intertwined. This causes problems in explaining the reasoning of the inference process to the user. ADVISE is being designed to avoid this problem by maintaining a separation between control or *meta* knowledge, and factual knowledge of the domain. While the exact method of maintaining this separation has not been found, active research is under way. This goal of a clean design is also supported by a common representation for data at the lowest level of ADVISE. ADVISE was designed in the form of modules that provide support tools for expert system development. tools for inference systems. This modular design makes ADVISE flexible and elegant.

1.2. Conceptual Organization of ADVISE

Figure 1 shows a conceptual level diagram of the proposed system. The system consists of four major components:

(1) Control Block and User Interface

(2) Knowledge Base

(3) Query Block

(4) Knowledge Acquisition Block

Each component supports operations on three types of knowledge representations: a network structure, a rule base, and a data base. The functions of these four components are described in the corresponding sections below.

1.2.1. Control Block and User Interface

The control block and user interface manages the user's interaction with the other three portions of the system. It handles three distinct modes of operation of the system:

- Query mode
- Knowledge acquisition mode
- Explanation mode

The user interface portion of the system provides utility routines to manage the terminal screen and supports the explanation of internal data representations and operations in a textual and graphical form.

Query mode (Q-mode)

Query mode is used during consultation. In this mode, the system:

- selects questions to ask the user,
- accepts user answers and
- conducts an inference process involving the knowledge base and information provided by the user, in order to compute advice with an associated strength of supporting evidence.

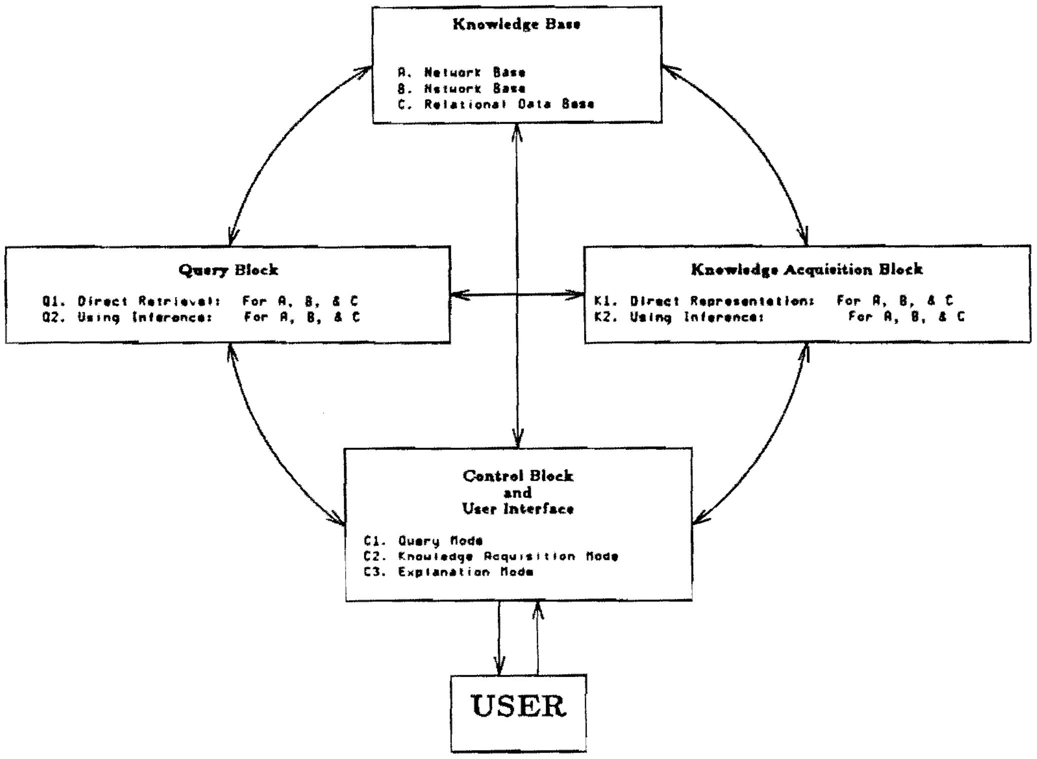

Knowledge Base
A. Network Base
B. Network Base
C. Relational Data Base
Query Block
Q1. Direct Retrieval: For A, B, & C
Q2. Using Inference: For A, B, & C
Knowledge Acquisition Block
K1. Direct Representation: For A, B, & C
K2. Using Inference: For A, B, & C
Control Block and User Interface
C1. Query Mode
C2. Knowledge Acquisition Mode
C3. Explanation Mode
USER

Figure 1: A conceptual diagram of the ADVISE system.

In one respect, the consulting portion of the system is radical in design. In particular, there is no single problem solving strategy. Rather, localized problem solving behavior is defined by the choice of an evaluation scheme (of which several are planned) and global problem solving behavior is governed by a control scheme within and among groups of rules. Specific provision has been made in the design for the inclusion of multiple control schemes and multiple evaluation schemes.

Knowledge acquisition mode (K–mode)

The knowledge acquisition mode coordinates both the encoding of expert derived rules into the knowledge base and the interactive invocation of the separate induction programs. This mode includes handling specific components for defining expert rules, manual refinement of rules, induction of rules from examples, and au[illegible]ated correction and improvement of the rules. The system also provides facilities for te[illegible]g rules in interactive mode on individual cases, as well as in batch mode on a collection of cases.

Explanation mode (E–mode)

The explanation mode paraphrases decision rules in English, enables a user to understand the organization and functioning of the system in query and knowledge acquisition modes, allows simple interrogation of the contents of the knowledge base, and displays the steps in the process which led to a given advice.

1.2.2. Knowledge Base

The network structure consists of three types of representation:

- a network base (e.g., conceptual network),
- a rule base, and
- a relational data base.

A unified "access protocol" is used for all three types of representation.

A Network Base

The network base contains network structures representing general domain knowledge about interrelationships among various conceptual units. For example, it can include hierarchies of terms from the application domain indicating the level of generality of such terms (a "generalization tree"), a representation of the structure of the rule base, and precedence relations defined over questions for the user. Links between nodes in the network represent "static" relationships between concepts. The network organization is a form of the "Logic Net" formalism described in [Baskin80].

Rule Base

The rule base contains rules in the basic form:

CTX CONDITION ::> CONCLUSION : α,β

where

CTX is a lexical expression describing the context within which the rule is applicable;

CONDITION is a formal expression (in VL2 [Michalski78]) which involves elementary conditional statements (called "selectors"), linked by various logic operators (including quantifiers);

CONCLUSION defines the decision or action which is executed when the CONDITION is satisfied by a given situation;

α is the strength of the evidence which supports the CONCLUSION when the CONDITION is completely satisfied $(0 \leq \alpha \leq 1)$ and

β is the strength of evidence which supports the negation of CONCLUSION when the CONDITION is not satisfied $(0 \leq \beta \leq 1)$.

The rule above is read: CONDITION implies CONCLUSION with forward strength "α" and backward strength "β". Specifically, the rule states that: if the left hand side (LHS) of the implication (::>) is satisfied, then the right hand side (RHS) is asserted with a degree of confidence α, and if the RHS is satisfied, then the LHS is asserted with a degree of confidence β. This rule is equivalent to the following group of rules:

```
CONDITION          ::>    CONCLUSION : α
not CONDITION      ::>  not CONCLUSION : α
CONCLUSION         ::>     CONDITION : β
not CONCLUSION     ::>   not CONDITION : β
```

By providing both "α" and "β" for each rule, it is possible to use rules for inference in both forward and backward directions.

The use of parameters (α,β) above can be illustrated by an example taken from contract bridge. In bridge, each member of a partnership learns the same set of rules for bidding (called a bidding convention). Qualifiers such as "must," "should," "usually," "seldom" and "never" are used in the verbal description of the rules for the strength of implication. A bidder uses the rules in the forward direction to decide what bid to make. The partner of a bidder uses the rules in the reverse direction to decide about the strength of bidder's cards.

One well known rule in the Standard American bidding convention is an opening bid of one no trump. A textbook description of this rule can be paraphrased:

> If you have a strong hand (16 to 18 high card points), a balanced hand (at worst one doubleton suit), and strength in all four suits (four stoppers) then you should *definitely* bid 1 no-trump. (i)

This rule can be expressed in the formalism which we are developing as:

[high card points = 16..18] [shortest suit = 2] (ii)
[number of doubletons $\leq$ 1] [number of stoppers = 4]
::>
[bid suit = no_trump] [level = 1] : α=1, β=0.8

where α=1 follows from the use of "definitely" in the rule. The value of "β" is the strength with which a bid of one no trump implies the hand described on the left hand side of the rule. The value of "β" is less than 1.0 because one no trump may be bid with other hands, as shown below.

The novice bridge player soon learns that like any other expert skill, bidding in bridge does not always deal in the absolutes described above. An experienced player will often use the following more general rule:

> If you have a hand which meets the above requirements for a 1 no-trump bid, except that it has less than three stoppers, then you should *usually* bid 1 no-trump. (iii)

The rule above can be represented using our formal language in the following way:

[high card points = 16..18] [shortest suit = 2] (iv)
[number of doubletons $\geq$ 1] [number of stoppers $\geq$ 3]
::>
[bid suit = no_trump] [level = 1] : α=.8, β=1

The parameter α=0.8 in the rule above indicates that if the left hand side of the rule is satisfied then the strength of confidence for a 1 no trump bid is somewhat less than it was in (ii). On the other hand, once this bid has been made, the partner can be certain (β=1.0) that the bidder's hand conforms to the requirements set forth in the left hand side.

The rules (ii) and (iv) above can be combined into a single rule by using "weights" associated with individual values of the variables. The following rule is a formal representation for both (i) and (iii) above:

[high card points = 16..18] [shortest suit = 2] (v)
[number of doubletons = 0,1] [number of stoppers = 3:0.7, 4:1.0]
::>
[bid suit = no_trump] [level = 1] : α=1, β=1

The coefficient 0.7 associated with "number of stoppers = 3" reflects the weakened strength of implication if there are three stoppers. Both the weights on the "number of stoppers" and the value of "α" are used to determine the strength of supporting evidence for the CONCLUSION. Since the weights have been associated with individual values, the global strength of implication, "α", can be assumed to be 1.

Relational data base

The relational data base contains relational tables which represent any factual information, e.g., examples of experts' past decisions. A modified relational algebra has been developed using constructs from Variable-valued Logic to make the user access more natural and more concise [Shubert77].

1.2.3. Query Blocks

The query block supports two types of queries: those which can be executed by direct retrieval from the knowledge base, and those requiring inference. Both types of queries are defined for all three types of representations in the knowledge base.

Query block using direct retrieval

Direct retrieval is used to display the contents of the knowledge base. The network base, the rule base, and the relational data base can each be retrieved and displayed using the query block. Direct retrieval is heavily used in the explanation mode of the system and also during knowledge acquisition.

Queries using direct retrieval on the relational data base include the traditional relational table operations such as as "project," "select" and "join" as well as various arithmetic or other transformations of the data items in the tables.

Query block using inference

One of the most important functions of the system is to compute the most plausible advice for the user in a specific situation. Queries involving inference (deductive and/or inductive) are supported for each form of knowledge stored in the knowledge base.

Queries using inference for the network involve "path following" within the network, e.g., "climbing the generalization tree." Inference over the network also occurs whenever the hierarchy is used to answer questions by searching the network for specified relationships between given concepts.

Queries using inference for the rule base are particularly important for providing expert advice. Rules are evaluated for a given situation using an "evaluation scheme" (a method of propagating uncertainties) in the order decided by a "control scheme." In this system, there is no single problem solving strategy. Rather, local problem solving behavior is defined by the choice of an evaluation scheme (of which several are planned), and global problem solving behavior is governed by a control scheme within and among groups of rules. We plan to implement several different evaluation schemes and a few control schemes in the system. In this way, a single knowledge base can be used for research into the performance of differing problem solving strategies for consultation.

The QUIN relational data base (Chapter 8) has been enhanced to allow queries using inference. These additional operations allow the inference of rules from examples.

1.2.4. Knowledge Acquisition Block

The knowledge acquisition block supports knowledge acquisition by the direct representation of knowledge provided by human experts and also by inductive inference from facts provided to the system. The design of the proposed system includes knowledge acquisition for each type of knowledge stored in the knowledge base.

Knowledge acquisition by direct representation

The direct representation of networks, rules, and data bases of facts or examples constitutes "learning by being told." This is the major way that knowledge bases are being constructed today. The direct representation of expert knowledge is particularly important in problem areas where "rules of thumb" or other generalizations about the problem domain are known. Material which is supplied by the expert for direct representation is entered into the knowledge base as specified, but it may be modified by further knowledge acquisition using inference as described below. Special user interface ("debriefing") for interactive specification of rules and networks is provided. Batch submission of sets of examples is supported as well.

Knowledge acquisition using inference

The inclusion of machine based inference as a part of the knowledge acquisition process is intended to reduce the burden on human experts. By defining inference procedures over each component of the knowledge base, the system no longer relies solely on the human expert to organize and present a complete, concise, and error free knowledge base.

Knowledge acquisition using inference for the network involves both deductive extensions to the knowledge base and the inductive derivation of new or improved network structures. As new information is added to the network base, rules of inference are "executed" to enforce the logical consistency and completeness of the network. This corresponds to inference of new concepts and relationships from existing ones. Also, machine derived categorizations and hierarchies can be inferred from the knowledge base using conceptual clustering techniques implemented in the program CLUSTER [Stepp80].

Knowledge acquisition using inference for rules includes the derivation of new or modified rules from existing rules or groups of rules using examples in the relational data base. This process will be implemented by adapting already developed inductive learning programs AQVAL [Michalski73], INDUCE [Larson77], and ID3 [Quinlan79]. Preliminary results by both principal investigators in this area suggest that the "refinement" of existing rule bases using induction is both possible and fruitful [Michalski80, Baskin78]. The derivation of patterns of rules or rule groups from the isolated rules is also supported by the proposed system. Although results in this area are still tentative, the inference of patterns in groups of rules should allow the iterative improvement of the control scheme by which rules are selected for evaluation.

Knowledge acquisition using inference for the data base corresponds to a form of clustering. In our previous experiments, clustering algorithms have been used to partition the set of examples into groups which are "similar." This operation corresponds to having a teacher label each example in the training set. The important property of the clustering algorithms is that they do not rely on a domain expert to categorize the examples. In addition, when the categories are not known, the clustering process can still be used. (The clustering operation corresponds to inductively deriving a relational operation which a human expert might have used to supply examples for the inductive derivation of rules.)

In addition to clustering, inference over a set of examples involves selection of the best "Representative" examples for use in the inference of rules. The program ESEL [Michalski78] has been developed for choosing examples from a large set of examples which are "representative" of the set. The proper selection of examples becomes particularly important when rule inference is computationally expensive. examples from a large set of examples which are "representative" of the set. The proper selection of examples becomes particularly important when rule inference is computationally expensive.

1.3. The Architecture of ADVISE

Figure 2 illustrates the architecture of the ADVISE system from a technical standpoint. Figure 2 shows the basic software modules in the ADVISE system and their interactions. A short description of each module is presented below:

- USER INTERFACE
  The user interface provides a set of software tools for creating sophisticated user interactions with the ADVISE program. It supports graphics, windows and menu driven user input. It is designed primarily to drive the Sun-2* Workstation, but is designed with minimum modification for portability in mind .
- CONTROL BLOCK
  This dispatches the major functions of ADVISE: parsing rules or networks using the parser modules, running a consultation using the rule base or network base modules, relational table query and inference using the QUIN module, and testing parts of ADVISE using the TESTER module. Currently the control block functions are implemented in a top-level window created using the user interface above.
- RULE EDITOR
  This module is an interactive menu-driven editor for rules. It uses both the rule parser and paraphraser. This module has been designed but not implemented.

*Sun-2 is a trademark of Sun Microsystems, Inc.

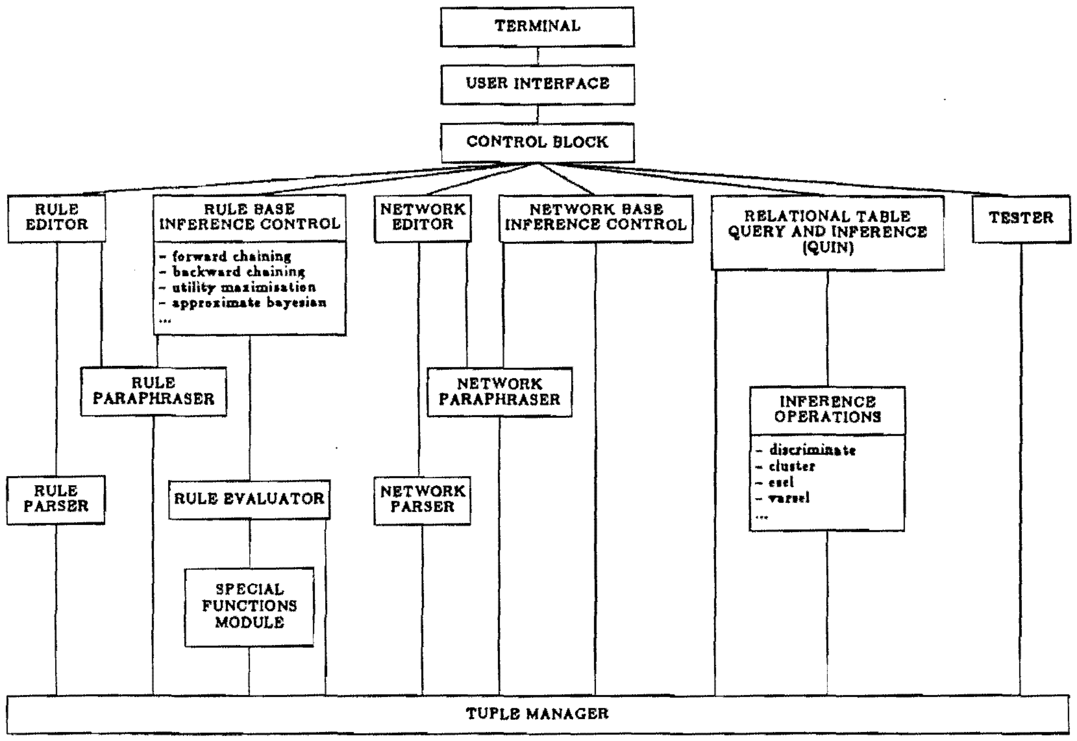


Figure 2: A technical diagram of the ADVISE Architecture.

- RULE BASE INFERENCE CONTROL
  The ADVISE system supports several types of knowledge base inference control (control schemes). They access knowledge in the tuple manager, request values for unknown variables and determine the truth value of pieces of knowledge via the rule evaluator.
- RULE PARSER
  This module parses an extended form of GVL_1 [Michalski80]. It outputs a parse tree that is read by the TUPLE MANAGER and stored in the tuple format.
- NETWORK EDITOR
  This module is an interactive menu-driven editor for networks. Its implementation is discussed in a chapter to follow.
- NETWORK PARSER
  An inference network is an alternate form of representing domain knowledge. This module parses the network representation into the tuple representation manipulated by the tuple manager.
- NETWORK BASE INFERENCE CONTROL
  This module is used to carry on inference on networks.

- QUIN
  This module is used to do queries and inference on relational tables. QUIN [Schubert77] calls a host of data analysis and learning modules such as AQ11 [Michalski78], ESEL [Michalski78], CLUSTER [Stepp80], PROMISE [Baim82], and CONVART [Davis81].
- TESTER
  This module is used to manipulate the tuple network directly. It also serves as a testing and debugging vehicle during the development of other modules in the system.
- PARAPHRASERS
  These modules are responsible for explaining to the user how rule and network inference is being used during a consultation. Another function of the PARAPHRASE module is used to "unparse" a rule from its parse tree form to the human readable form. This module is also used to explain the evaluation of particular rules to the user.
- RULE EVALUATOR
  This module is responsible for evaluating the premise part of a rule and asserting its consequent if it fires. It evaluates and asserts rule parts under a variety of semantics for logical connectives in a multi-valued logic interpretation.
- SPECIAL FUNCTION EVALUATION
  This module, also known as the TRAP module, is used to evaluate special functions. These functions can do such things as permit special displays, start up sensors, run models or simulations, etc. Presently there is one version of this module for PLANT/cd.
- TUPLE MANAGER
  The basic structure for storing information in ADVISE is the tuple. (Information is also stored in Pascal local variables, but this type of data is particular to the local environment and is not meant to be preserved.) An ADVISE tuple resembles the mathematical definition of a tuple (an ordered set) in which a set of tuples form a graph or network. Tuples, much like LISP property lists, are accessed by *context.* The tuple manager is based on the work in [Baskin80].

The overall system architecture outlined in this section has served as a guide for the development of the ADVISE system. In the following chapters, a detailed account of the current state of ADVISE is presented.

CHAPTER 2

The User Interface

2.1. Introduction

This chapter describes the development and current state of the ADVISE user interface. The problem of human–computer interaction has received much attention [Bo82]. The study of computer user psychology, an outgrowth of earlier work in human–computer interaction, has emerged as a viable subfield in computer science [Moran81]. A difficulty in working in this area is that so many factors are involved in designing such interactions that cannot be pinned down with algorithms. The designer must rely on his own intuition, which can be remarkably deceptive. The aesthetic aspect of this problem (i.e., what is the most appealing way of presenting information) is most certainly a matter of personal taste. In view of these problems, our approach has been to refine our program interfaces by subjecting them to several cycles of group criticism. Some general guidelines that evolved from this effort are presented in the next section.

2.2. Philosophy of the Interface

Although computer scientists seem often to lose sight of this fact, the human user is a far more sophisticated "computing device" than any current computer program. With this in mind, we offer some general principles that have proved useful in the development of the user interface.

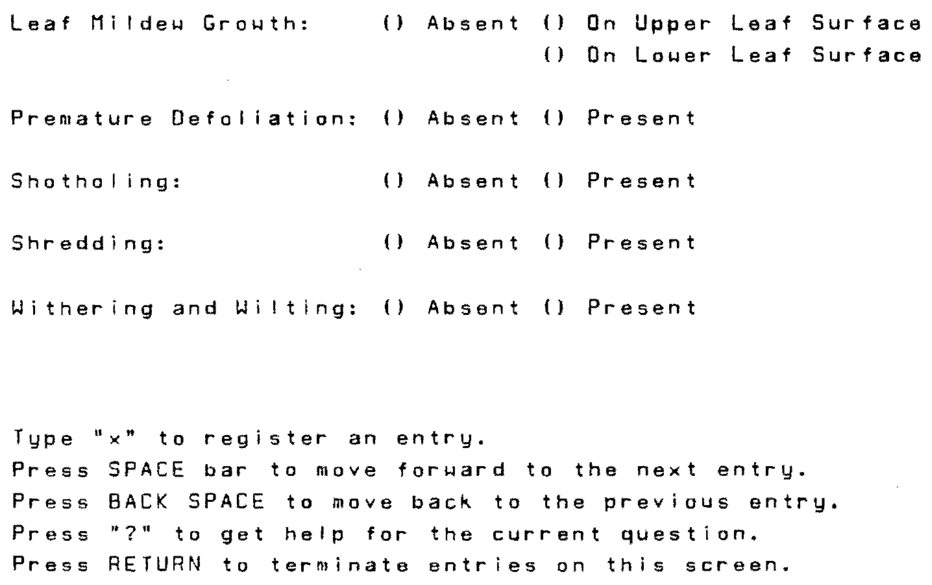
- Feedback : This can be as simple as verifying the user's input by prompting, or highlighting his response (in the case of option selection from a menu). If processing time between user responses is too long (as little as two seconds) it is important to indicate that the computer is doing something. This feedback should be placed somewhere near the current text insertion point. Particularly long response times are acceptable only if the user thinks that something particularly useful and important is being accomplished.
- Help : Help should always be made available to the user. With regard to expert systems, some indication of the status of the consultation should be provided. The program should distinguish between novice and experienced users. The novice should be provided with introductory material and perhaps more specific prompts. The user's name is requested prior to a session, and a history of interaction is maintained with the program, in order to determine his user class. The novice user learns a great deal about a program in the first encounter, and the program should respond to this within a single session. For example, explanatory prompts may be presented the first few times they are used and then become more brief as the consultation progresses.
- Backup and Error Accommodation : The user should be allowed to "undo" anything he/she has done. A related issue is that the user should be allowed to query the program about answers to previous questions. A useful mechanism with respect to user errors is to provide immediate feedback after a user response (a definitive statement of what has been requested).
- Consistency : The display should be logically laid out. Option menus should always be placed in the same area of the display. Each keyboard character should have a single

function and user typing should be minimized.

- **User Bandwidth** : We favor a block based interaction where a *block* is a single screenfull of information. Each block should provide multiple options and allow several questions to be answered before moving on to the next block.

These guidelines alone do not guarantee a successful interactive program. Each interaction should be be analyzed to minimize false expectations in the user. This analysis should not be performed by the program designer, but by a variety of outside sources. To illustrate some of these concepts, some blocks from the PLANT/ds program are presented.

Figure 3 shows a multiple question block that is used to gather information concerning the leaves of a diseased plant to be diagnosed:



```
Leaf Mildew Growth:        () Absent  () On Upper Leaf Surface
                                      () On Lower Leaf Surface

Premature Defoliation:     () Absent  () Present

Shotholing:                () Absent  () Present

Shredding:                 () Absent  () Present

Withering and Wilting:     () Absent  () Present


Type "x" to register an entry.
Press SPACE bar to move forward to the next entry.
Press BACK SPACE to move back to the previous entry.
Press "?" to get help for the current question.
Press RETURN to terminate entries on this screen.
```

Figure 3 : Multi-question frame from PLANT/ds.

The user moves back and forth between questions, answering those appropriate to the situation. A single key press guides all of these functions. Help concerning these questions is always available.

Figure 4 shows a block that gets the value for a single variable. The user first enters the value (or any option), then he may or may not be asked to enter a confidence in that answer. After input is complete, the program prints the message that it is preparing the next question.

```
How would you describe the pattern of leaf spots growth?
     1 -  From edge of leaf inward.
     2 -  Scattered and plain.
     3 -  Scattered with concentric rings.
     4 -  Brown veinal necrosis.
     5 -  Does not apply.

     b -  go back one question
     d -  display a rule
     e -  explain how to answer the question
     p -  list pursued hypotheses                 high      - >85%
     r -  list rejected hypotheses                low       - >35%
     w -  why is the question being asked         certain   - 100%

 Type one number or letter indicating your choice

     #  with confidence in the answer:   c (certain) / h (high) / l (low)   #

     Preparing next question
     |-------------------..............................................|
```

Figure 4 : Single question frame from PLANT/ds.

Although PLANT/ds manages to meet the guidelines stated above, its interface has become outdated by the advent of windows, mice, and workstations. The next section traces the development of the user interface from the beginning of the ADVISE effort, from the *blocks* of the *display module* to windows and pop-up menus.

2.3. Historical Development of Interface Tools

As long as ADVISE has existed, a user interface has been needed. Along with the evolution of the ADVISE computing environment, the user interface has developed considerably. The first attempt was called the *display module*. Many ideas emerged from the display module work to shape further development. The display module lacked a sophisticated degree of terminal independence which *Advisecore* [Channic84], the second generation interface, sought to resolve. When development settled into the workstation environment, the third generation interface, the SunWindows* interface was born. Each of these interface generations is described briefly below.

*SunWindows is a trademark of Sun Microsystems, Inc.

2.3.1. The Display Module

The primary goal in the design of the Display Module was to provide tools for the construction of a user interface that is as independent as possible from the rest of the ADVISE system. By doing this, the interface designer is freed from concerns regarding the rest of the program and can concentrate on the the user interface alone. It is important to be able to cycle through an interface design in order to arrive at "friendly" interaction.

With this in mind, the Display Module was developed as a separate, independent module. Some concepts which guided its development draw from the work of [Thursh80]. In that work, the authors address the problem of developing a teaching tool for general and systemic medical pathology. The software that evolved, Blockr, views a man–machine dialog as consisting of a series of *blocks* of single screenfulls of text and diagrams. These *blocks* can point to each other or themselves, forming a very general network structure. *Blocks* are treated as data, consisting of text and instructions that, when interpreted, cause an organized page of information to be presented at the terminal. Since the system is data (*block*) driven, the interaction can be prepared independently of the program that interprets it. We have, in effect, an expert system for user interface design.

As mentioned earlier, the primary data structure manipulated by the Display Module is the *block*. Since *blocks* consist primarily of data, they can be created via a simple editing process. One consequence of the single screenfull of information organization is that it encourages the presentation of several questions on a single *block*. This is consistent with the goal of high bandwidth discussed in the previous section.

The Block Manager controls the interface between the *blocks* and the user program (in this case the Control Scheme). This interface was organized in co–routine fashion; the block manager would be invoked, cycle through a series of help *blocks* and return control to the Control Scheme for user input. All user input was passed to the Block Manager which would handle range checking and error processing. One component of the Block Manager, the Block Interpreter, was be responsible for translating *blocks* into a form that can drive a specific output device. It had access to a set of low–level routines of the form consistent with the proposed CORE graphic standards [Foley82].

2.3.2. Advisecore

As computer interfaces developed outside Advise, the display module became outdated since it had no facilities for overlapping windows or pop–up menus. The display module also lacked terminal independence. To utilize windows and menus and to facilitate terminal independence, Advisecore was developed. Advisecore was also based on the CORE graphic standard, primarily for (but not limited to) use with the SunCore graphics package on a Sun Workstation.* There were two major goals for Advisecore as described below.

Concurrent Processes with Status Reporting. Multiple active windows should be able to co–exist on a single screen if desired. Effective screen management must allow several processes to be active at any given time.

Processes Bound to Windows. In a window system, it is usually desirable to be able to choose the location and size of a window in which a program runs. Being able to do this without any modification to an existing program is also desired. To accomplish this, screen management must provide a means for running a program which runs on a standard terminal within a window of any reasonable size.

*SunCore and Sun Workstation are trademarks of Sun Microsystems, Inc.

In the Advisecore interface, screen management consisted o: o aspects. The first is a screen manager process which handles window requests from all other modules. The second is a window filter process which allows a program to be bound to and run inside a window as if it were running on a standard terminal. Figure 5 shows how these two processes fit into the Advise system. The screen manager process handles all calls to display or receive information to/from the user's terminal. If an Advise module does not use screen manager

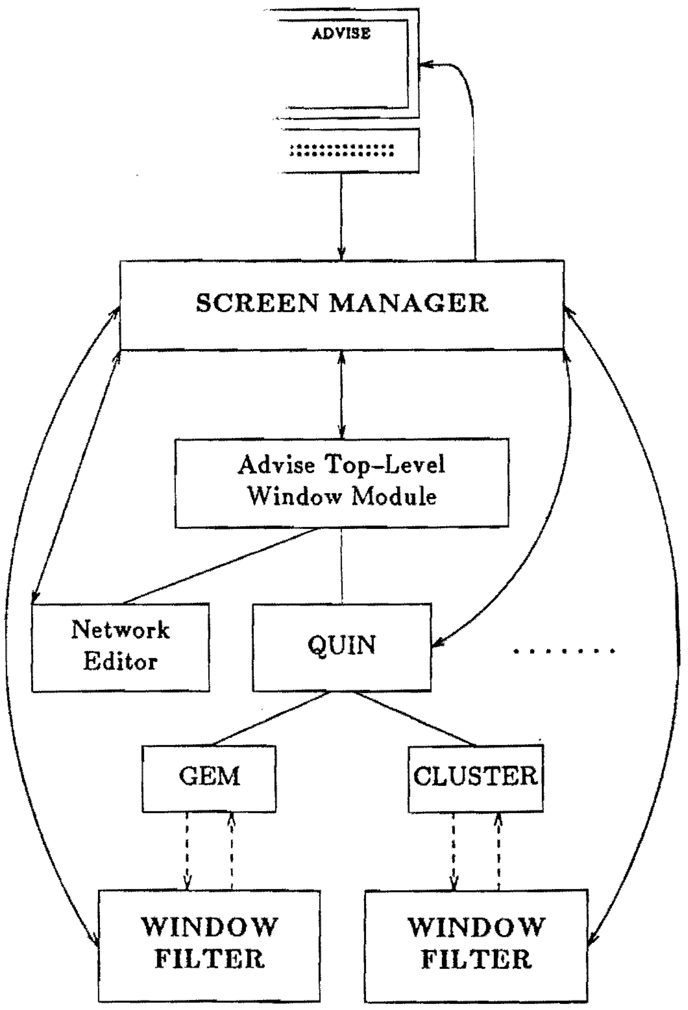


Figure 5 : Screen Management :n Advisecore.

calls for such information, it must use an instantiation of the window filter process for communication with the screen manager process. Both the screen manager and window filter processes are described in detail in the appropriate section below. The processes are described in terms of their existing or proposed implementation.

2.3.2.1. The Screen Manager Process

The main feature of the Advisecore screen manger is interprocess communication. As mentioned earlier, screen management loses a lot of functionality if multiple processes cannot be concurrently active within different windows. For this reason, some sort of interprocess communication is essential. The Advise screen manager uses sockets in the UNIX* operating system for interprocess communication. The sockets are represented in Figure 5 by bidirectional arrows. Sockets are a reliable means of two-way communication between processes. The Advise screen manager is designed to receive window requests from a process and also to deliver any input directed to that process from any window that process may have on the screen. This communication between a process and the screen manager is accomplished through a socket which is established during initialization of the Advisecore interface. Once the socket is established, further window routine calls merely send the request along with its parameters to the screen manager via the socket. The screen manager then executes the appropriate output action.**

Delivering input to a window is somewhat more involved. The screen manager must maintain a list of which windows belong to which processes and whether or not the process is awaiting input in those windows. At any given time, only one window is active with regard to input. The active input window is the window in which the mouse device is currently located. Any input which occurs is delivered to the appropriate process if that process is awaiting input. Otherwise, the input is ignored.

In order to handle input properly, a facility for polling the terminal input must be available so that the screen manager isn't stuck waiting for input when it could be processing other window requests. This facility is referred to as non-blocking input/output which means that a process does not get blocked if input is not available or if output is not currently possible. The screen manager must not be blocked when looking for input either from the terminal or from any socket for window routine requests. UNIX supplies this mechanism via the select system call. This call is essential to the Advise screen manager design.

The main algorithm of the Advise screen manager is briefly described below.

(1) Poll (select) socket for new connections to processes calling the coreinit routine.

(2) Poll (select) connections on socket for a request and process if present.

(3) Poll (select) standard input.

(4) If input is pending find out if the active window is expecting input. If it is, echo the input (if indicated by request) and send the input over the appropriate connection. Otherwise ignore the input.

(5) Go to (1).

*UNIX is a registered trademark of Bell Laboratories.

**Executing the appropriate output action, however, is much easier said than done. Problems of overlapping windows and redrawing damaged regions are non-trivial but are not dealt with here. These problems are solved by the screen packages used by the Advise screen manager and not by the Advise screen manager directly.

2.3.2.2. The Window Filter Process

The window filter process allows processes which run on standard terminals to run within a window in the Advise interface. The window filter process currently exists only on the Sun version of the interface as part of the SunWindow screen manager package.

In the VAX version, the filter is designed as follows The filter uses a socket to communicate with the screen manager and *pipes* to communicate with the process. Pipes are represented as dashed arrows in Figure 5. The window filter performs the following functions.

(1) Requests that a window be opened on behalf of the process.

(2) Receives output from the process via an output pipe and translates the output into window routine requests which are sent to the screen manager over the socket.

(3) Receives input to the process via socket from the screen manager and passes that input to the process over the input pipe.

(4) Requests that the window be closed when the process terminates.

2.3.3. The SunWindow Interface

As the ADVISE effort has progressed, the workstation environment proved increasingly productive until it clearly became the environment of choice. Development of the user interface focused largely on utilizing the existing window management features of the workstation to satisfy the interface goals. A Pascal interface to the SunWindow package was created to facilitate the use of existing window management programs, obviating the need for sockets and pipes. The SunWindow package was sufficiently flexible to be adapted to meet the screen management goals.

Two applications of the SunWindow interface have been developed. The first was a screen-oriented network editor which is described in a later chapter. The second is a top-level window which provides the necessary "hooks" and tools for existing ADVISE programs to run within a unified window format. The following section describes the top-level interface to ADVISE.

2.4. The Current User Interface

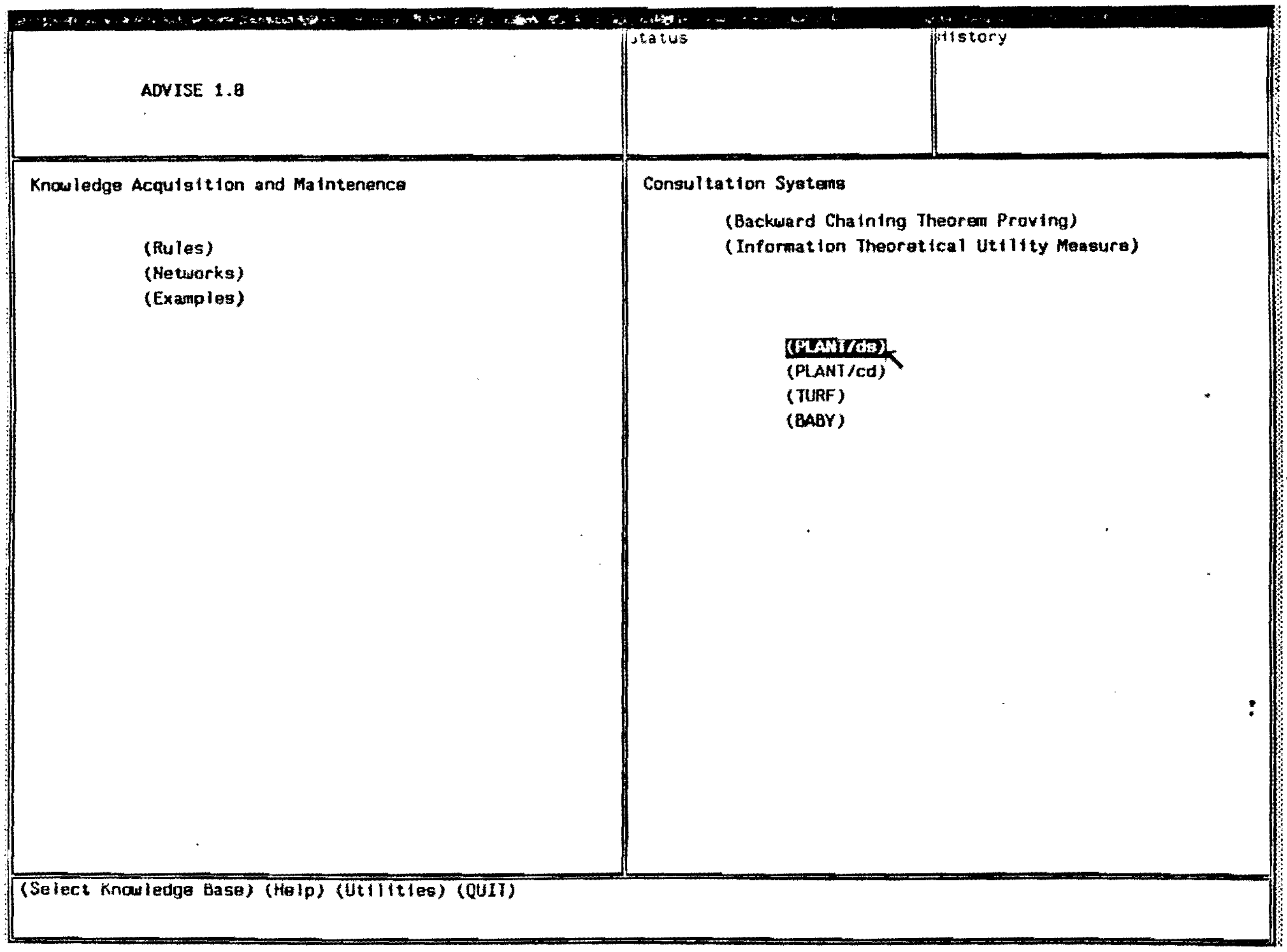
This section contains six screens that represent a flavor of the initial entry into the ADVISE interface. The first slide is the top-level screen. It offers a variety of options via static menus.

Following slides show entry into a consultation system (PLANT/ds) and into an interactive editor (the Network Editor). A knowledge base (backup file) is passed to knowledge base editors as an argument if a knowledge base has already been selected at the top level. Once an editing session begins, the options are sufficiently different as to make impractical a common editing language for rules, networks and tables.

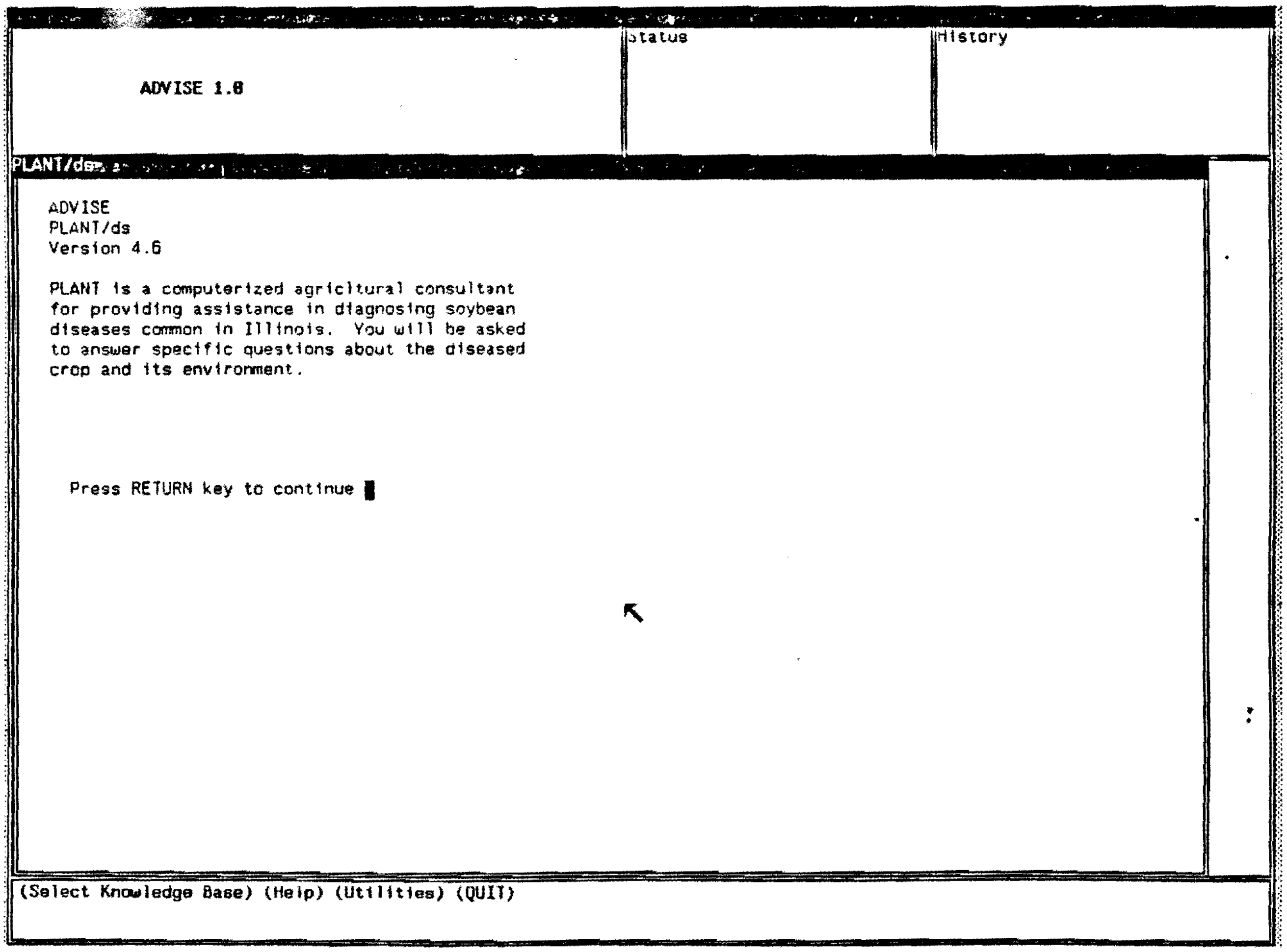
These screens represent an approximation of the final interface. Continued use of the interface warrants regular refinements and modifications.

The first screen is the top-level screen for ADVISE. At the top of the screen are two windows – status and history. The purpose of the status window is to capture diagnostic output from other ADVISE modules (that may or may not run in the background) and allows the user to examine that output at will. The history window was designed so that the user can see where he's been in the system. The history window might indicate, for example, what windows if any are currently overlapped. At the bottom of the screen is a global menu that may change from time from time, depending on the interaction with the user. Options here will generally be extraneous things to do and not directly related to knowledge engineering tasks. The main window on the left allows the user to select a way of looking at a knowledge base. The right window offers control scheme strategies, as well as manifestations of these control schemes – actual consultation systems.

Here the user is selecting the PLANT/ds consultation system.

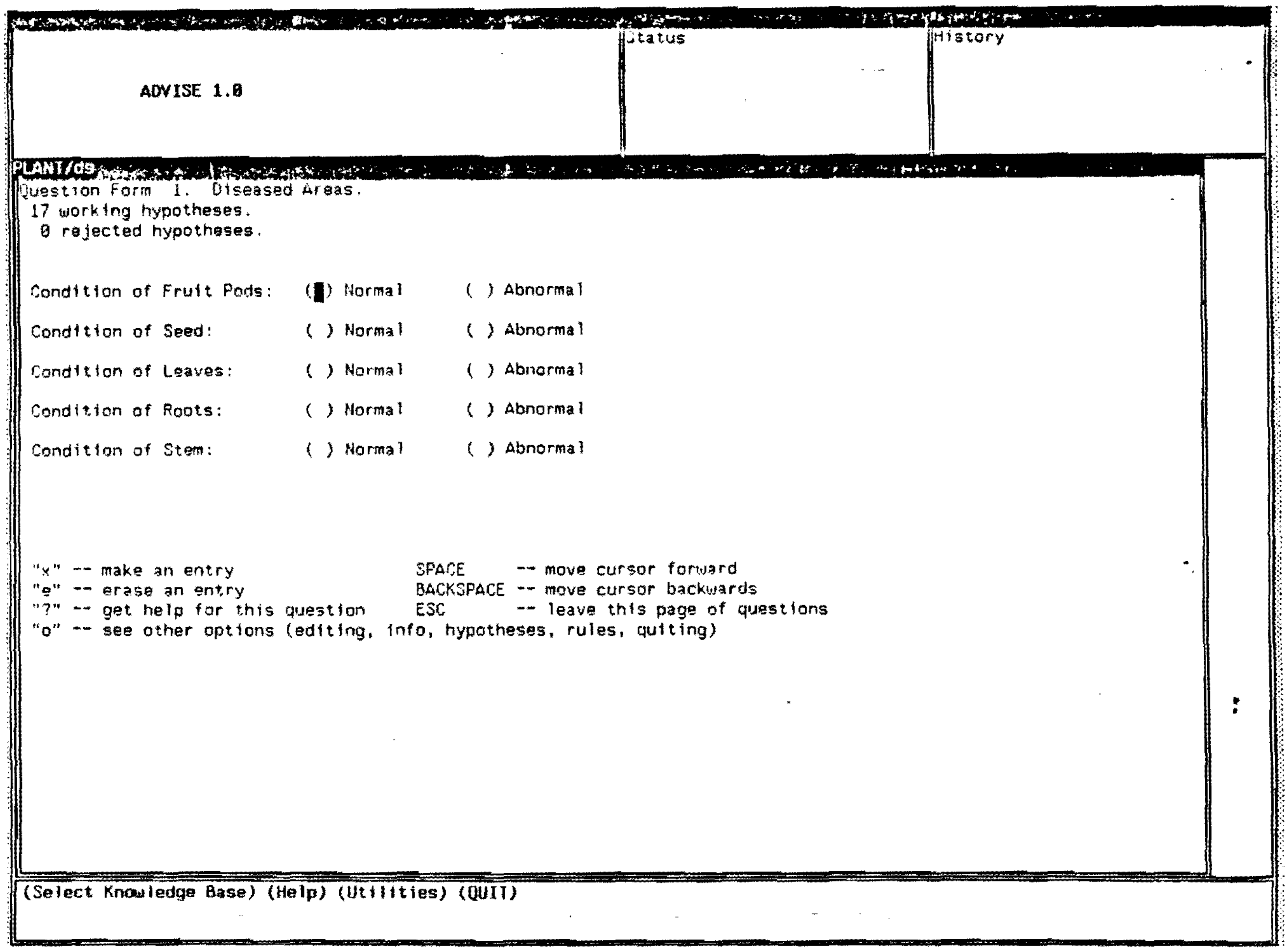

Status
History
ADVISE 1.8
Knowledge Acquisition and Maintenence
(Rules)
(Networks)
(Examples)
Consultation Systems
(Backward Chaining Theorem Proving)
(Information Theoretical Utility Measure)
(PLANT/ds)
(PLANT/cd)
(TURF)
(BABY)
(Select Knowledge Base) (Help) (Utilities) (QUIT)

This screen shows the initial entry into PLANT/ds. Note that the plant window obscures all the other options on the top-level window (except for the extraneous ones at the bottom). PLANT is not open to modification by the naive user, hence he is not allowed to play with control schemes or knowledge bases at the time he runs PLANT.



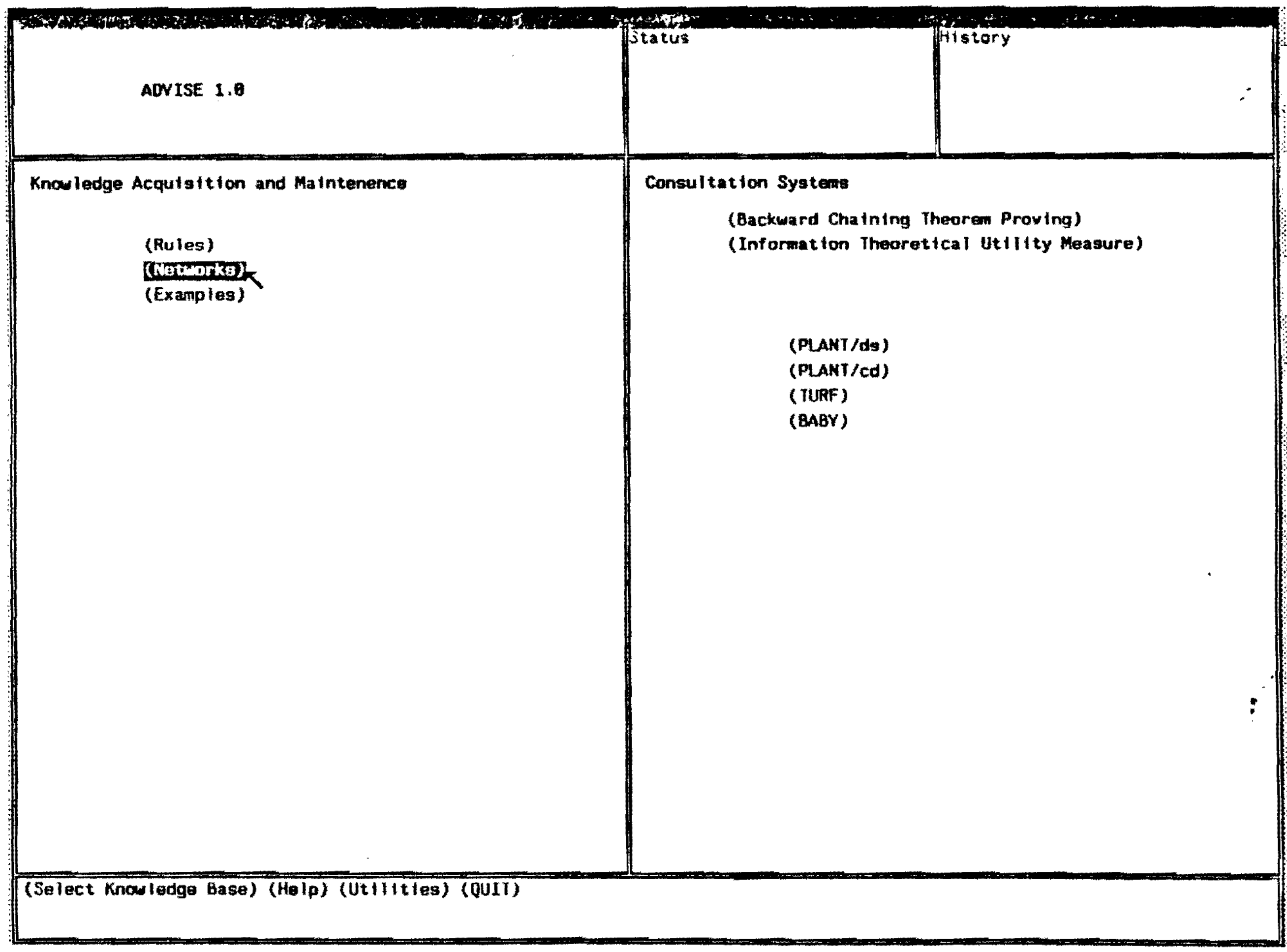
```
ADVISE
PLANT/ds
Version 4.6

PLANT is a computerized agricltural consultant
for providing assistance in diagnosing soybean
diseases common in Illinois.  You will be asked
to answer specific questions about the diseased
crop and its environment.



  Press RETURN key to continue
```

The PLANT window allows plant to run in a window as if it were on a terminal. This allows programs to run in the window system without any modification whatsoever. Of course, programs being developed now make explicit use of window management routines, such as the network editor. (See later screens.)



```
Question Form  1.  Diseased Areas.
 17 working hypotheses.
  0 rejected hypotheses.

 Condition of Fruit Pods:   (█) Normal      ( ) Abnormal

 Condition of Seed:         ( ) Normal      ( ) Abnormal

 Condition of Leaves:       ( ) Normal      ( ) Abnormal

 Condition of Roots:        ( ) Normal      ( ) Abnormal

 Condition of Stem:         ( ) Normal      ( ) Abnormal



 "x" -- make an entry                  SPACE     -- move cursor forward
 "e" -- erase an entry                 BACKSPACE -- move cursor backwards
 "?" -- get help for this question     ESC       -- leave this page of questions
 "o" -- see other options (editing, info, hypotheses, rules, quiting)
```

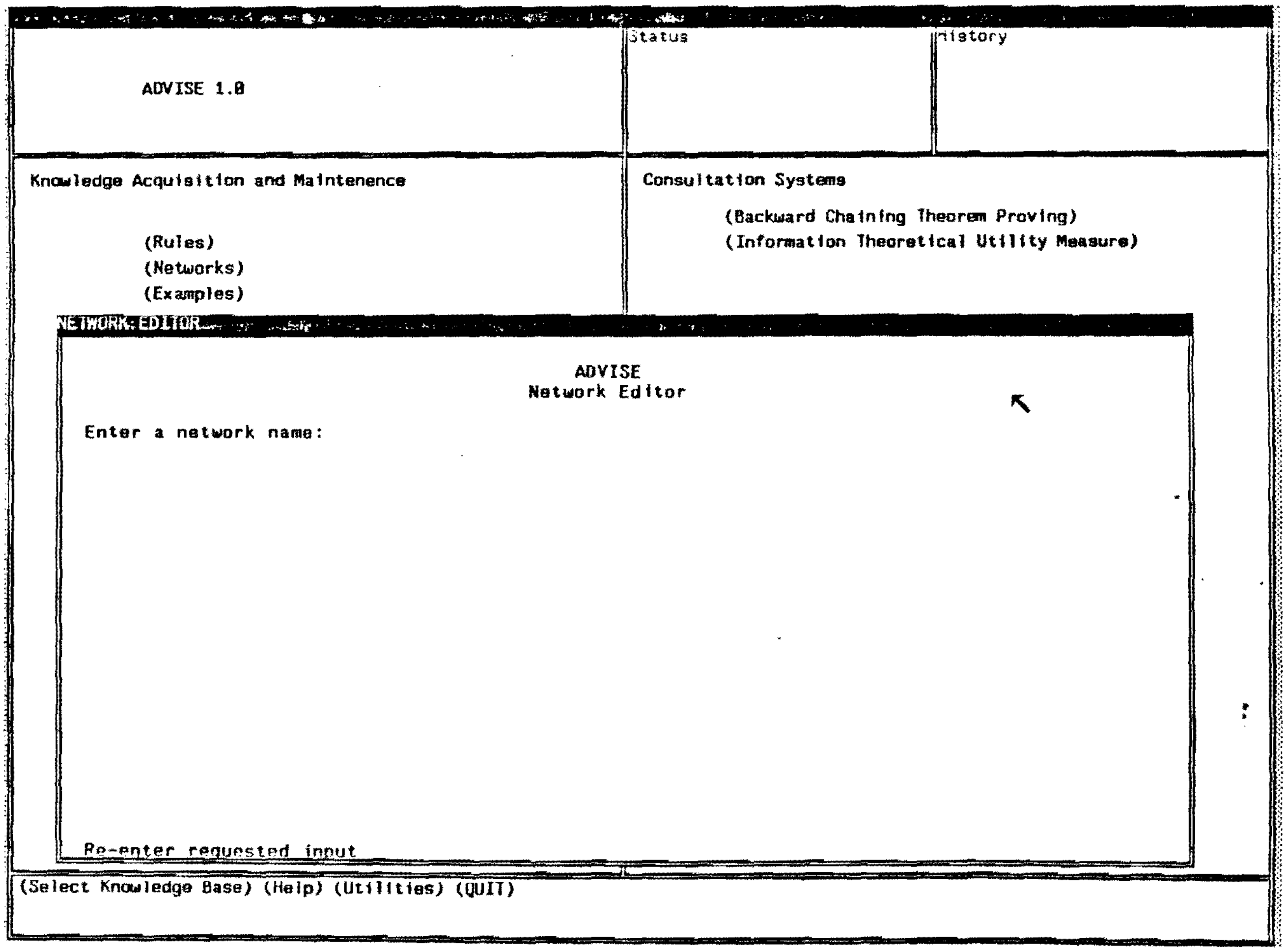
After exiting PLANT, the user returns to the top-level window. Here the option of looking at a knowledge base as a network is being selected.



```
ADVISE 1.0                              Status          History

Knowledge Acquisition and Maintenence   Consultation Systems

                                             (Backward Chaining Theorem Proving)
        (Rules)                              (Information Theoretical Utility Measure)
        (Networks)
        (Examples)

                                                 (PLANT/ds)
                                                 (PLANT/cd)
                                                 (TURF)
                                                 (BABY)

(Select Knowledge Base) (Help) (Utilities) (QUIT)
```

The screen below shows the initial entry into the network editor. If there were other facilities relating to networks the user would instead get a menu of available options from which to select. Since no knowledge base was selected prior to selecting networks, the network editor prompts the user for one. If a knowledge base had been selected, the network editor would have tried to open that knowledge base.

Unlike the PLANT window, the editor does not obscure all the options on the top–level window. Conceivably, a user may want to view the same knowledge base as rules, networks, and tables. In addition he may want to transfer data between the two. For example, a user could create a rule in the rule editor and add it as a node in a network by using the mouse to "pick up" the rule from the rule window and "carry" it to the network editor window.*

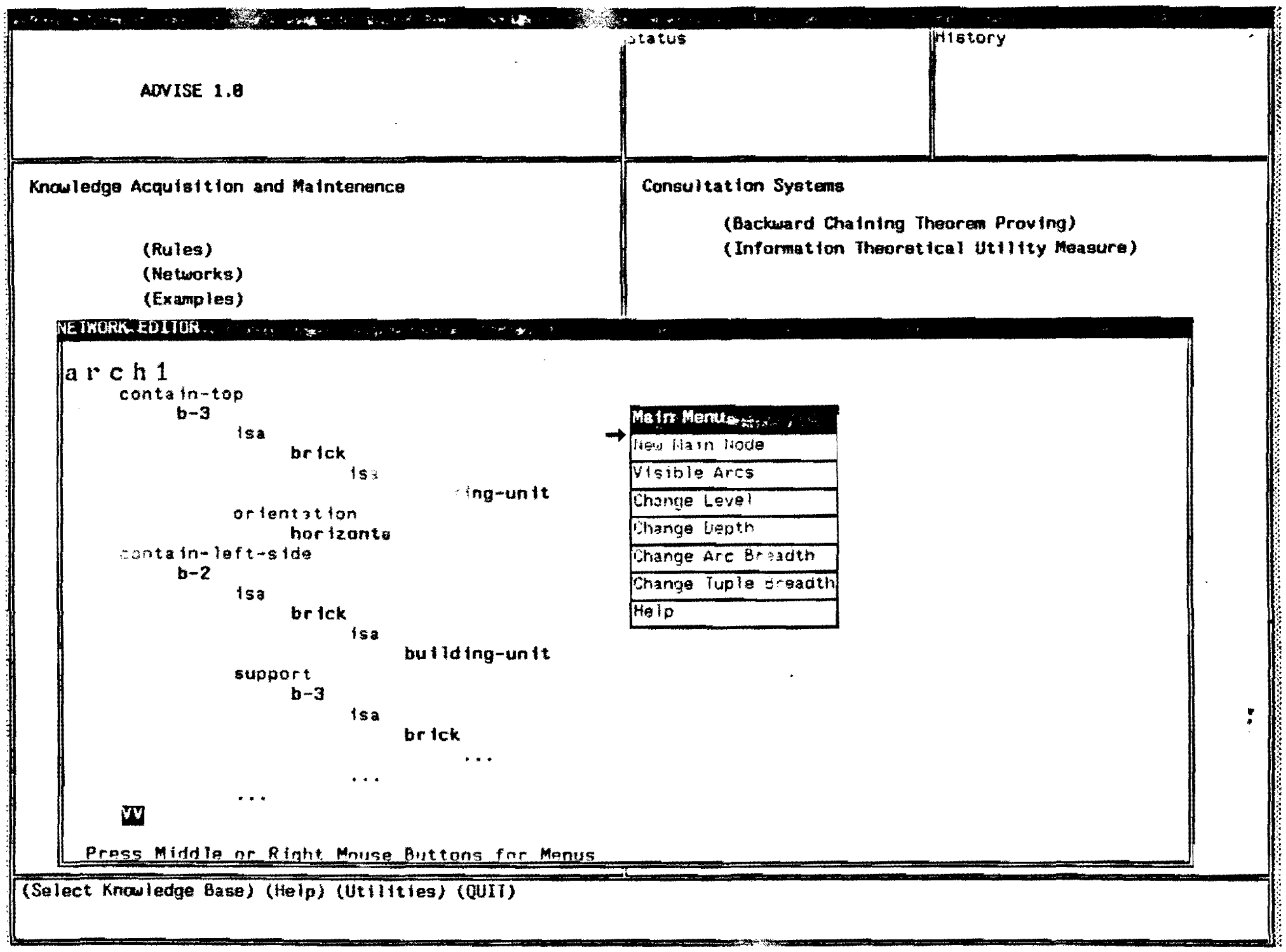

ADVISE 1.0
Status
History
Knowledge Acquisition and Maintenence
(Rules)
(Networks)
(Examples)
Consultation Systems
(Backward Chaining Theorem Proving)
(Information Theoretical Utility Measure)
NETWORK EDITOR
ADVISE
Network Editor
(Select Knowledge Base) (Help) (Utilities) (QUIT)

Enter a network name:

Re-enter requested input

*Currently this transfer of data is not implemented.

This screen shows the display of the selected network along with the main menu of options. At this level, options are peculiar to the individual programs and the menus are the individual program's responsibility. The top-level menus provide all the options by which these lower levels may be entered, and are meant to be as flexible as possible without imposing any arbitrary language for starting up a variety of knowledge engineering tools.



ADVISE 1.0

Knowledge Acquisition and Maintenence

(Rules)
(Networks)
(Examples)

Consultation Systems

(Backward Chaining Theorem Proving)
(Information Theoretical Utility Measure)

NETWORK EDITOR..

```
arch1
    contain-top
        b-3
            isa
                brick
                    isa
                        ing-unit
            orientation
                horizonta
    contain-left-side
        b-2
            isa
                brick
                    isa
                        building-unit
            support
                b-3
                    isa
                        brick
                            ...
                    ...
            ...
```

Press Middle or Right Mouse Buttons for Menus

CHAPTER 3

The Network Editor

3.1. Introduction

The network editor provides the facility for directly manipulating and editing Advise knowledge bases. Previously, when a knowledge base needed to be changed, either a text file (which is frequently not an accurate representation of an ADVISE knowledge base) had to be edited or the program that created the knowledge base must also include code to alter the knowledge base. For example, the only way to alter the PLANT knowledge base was either to text edit backup knowledge base files or run a rule parser on new input rules. QUIN, a program for editing knowledge bases represented as relational tables (Spackman 1983), is available but has minimal benefit for the rules and network representations of currently implemented systems.

This chapter describes the network editor, which provides ADVISE with the capability for interactive manipulation of knowledge bases. A brief description of the ADVISE knowledge representation is provided below followed by the features of the editor and a presentation of a sample interaction.

3.2. The ADVISE Network Representation

The basic structure for representing knowledge in ADVISE is a *tuple*. A tuple is similar to a list in LISP. *Nodes* are like LISP atoms (nodes *cannot* be tuples), and a tuple is just a list of nodes. The second node of the the tuple usually has special meaning as a relation or arc between the head node and subsequent nodes in a tuple. A typical tuple looks like the one. below.

```
(headnode arc subnode1 subnode2 subnode3 ...)
```

Of course, the same head node can have many arcs (relations) under it. These can be represented simply by additional tuples as follows.

```
(headnode arc1 subnode11 subnode12 ...)
(headnode arc2 subnode21)
(headnode arc3 subnode31 subnode32 subnode33 ...)
```

For efficiency reasons the above tuples would be represented internally as follows.

```
(headnode (
      (arc1 subnode11 subnode12 ...)
      (arc2 subnode21)
      (arc3 subnode31 subnode32 subnode33 ...)
))
```

In the actual implementation of this representation, nodes are memory addresses. Nodes have printnames associated with them as well as being associated with the tuples in which they appear as head node. The ADVISE tuple manager (see Chapter 11) handles all the manipulations of the knowledge base on the tuple level. The network editor simply makes the appropriate calls to the tuple manager based on its interaction with a user.

The tuple representation represents an important generalization over the basic concept of semantic networks (as described, for example, in [Winston84]). Thinking about tuples in light of these networks, each tuple with the same head node can be considered a slot, each slot has a name (arc) and a value. Slot/value combinations are also known in ADVISE as *attributes*. The generalization over other representations is that slots or attributes can have many values associated with them. Thus, similar slots can be combined into a single slot

(house ((has-room living-room dining-room bedroom kitchen)))

or a single slot may have several values associated with it, for example, both a qualitative and quantitative value.

(block-1 ((orientation vertical 89.5)))

The ADVISE representation of knowledge via tuples is a general mechanism for representing, not only networks, but rules and relational tables as well. These representations, however, are beyond the scope of this chapter.

3.3. Features of the Network Editor

The network editor is a menu-driven interactive program with modest use of graphics, which runs on a Sun-2 Workstation. The interface is written on top of the SunWindow package developed by Sun Microsystems, Inc. (See Chapter 4). Naturally, being menu-driven, it is easy to figure out how it works just by pressing the right buttons. Hands-on experimentation is the best way to learn to use the editor. For a detailed user's guide see [Channic85]

The following sections describe the display of networks and the options available for editing networks.

3.3.1. Screen Representation of Networks

In displaying a network, a non-graphic approach was taken to allow minimum modification for running the program on machines without graphic capabilities. Nevertheless, the network structure is readily apparent as the screens in Section 5.4 demonstrate. Nodes are represented in boldface. Arcs under nodes are not in boldface, and are set one line below and indented from the main node. Subnodes under arcs are placed similarly under the arc. Additional subnodes are placed on the same line immediately following the preceding subnode.

The only other thing a user need know in order to use the network editor is how it clips the network to fit on a display. There are three parameters which affect the display – namely, depth, arc breadth and tuple breadth. Depth is the number of arcs down from the main node to display. Arc breadth is the number of arcs to traverse from each node. And tuple breadth is the number of subnodes to display under the head node. How these parameters affect the display will be seen in the interaction section.

If in spite of these parameters the network still cannot fit on the screen, the network editor leaves markers that indicate information has been clipped from display. At the top level of the network, these markers are arrows that point in the direction of the missing information. Menus are available at these markers to scroll the top level of the network in order to see the missing information. Beyond the top level of the display, missing information is indicated by a string of dots – "...". Missing information at this level can usually be viewed only by descending the network to make this level the new top level and, if necessary, scrolling or changing the appropriate parameters.

3.3.2. Local Editing Options

At each node or arc in the network, two sets of options are available. One set of options affects the node or arc itself, the other set affects the environment around the node or arc. An example of a *local* option is changing a printname of a node. An example of a *global* option is adding an attribute after a node. Various local options are discussed in the remainder of this section. The following section describes the global options.

Options Available When Not At an Arc or Node

New Main Node	Allows you to enter the name of a node which will become the new top node in the display.
Visible Arcs	Allows you to select a subset of arcs to follow in displaying the network
Change *****	Allows you to enter a new value for ***** – depth, breadth, or tuple breadth – which will affect the display accordingly
Back Up	If present in menu, allows ascension of the network to the previous top node
Help	Prints this message

Options Available from Arcs

Change Arc	Allows a new arc to be inserted in place of the arc in the current attribute.
Change Printname	Allows the printname of the current arc to be changed EVERYWHERE it occurs in the network.
Delete Attribute	Removes this arc and all subnodes from underneath the head node, i.e. the entire tuple is removed.
Yank Arc	Places this arc into the arc buffer to be used in subsequent Put Arc operations
Yank Attribute	Places the attribute (this arc and all nodes underneath it) into the attribute buffer to be used in subsequent Put Attribute operations.
Make Invisible	Inhibits the display of this arc and all other occurrences of this arc as well as everything underneath them.
Enter Dictionary	If an arc, does not appear in the dictionary, this option allows you to put it there.
Help	Displays this message.

Options Available at Nodes

Change Node	Allows you to change a numeric node to a new number or to a new node.
Change Printname	Allows you to change the printname of this node EVERYWHERE it occurs in the network
Delete From Tuple	This node is removed from its current tuple position.
Yank	Allows you to yank this node into the node buffer for subsequent 'Put Node' operations
Make Focus	This node becomes the new top node in the display of the network.
Enter Dictionary	If the node is not in the dictionary, you may enter it there if this option is present. If and only if a node is in the dictionary, it can be made the main node via the 'New Main Node' option on the Main Menu
Help	Prints this message

3.3.3. Global Editing Options

Global editing options reflect options that affect the environment of the node or arc pointed to by the mouse.

Options Available When Not at an Arc or a Node

Edit/Create	Start a new session with a new network
Write (Backup)	The edited network will be written to the file given at startup
Write (Text)	A text representation of the edited network will be written to a specified file.
Quit	Graceful exit from a session, updating the network
Abort	Immediate exit from editor, no update.
Help	This message

Options Available from Arcs

Add Node	Allows a node to be added immediately under the current arc in the attribute in which the current arc occurs. Nodes presently under the arc are shifted to the right.
Add Attribute	Allows an attribute (an arc followed by zero to 254 nodes) to be added under the main node below the attribute which contains the current arc.
Put Node	The contents of the node buffer will be put immediately under the current arc in the attribute in which the current arc occurs. Any nodes presently under the arc are shifted to the right.
Put Arc	The contents of the arc buffer will be put under the main node below the attribute which contains the current arc.
Put Attribute	The contents of the attribute buffer will be put under the main node below the attribute which contains the current arc.
Help	This message is displayed.

Options Available From Nodes

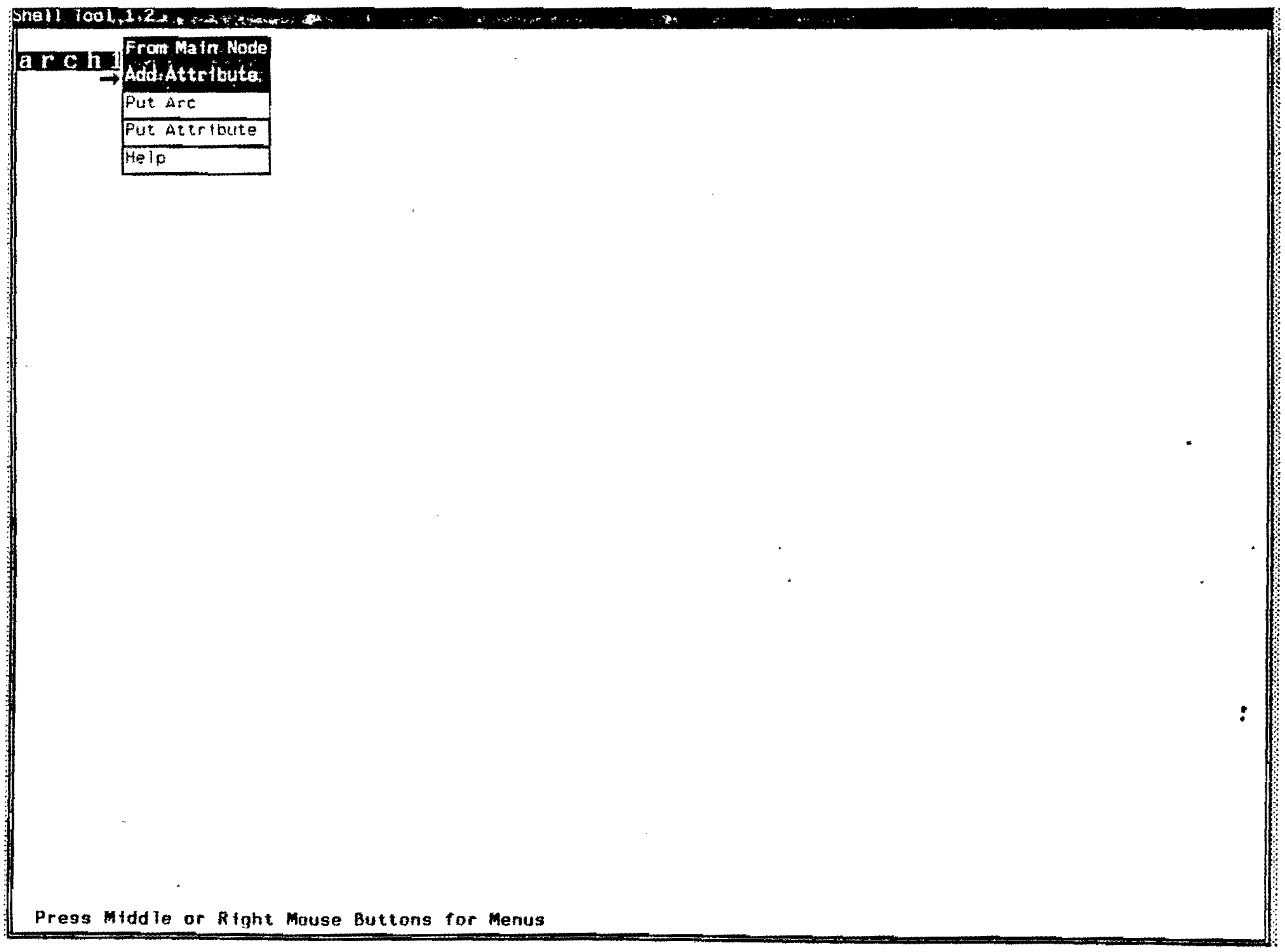
Add Attribute	Allows an attribute (an arc followed by zero to 254 nodes) to be added under the main node
Put Arc	The contents of the arc buffer will be put under the main node as the first attribute.
Put Attribute	The contents of the attribute buffer will be put under the main node as the first attribute.
Add Node	Allows a node to be added to the right of the current node in the attribute in which the current node occurs.
Put Node	The contents of the node buffer will be put to the right of the current node in the attribute in which the current node occurs.
Help	This message is displayed.

3.4. A Sample Interaction

In this section, screens are presented that show steps in the construction of a simple network. The example is chosen to illustrate the features of a network editor, and is not intended to have any semantics in the context of ADVISE. Therefore any resemblance of the network to ADVISE systems, living or dead, is purely coincidental. The network represents a arch made of building blocks.

In the first screen, the network editor has been invoked and a node, 'archl', to be taken as the root node for the display has just been typed in. The editor must be supplied with a network name and a root node before it can begin a session. The network name can be passed as argument or typed in when the editor starts up. If "archl" already existed in the network, the structure under this node would be displayed under the default parameters. The default parameters are set to not affect the display, i.e. the window size is the only limiting factor to the display.

A prompt for menus appears at the bottom of the screen. The user moves the mouse to the "archl" node, which becomes highlighted. Pressing the middle button while at the node reveals the desired option of adding an attribute (slot).

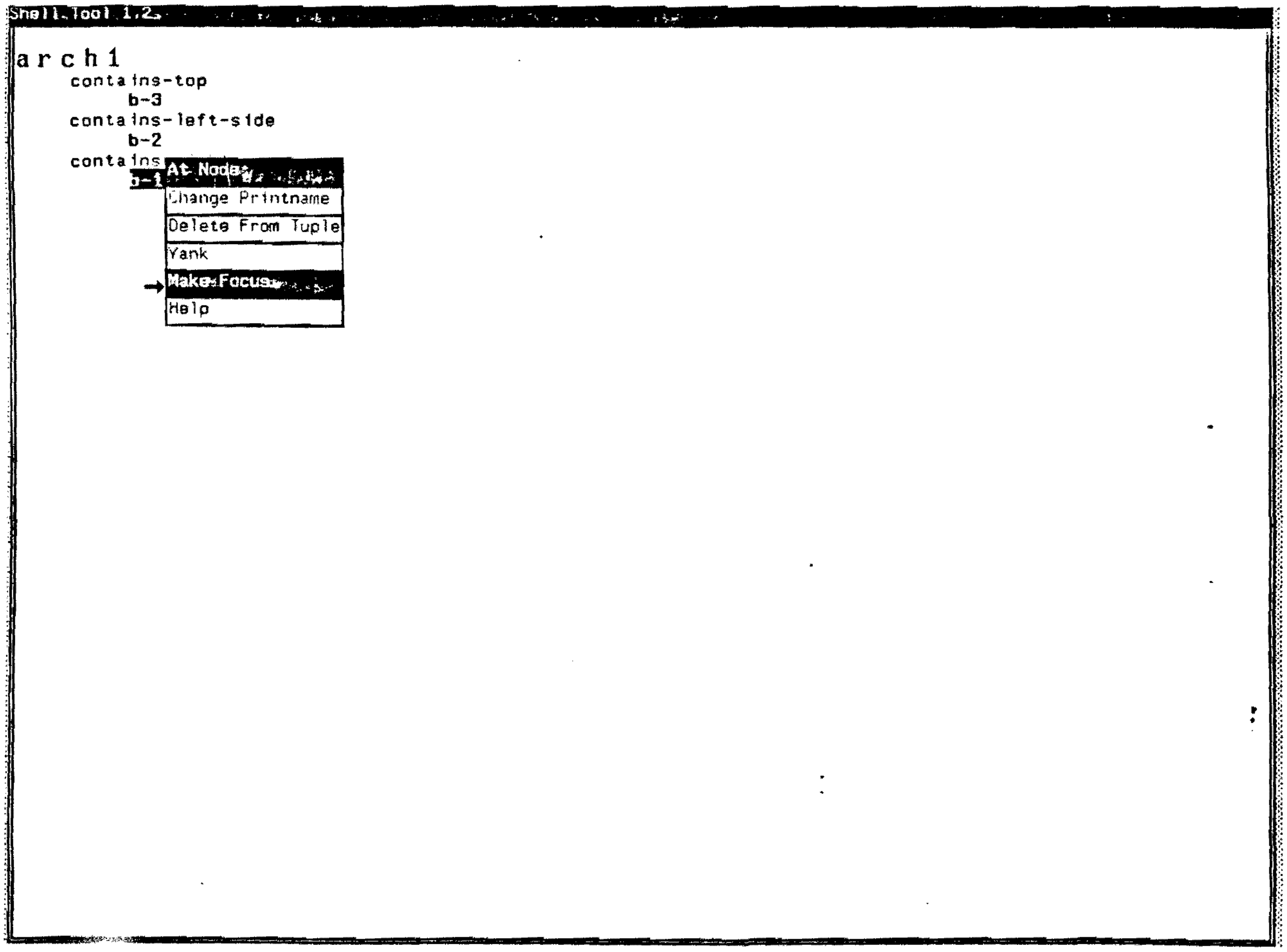


Press Middle or Right Mouse Buttons for Menus

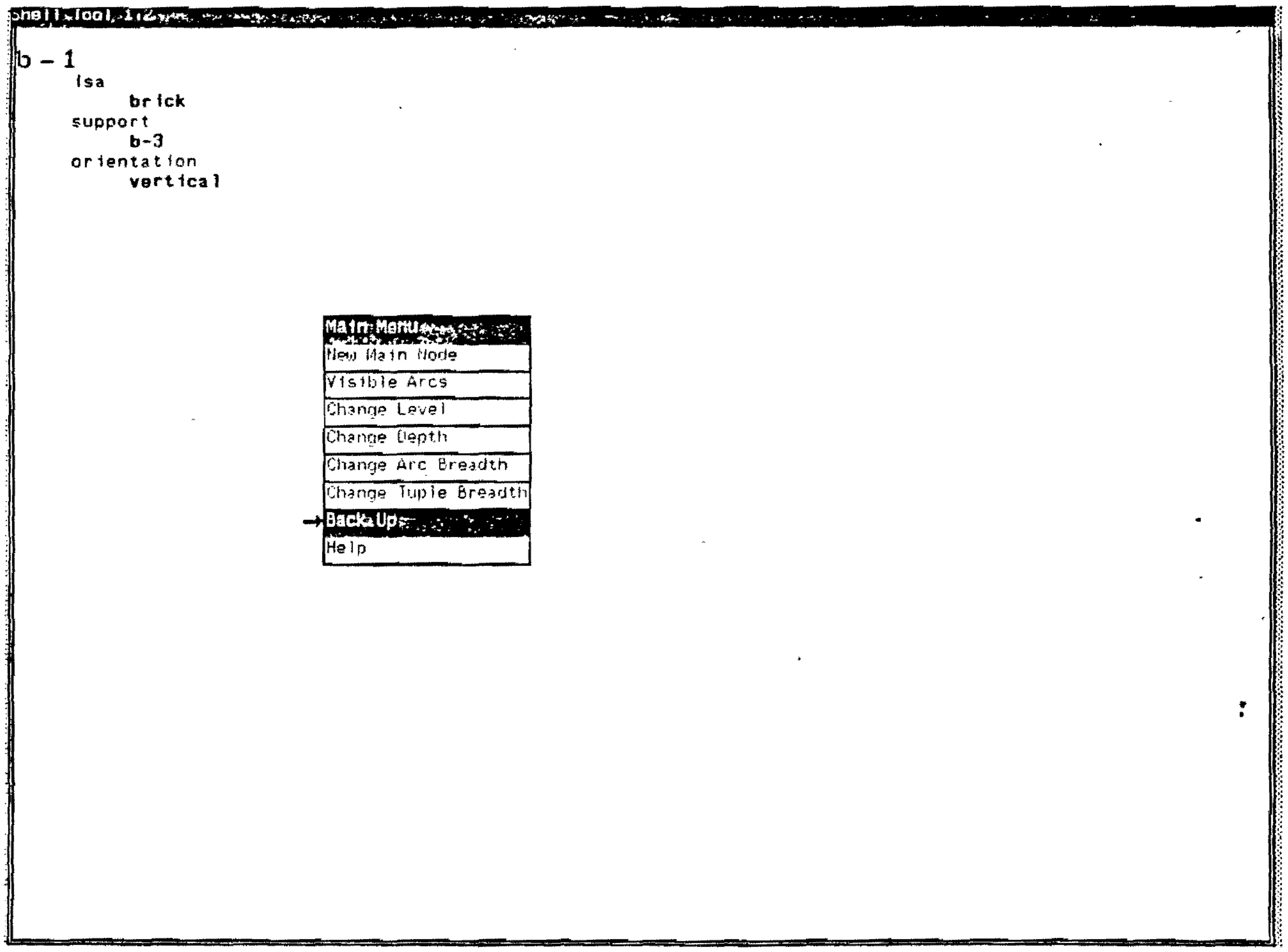
Selecting "Add Attribute" brings up a prompt for the number of nodes (printnames) including the arc in the tuple which the network editor will add into the network.

Next the user is prompted for the printname of the arc. The user types in this name. When the users presses return, the arc appears in the network and the names of the expected number of nodes are solicited. The user is prompted for each node name.

After entering all the nodes in the attribute, the attribute is displayed in the network. The user can now move to the arc to add the next attribute below the first. Continuing as with the first attribute the user has added all the arcs under "arch1". He now wishes to add arcs under the "b-1" node. To do so he must first make b-1 the new focus node.


```
arch1
    contains-top
        b-3
    contains-left-side
        b-2
    contains
        b-1
```

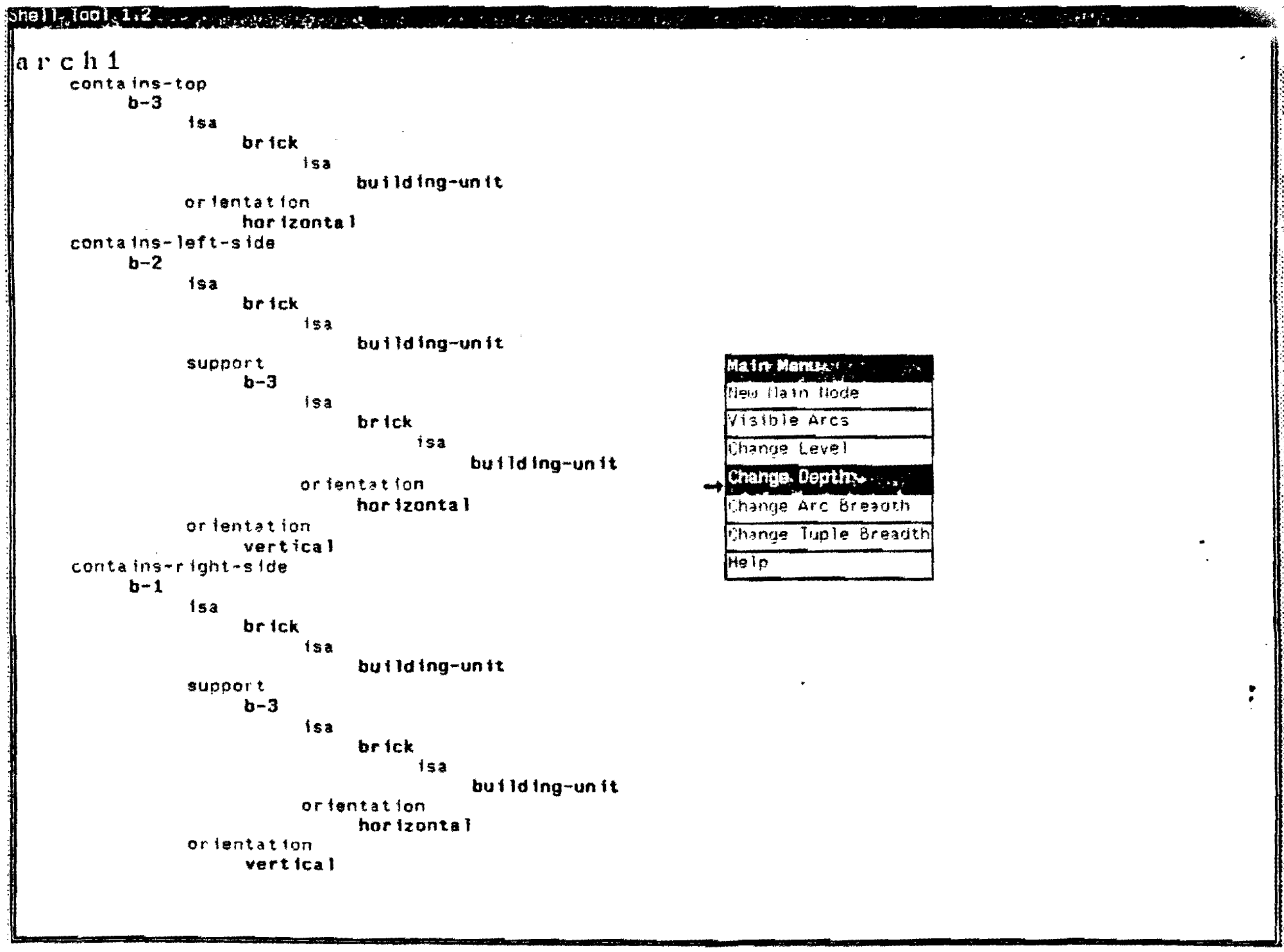
"b–1" becomes the new focus node. The user has used "Add Attribute" as before to add all the appropriate nodes and is now ready to "Back Up" to the previous root node. "Back Up" is an option from one of two menus that aren't associated with any node. The other is a global menu with options such as editing a new file, writing this file, quitting, etc.



```
b - 1
     isa
          brick
     support
          b-3
     orientation
          vertical
```

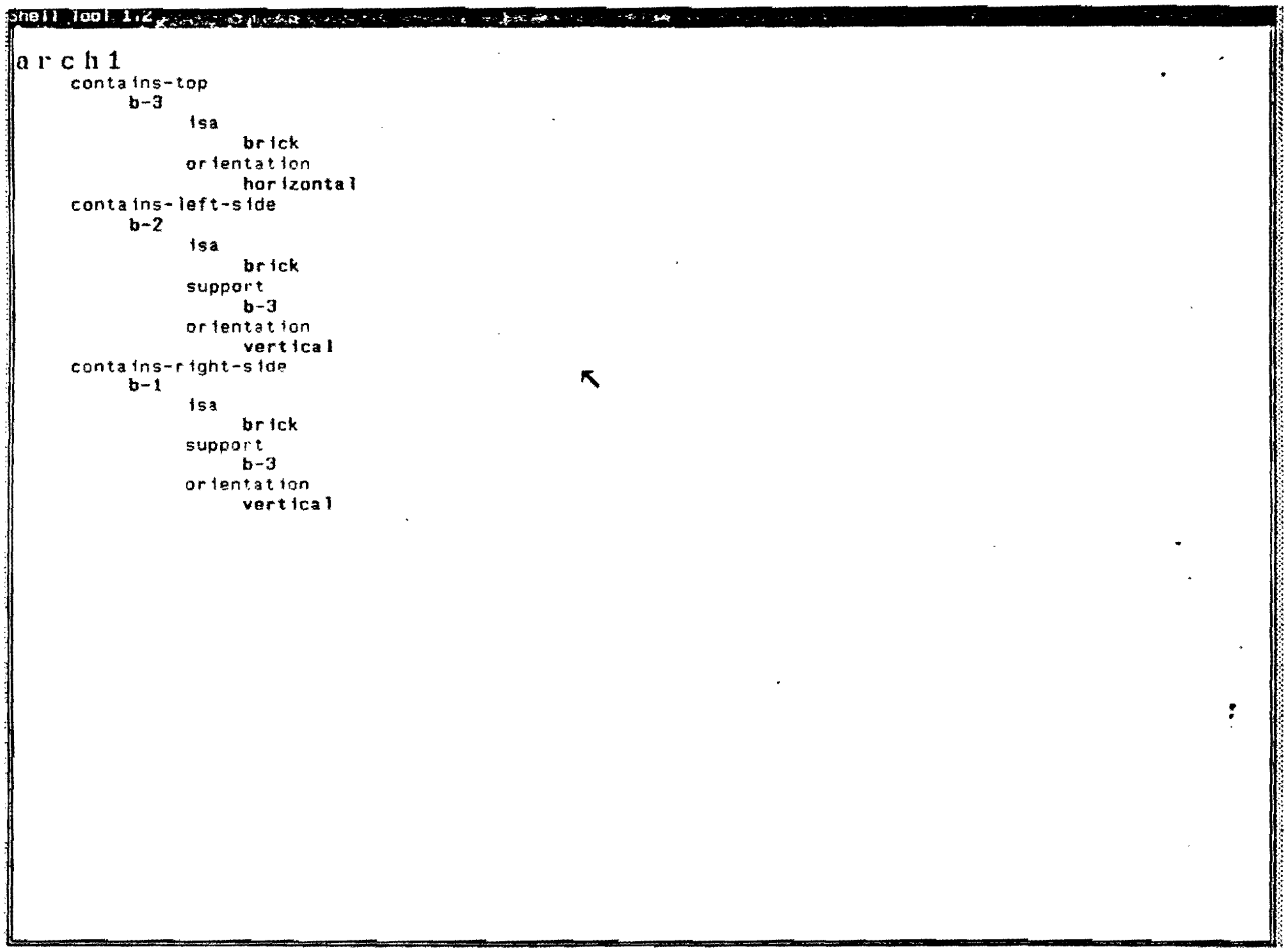
Now the network for "arch1" is complete.

At this point the user may enter a new root node, such as "arch2", and create a network from there or he may choose to alter the display by changing depth, for example.



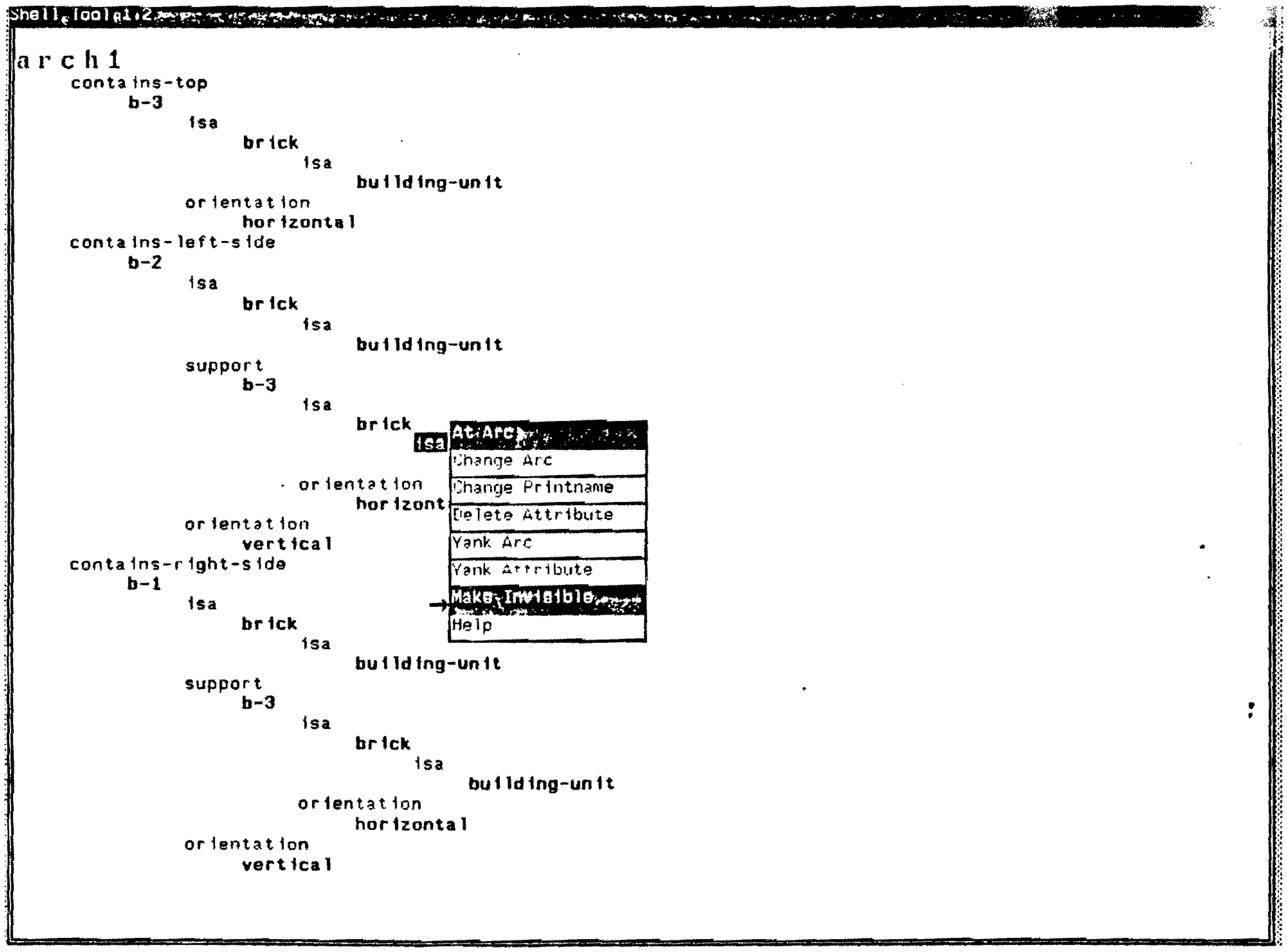
```
arch1
    contains-top
        b-3
            isa
                brick
                    isa
                        building-unit
            orientation
                horizontal
    contains-left-side
        b-2
            isa
                brick
                    isa
                        building-unit
            support
                b-3
                    isa
                        brick
                            isa
                                building-unit
                    orientation
                        horizontal
            orientation
                vertical
    contains-right-side
        b-1
            isa
                brick
                    isa
                        building-unit
            support
                b-3
                    isa
                        brick
                            isa
                                building-unit
                    orientation
                        horizontal
            orientation
                vertical
```

The user has indicated he wishes the depth changed from an "unlimited" default to 2. The network display is clipped accordingly.



```
arch1
    contains-top
        b-3
            isa
                brick
            orientation
                horizontal
    contains-left-side
        b-2
            isa
                brick
            support
                b-3
            orientation
                vertical
    contains-right-side
        b-1
            isa
                brick
            support
                b-3
            orientation
                vertical
```

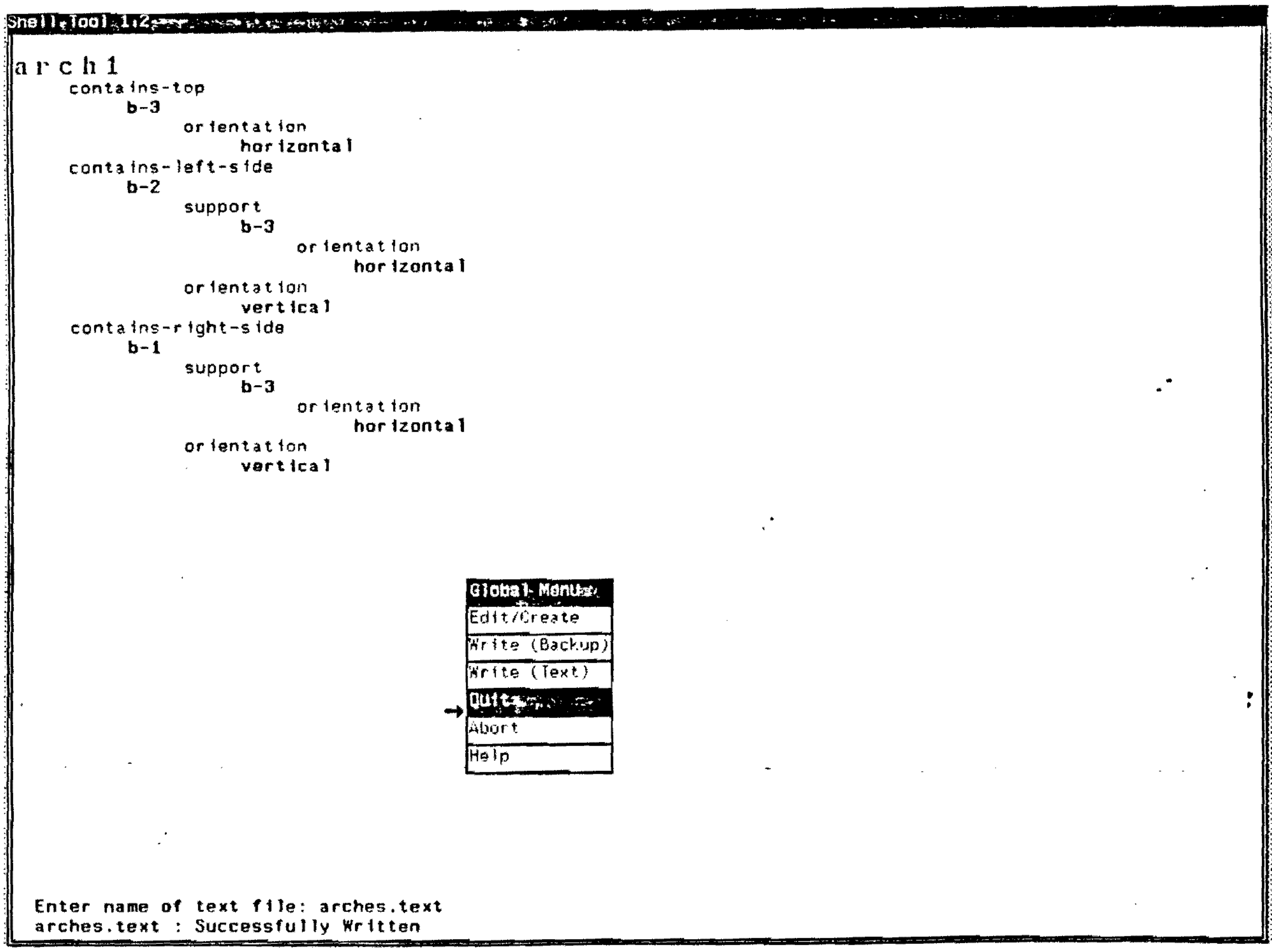
Instead of limiting the depth, the user may have chose to limit the breadth of the network instead. Another way to alter the display is by making arcs invisible. With the breadth and depth reset to their default values, the user wants the "isa" links to disappear from the display.



```
arch1
    contains-top
        b-3
            isa
                brick
                    isa
                        building-unit
            orientation
                horizontal
    contains-left-side
        b-2
            isa
                brick
                    isa
                        building-unit
            support
                b-3
                    isa
                        brick
                            isa
                    orientation
                        horizont
            orientation
                vertical
    contains-right-side
        b-1
            isa
                brick
                    isa
                        building-unit
            support
                b-3
                    isa
                        brick
                            isa
                                building-unit
                    orientation
                        horizontal
            orientation
                vertical
```

This action, as did the change depth option, also caused significant clipping to the display. Still another way to limit the display would have been to specify a subset of the visible arcs as the only ones to be displayed. For example, the user has could select the "contains" arcs and the "isa" arcs to be the only ones visible. This would allow the user to see inheritance relationships.

Now the user decides to end the session. He presses the middle mouse menu for the the global option menu. To get a textual representation of the network written to a file the user can choose "Write (Text)". After the user has typed in a file name for the text file, the system notifies the user of success (or failure). The textual representation for this network is shown in Figure 6. Now the user "Quits". The actual network is written to file given at the start of the program.



```
arch1
    contains-top
        b-3
            orientation
                horizontal
    contains-left-side
        b-2
            support
                b-3
                    orientation
                        horizontal
            orientation
                vertical
    contains-right-side
        b-1
            support
                b-3
                    orientation
                        horizontal
            orientation
                vertical

Enter name of text file: arches.text
arches.text : Successfully Written
```

```
(arch1 (
    (contain-top b-3 )
    (contain-left-side b-2 )
    (contain-right-side b-1 ) ))
(contain-top ( ))
(b-3 (
    (isa brick )
    (orientation horizontal ) ))
(contain-left-side ( ))
(b-2 (
    (isa brick )
    (support b-3 )
    (orientation vertical ) ))
(contain-right-side ( ))
(b-1 (
    (isa brick )
    (support b-3 )
    (orientation vertical ) ))
(isa ( ))
(brick (
    (isa building-unit ) ))
(support ( ))
(orientation ( ))
(vertical ( ))
(horizontal ( ))
(building-unit ( ))
```

Figure 6: The textual representation of tuples for "arches" .

CHAPTER 4

QUIN

4.1. Introduction

This chapter describes the QUIN (QUery and INference) program. QUIN is a tool for database management and analysis. It represents a marriage between relational database and inductive inference technologies. Its purpose is the management of large amounts of data for input to and output from several programs that use induction to generate knowledge from examples. It has potential applicability in the logic-based analysis of data and in the creation of knowledge for expert systems. This description is adopted from the Masters thesis by [Spackman82] and the user is referred to that document for a detailed description of the system.

QUIN may be used for the management and analysis of data. Management here refers to the creation, retrieval, and modification of the data, while analysis refers to activities that attempt to discover more about 1)interrelationships within data and 2) phenomena that produce those interrelationships. These operations can be either data management (relational) operations or machine inference (inductive) operations (Figure 7).

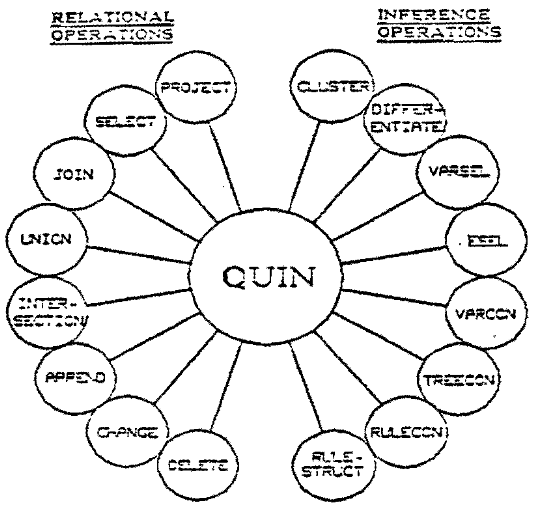


Figure 7 : Operations available in QUIN.

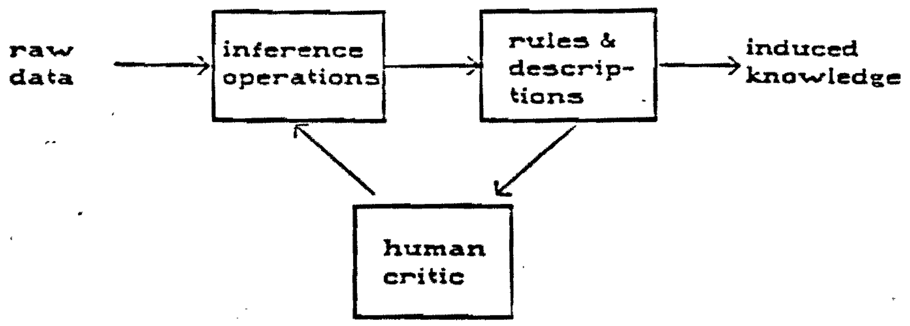


Figure 8 : The knowledge refinement cycle.

The induction programs that QUIN interacts with form a set of inference utilities that can be useful in sequence or in cycles with each other and the human critic. The databases [illegible] to test and experiment with these algorithms are more easily handled with database management techniques that store, modify, and restructure data for input to the inference programs. The cycle of knowledge refinement by iteration of the mechanized inference with a human critic is illustrated in Figure 8.

4.1.1. The Relational Model

This chapter gives a brief overview of the relational model of database organization and describes the interpretation of the model by QUIN. The concept of a table of data and the way it represents the mathematical notion of a *relation* is fundamental to the relational model of data used by QUIN. The model also includes the concepts of *keys*, *normalization*, and *relational operations*, each of which will be discussed in turn.

4.1.2. Relational Tables

A relational table is simply a table that represents a relation. Tables are familiar as a format for representing data. Consider Figure 11, an example of a table of clinical laboratory values obtained from blood specimens.

In Figure 9 each column corresponds to an attribute and each row represents an individual data object. The values within each row of the table represent the description of an object with respect to each of the attributes. Thus *spec#* refers to the specimen number, while *Hgb*, *MCV* and *RBC_morph* refer to the hemoglobin, mean corpuscular volume and red cell morphology of the specimen. These four names (spec#, Hgb, MCV and

labvals			
spec#	Hgb	MCV	RBC_morph
1024	10.3	78	microcytosis
891	13.1	90	normal
555	14.2	88	poikilocytosis
423	16.5	85	anisocytosis
425	11.1	78	microcytosis
455	10.4	77	microcytosis

Figure 9 : Clinical Laboratory Values

RBC_morph) comprise the *attribute list* of the table. The values obtained from each specimen occupy a single row in the table.

A **relation** is a set of ordered rows each of length n, (called *n–tuples*), where the value of the ith column in a tuple (V_i) is drawn from a domain D_i. The relation has *domain sets* D_1, D_2, ..., D_n, where n is the *degree* of the relation. Table 2 is of degree four. Its domain sets include the set of all possible specimen numbers, the set of all possible Hgb values, the set of all possible MCV values and the set of all RBC morphologies. These domain sets need not be explicitly delineated in a database, but are important in the mathematical definition of the concept of a relation. For further reading see [11].

Relations are intuitively well represented as tables, but relational tables in QUIN differ in some ways from the strict interpretation of a mathematical relation. First, the attributes (columns) are named, and therefore two tables in which the only difference is altered column order are considered to be equivalent. Second, in relations the rows are not considered to be ordered, but QUIN allows rows to be ordered according to the values of attributes, e.g. in increasing order by index number (value–controlled ordering). Third, the "zeroth" row of a table in QUIN is occupied by the attribute list, and data then follows beginning with the next row.

4.1.3. Keys

A key is an attribute or combination of attributes that have unique values for each tuple in the relation. In other words, no two tuples in a relation may have identical values of the key attributes. This constraint ensures against duplication of data records. Some examples of keys include an identification number (such as specimen number in Figure 11), a unique name, or a unique combination of two more attributes, such as name and date. To allow purposeful duplication of data for use in the inference programs, a table may optionally have no key defined.

4.1.4. Normalization

A table is said to be *normalized* (in first normal form) if each entry in the table is non–decomposable, i.e., a table or set of values cannot constitute an entry in a normalized table. Several levels of normalization have been defined (1st, 2nd, 3rd, Boyce/Codd, 4th, Projection/Join – see [11]) but the attainment and management of normalization beyond first normal form in QUIN is left entirely to the discretion and effort of the user.

4.1.5. Relational Operations

The relational model includes operations that take relations as input operands and give a relation as output. These operations can be classified as traditional set operations (union, intersection, difference and Cartesian product) and special relational operations (project, select and join). These relational operations are incorporated within the query language provided in QUIN. They are briefly introduced here and examples of their implementation are given in the next chapter.

Union	The union of two relations is the set of all tuples contained in both relations (without duplication). To perform the union of two relational tables in QUIN, they must be *union compatible*, which means they must have identical attribute lists. The same constraint applies to the operations of intersection and difference.
Intersection	Intersection comprises the set of tuples common to both relations.
Difference	The difference of two relations is the set of tuples contained in the first relation but not in the second.
Product	The Cartesian product of two relations is the set made up of the concatenation of each of the tuples in the first relation with each of the tuples in the second.
Selection	Selection provides a subset of tuples from a relation that meet certain selecting criteria. It produces a row-wise or horizontal subset of the relation. For example, a selection requiring the specimen number to be less than 500 from Figure 9 would give the result found in Figure 10.
Projection	Projection, on the other hand, provides a column-wise or vertical subset of the relation. Redundant tuples are eliminated from the resultant relation. For example a projection of the RBC_morph column would yield Figure 13.
Join	Join is slightly more complicated than selection and projection. It produces a combination of two (or more) tables based on all attributes they have in common. There are really several different kinds of join, the one referred to

labvals			
spec#	Hgb	MCV	RBC_morph
423	16.5	85	anisocytosis
425	11.1	78	microcytosis
455	10.4	77	microcytosis

Figure 10 : Results of Selection Operation

labvals
RBC_morph
microcytosis
normal
poikilocytosis
anisocytosis

Figure 11 : Results of Projection Operation

here being the *natural join*. The resultant table will have a tuple for each pair of tuples in the original tables that share identical attribute-values for every attribute the tables share. If the original tables have no attributes in common then the resultant table is the Cartesian product of the two tables. If no pairs of tuples have identical attribute-values (assuming a common attribute) then the join results in a null table. For examples, see section 4.2.1. and Figures 17 and 18.

The operations of Figure 16 can be incorporated into a powerful retrieval language called a relational calculus. The following chapter describes the fundamental constructs of the language QUIN uses as such a calculus and retrieval language.

4.2. Data Language VL

This chapter describes the capabilities and use of the VL data language used by QUIN. VL instructions provide the capabilities for relational table creation, retrieval and modification. The language is easily learned and requires a minimum of procedural specification so that it is reasonable to expect that users with minimal computer background could quickly learn and use it.

4.2.1. Table Creation

The instructions for creation of tables are **define** and **add**. **Define** creates an empty table and sets up the specifications for the attribute list and the key, while **add** places new tuples into a table.

4.2.1.1. Define

This instruction specifies a new table, its name, the names of the attributes, and (optionally) the name(s) of the key(s). The names of tables and attributes must begin with a letter and can contain any combination of letters, numerals, and the characters "#" and "_". No two tables may have the same name, nor can a table-name be the same as any attribute-name or reserved word. A table may not have two identical attribute-names, but two different tables may (and often do) share a common attribute-name. Keys are optional but if declared they should be the first (i.e., leftmost) attribute(s) in the table.

Consider as an example the definition of a database that keeps track of results of blood tests on patients, as in the example in the previous chapter, Figure 11. The table, called "labvals", stores the information on specimens and the values measured. The unique attribute (key) of each record would be the specimen number. The way to create this table using the define instruction would be:

```
define labvals (spec#, Hgb, MCV, RBC_morph)  key := spec#
```

We could also define a table called "spec" to keep track of the dates of individual blood specimens:

```
define spec (spec#, ID#, day, month, year)  key := spec#
```

Another table called "ptrc" would store a patient's identification number, his name, and his admitting diagnosis:

```
define ptrc (ID#, name, dx)  key := ID#
```

4.2.1.2. Define Event

An event is a table with only one row. Its purpose is to specify a complete single data object with attributes that may be found in several different tables, so that adding the event to each of those tables is easier and more reliable. Events are defined by the define event instruction followed by the event name and then a parenthesized list of attribute-value pairs. Continuing the previous example, we could define an event that contains all the attributes of the three tables (ptrc, spec and labvals):

```
define event E1
    (ID# := 988,
     name := Jones,
     dx := iron_deficiency,
     spec# := 1024,
     day := 25,
     month := 6,
     year := 1982,
     Hgb := 10.3,
     MCV := 78,
     RBC_morph := microcytosis)
```

Event "E1" records that a blood test was done on patient number 988 whose name is Jones and whose diagnosis was iron_deficiency. The blood, specimen number 1024, was drawn on 25 June 1982 and the results showed a hemoglobin of 10.3, a mean corpuscular volume of 78, and red cell morphology was microcytosis. The attribute-value pairs in the event definition can be arranged in any order.

4.2.1.3. Add

The add instruction places tuples (rows) into a table. There are four forms of the instruction: one for single row addition, another for multiple rows, one for adding an event to a table, and one for adding an external file of tuples to a table.

(1) A single row may be added as follows:

```
add (365, Smith, aplastic_anemia)  to ptrc
```

(2) Multiple rows are added in similar fashion:

```
add to ptrc
(398, Clark, folate_deficiency)  (404, Blake, iron_deficiency)
(425, Smith, hemolytic_anemia )  (241, Jones, iron_deficiency)
end
```

(3) Adding an event to several tables is simple:

```
add E1 to ptrc
add E1 to spec
add E1 to labvals
```

(4) Adding an external file named "vls" to the "labvals" table would be done as follows:

```
add vls to labvals
```

The external file must be set up in tabular form. For example, the file "vls" might appear as in Figure 12.

Addition of tuples may be done at the beginning of the table, the end, or before or after any specified row in the table by using a *row condition*. All four forms of add may be used with a row condition. If no row condition is specified then the addition is done after the last row of the table. For example, the following places a new tuple at the first row:

```
add (425,404,26,6,1982) to specs : [row<1]
```

The colon is to be read "such that" and the row condition is of the same form as

```
891   13.1   90   Normal
555   14.2   88   Poikilocytosis
423   15.5   85   Anisocytosis
```

Figure 12. Format of File "vls"

re[illegible]al conditions (see section 4.2.2). The reserved word *last* may be used to insert before the last row:

add datafile to specs : [row<last]

The condition "[row>last]" would be redundant because that is the default. If there are not as many rows in the table as specified in the row condition, the new tuples will be added at the end of the table.

4.2.2. Table Retrieval

The retrieval commands are get and let. Simple retrieval of an entire table requires only listing the table name after the keyword **get**. Selected portions of the table can be retrieved and displayed also (see sections 4.2.1. and 4.2.2.). A new table can be created with the keyword let followed by the name of the new table, ":=", and the description of the new table. For example, the following command creates a new table called "tests" which is the same as the "labvals" table:

let tests := labvals

The new table would be created but not displayed. The command to display the table is:

get tests

Figure 13 would then be displayed. It would be identical to the "labvals" table except for its name.

The combined effect of the get and let could have been accomplished by simply saying:

get tests := labvals

tests			
spec#	Hgb	MCV	RBC_morph
1024	10.3	78	microcytosis
891	13.1	90	normal
555	14.2	88	poikilocytosis
423	16.5	85	anisocytosis
425	11.1	78	microcytosis
455	10.4	77	microcytosis

Figure 13 : Result of Retrieval

Symbol	Meaning
*	Join
v	Union
&	Intersection
-	Difference
+	Append

Figure 14 : Relational Table Expression Operators

The let command is used to create temporary tables that can be used as working copies or can be saved as new permanent tables. It never displays the results of its work. The get command always displays its results, and can also be used to create temporary tables. A wide variety of more complicated retrieval instructions can be specified by appending the appropriate modifying expressions to these two commands. These additional expressions are specified by a *relational table expression* (see section 4.2.1.) optionally followed by a *VL condition* (see section 4.2.2.).

4.2.2.1. Relational Table Expressions

The table expression specifies the table or tables and the attribute or attributes to be retrieved. All operations described in section 3.4 except selection can be specified with a table expression. When more than one table is listed in an expression, tables must be separated by an operator. The operator symbols and their meanings are given by Figure 14.

spec				
spec#	ID#	day	month	year
1024	988	25	6	1982
425	404	26	6	1982
850	405	27	6	1982
455	406	27	6	1982

Figure 15 : The "spec" Table

These operators take precedence over all others in the retrieval instruction. All tables listed together with the logical operators (union, intersection, difference) and the append operator must be *union compatible*, which means that they must have identical lists of attributes, in the same order, and of the same type (e.g. if attribute N is an integer in one table, it must also be an integer in the other table(s) in the instruction).

To illustrate the use of operators in table expressions, let us assume we have a table named "spec" as shown in Figure 17.

The following instruction would create a table called "T1" which is a join of the "spec" and "labvals" tables (the common descriptor being the specimen number):

```
let T1 := spec * labvals
```

The join of tables "spec" and "labvals" would appear as in Figure 16.

If no attributes are listed in the retrieval command (as in the example in Figure 16) then the full set of attributes for both tables is retrieved. If a subset of attributes is specified then the **projection** of those attributes on the table is retrieved. For example:

```
get spec * labvals (ID#, Hgb)
```

will retrieve a table with two columns. It will be the projection of ID# and Hgb on the join of spec and labvals. Figure 17 shows the result.

For the purposes of the inference algorithms it is sometimes not desirable to eliminate redundancy when doing projection, so QUIN provides two other methods of specifying projection. One method, using &, simply does a "column selection" and retrieves all rows even if redundant. The other method, using #, eliminates redundancy but provides an additional column that shows the number of times that a particular row occurs. All three forms of projection instruction are illustrated in Figures 20, 21, and 22.

An attribute may be replaced by a function of an attribute in the retrieval expression. Available functions include **min**, **max**, **sum**, **count** and **domain**. Figure 21 gives an example of the use of the **min** function.

T1							
spec#	ID#	day	month	year	Hgb	MCV	RBC_morph
1024	988	25	6	1982	10.3	78	microcytosis
425	404	26	6	1982	11.1	78	microcytosis
455	406	27	6	1982	10.4	77	microcytosis

Figure 16 : Join of "spec" and "labvals"

ID#	Hgb
988	10.3
404	11.1
406	10.4

Figure 17: Projection & Join

get labvals(RBC_morph)

labvals
RBC_morph
microcytosis
normal
poikilocytosis
anisocytosis

Figure 18 : Ordinary Projection

get labvals(RBC_morph,#)

labvals	
RBC_morph	#
microcytosis	3
normal	1
poikilocytosis	1
anisocytosis	1

Figure 19 : Projection & Count

get labvals(RBC_morph,&)

labvals
RBC_morph
microcytosis
normal
poikilocytosis
anisocytosis
microcytosis
microcytosis

Figure 20 : Projection with Redundancy

get labvals(min(Hgb))

labvals
Hgb
10.3

Figure 21 : Use of "min"

4.2.2.2. VL Conditions

A VL *condition* is the part of a retrieval command which specifies **selection**. The following example illustrates the major features of a VL condition. The condition begins with a colon which should be read "such that."

get labvals : [Hgb = 14..16] [RBC_morph <> normal] v [Hgb < 14]

The command would retrieve all rows from table "labvals" in which either a) the Hgb is in the range 14 to 16 and the RBC_morph is not normal, or b) the Hgb is less than 14.

A VL condition thus consists of a disjunction of one or more *complexes*. Complexes consist of a conjunction of one or more *selectors*. In the instruction in Figure 21, "[Hgb = 14 .. 16]" is a selector. Selectors may be separated by the conjunction operator &, or simply listed one after the other, as in the complex "[Hgb = 14..16] [RBC_morph <> normal]" in above. Selectors or groups of selectors (complexes) may be separated by the disjunction operator v. Thus a condition is a "sum of products" of logical (VL) selectors.

VL selectors are used to specify the body of the condition. They can be of two types, row-oriented selectors ("tuple calculus") and set-oriented selectors ("domain calculus"). The example given in the Figure uses row-oriented selectors.

A row-oriented selector consists of a left square bracket, an attribute name (the referee), a comparison operator (=, <>, <, >, <=, >=), a comparison value (the reference), and a right square bracket. The comparison value may be a single value (e.g. "normal"), an arithmetic range of values (e.g. "14 .. 16"), an arithmetic expression (e.g. "Hgb + 2.5"), or a list of values, ranges, or expressions separated by the "or" operator (e.g. "3..5 v 7 v Hgb/10").

A domain-calculus selector consists of a referee set, a set comparison operator and a reference set. The referee set is called an *image set* of the attributes being retrieved. An image set is the set of values of the image attribute (or of unique combinations of values of the image attributes) corresponding to each retrieval value (or unique combination of retrieval values). The comparison operator is the same as those in the tuple-calculus selector (using =, <>, <, >, <=, >=) but the meanings are set comparisons instead. Thus "=" tests set equality and "<" tests to see if the first set is a proper subset of the second. The reference set has the same attribute list as the referee set but may contain a VL condition within it, as in this example:

```
get spec(ID#) : {day,month,year} = {day,month,year:[ID# = 365]}
```

Day, month, and year are the image attributes. {day,month,year} specifies the referee set. It may also be written {day,month,year : ID#}, which reads "the set of day-month-year triples corresponding to each ID#." It is calculated anew for each unique value of ID#, the retrieval attribute. [ID#=365] is the VL condition within the reference set. The meaning is that the user wants to retrieve the ID# of all patients who had specimens done on precisely the same days as patient number 365. The same thing could be accomplished using the tuple-oriented calculus only by repeatedly doing the following for every value of n:

```
get spec(day,month,year):[ID# = n]
```

The results would then have to be compared with the result of:

```
get spec(day,month,year):[ID#=365]
```

and those values of ID# for which the results matched that of 365 would be the final result.

4.2.2.3. Ordering of Rows

All retrievals may optionally have an ordering condition. The phrases "order up on" and "order down on" are appended to the retrieval instruction, along with the name of the attribute to be ordered on. For example, the instruction

```
get ptrc order up on ID#
```

will retrieve the table "ptrc" in ascending order of ID numbers.

4.2.3. Table Modification

The table modification instructions are **change**, **delete**, and **save**.

4.2.3.1. Change

The change instruction is used to assign new values to existing rows in a table or to change the name or type of an attribute. When the user types:

```
change tablename
```

he enters a "sub-instruction" mode in which all commands refer to the table being changed. A working copy of the original table is made for security in case of error, and the user's prompt is ">>". To leave the change mode the user types **abort** or **exit**, with only the latter exit resulting in factual modification of the original table.

There are several commands available in the change mode. The user may use ordinary assignment statements to change the values of each attribute. Some examples are given in Figures. The assignments may be followed by a VL condition that restricts the assignment of values to specific rows of the table. Attribute names may be changed by specifying the condition "[row=0]". The **display** sub-instruction displays the working table; the get sub-instruction displays the original table before any changes. A simple change instruction sequence may be entered as shown with Figure 22.

The commands in Figure 23 illustrate how the table might be modified within the change mode.

4.2.3.2. Delete

Delete is used to remove rows or columns from a table, or to remove a table from the database. Each of these three functions is accomplished by a different form of the instruction.

(1) Deleting rows is accomplished by specifying a VL condition:

```
delete ptrc : [ID# = 250 .. 500]
```

This will delete all rows in table "p[illegible]" where the ID number is in the range 250 to 500 inclusive.

(2) Deleting columns is accomplished by specifying a projection:

```
delete spec(day,month)
```

This will delete the day and month columns from table "spec".

(3) Deleting an entire table or event is done by simply giving the table name:

```
delete T1
```

This will remove the table named "T1" from the database.

4.2.3.3. Save

Any tables created with the get or let instructions will be given temporary status; save is the instruction that changes temporary to permanent status. Tables with permanent status will stay in the database after a session is completed, whereas tables with temporary status will be deleted at the end of a session.

4.2.4. Help

The system has on-line help available to describe the use of each command. Help can be obtained by typing help or by simply typing a question mark at a prompt. If specific information is desired about a particular command, the command name should be entered following the word "help," followed by a carriage return.

4.3. Inferential Operators

This chapter describes the inferential operations on an informal conceptual level. References are provided for more detailed explanations of the algorithms and the theories supporting them. In the current implementation, only cluster and diff are operational. However, the same methods of interaction can, in principle, be used with all the inference programs mentioned here. There are many inference commands described for QUIN. These all interface with other software through relational tables. The general format of the commands is:

```
command(parameter1,parameter2,...).
```

Each command has at least two variants. One variant allows the user to wait for results, and the other allows him to run the inference command as a *background process* (allowing him to proceed on other QUIN commands concurrently with the execution of the inference command). Other variants exist for some commands for specifying a result table name or giving non-

```
> change labvals  /* enter change sub-mode  */
ok               /* system response */
>> get           /* look at original table */
```

labvals			
spec#	Hgb	MCV	RBC_morph
1024	10.3	78	microcytosis
891	13.1	90	normal
555	14.2	88	poikilocytosis
423	16.5	85	anisocytosis
425	11.1	78	microcytosis
455	10.4	77	microcytosis

Figure 22 : Original Table to be Changed

```
>> Hgb := high :[Hgb>16]
>> Hgb := low  :[Hgb<14]
>> Hgb := normal :[Hgb=14:16]
>> display   /* look at changed table  */
```

change$table			
spec#	Hgb	MCV	RBC_morph
1024	low	78	microcytosis
891	normal	90	normal
555	normal	88	poikilocytosis
423	high	85	anisocytosis
425	low	78	microcytosis
455	low	77	microcytosis

```
>> end            /* exit, making the changes permanent */
change completed  /* system response */
```

Figure 23 : Table with Modifed Hgb Column

default parameters. The current implementation of QUIN has clearly defined the arguments required for the following commands:

command	program	format
diff	GEM	diff(table1,table2, ... ;parmtable,results)
aq11	AQ11	aq11(table1,table2, ...)
cluster	CLUSTER	cluster(table,parmtable,results)
esel	ESEL2	esel(table,parmtable,results)
varsel	PROMISE	varsel(table1,table2,...;parmtable,results)
varcont	CONVART	convart(table1,table2,...;parmtable)
sparc	SPARC	sparc(vars,vars.con,advices,events,results)

Other commands which are not yet implemented are:

command	program	format
apply	AQ11	??
treecon	OPTREE	??
varcon	NEWVAR	??

4.3.1. Fetch and Results

In addition to the basic induction commands, there are a couple of commands for managing processes which have been run in background. These are RESULTS, which reports the status of each induction job submitted since the beginning of the current QUIN session, and FETCH, which permits the results of a background job to be read back into a QUIN table (the default action of induction programs is to create files which need to be reread or *fetched*). RESULTS takes no arguments and reports something like the following.

```
Job-Number   Program  Status
1            Varsel   done
2            Esel     done
3            Gem      running
```

Here, the results of job #1 and job #2 could be *fetched*. The format of the FETCH command is :

fetch(job-number,result-table) ,

where job-number refers to an entry in the table reported by RESULTS and results-table is the name of a table to be created for storing the results of that job.

4.3.2. Cluster

The purpose of the cluster operation is to divide a collection of objects into smaller groups of similar objects based upon some criterion or measure of similarity. Clustering is the process of developing a taxonomy or classification scheme for the objects of a study.

The program invoked by the cluster command in QUIN is called *CLUSTER/paf* [14]. The reader is urged to consult the references cited for more complete explanations of the details of the program's operation and theoretical background. Unlike most numerical taxonomic techniques, this program uses a "concept-based" method of clustering that produces descriptions of the clusters (categories) that it derives. It also permits the user to specify the criteria which are to be used to evaluate clusters. One or several criteria can be maximized simultaneously to produce the optimal clusters. Some of the criteria available to characterize clusters include:

- the fit between the clustering and the data (sparseness),
- the total inter–cluster differences (degree of intersection),
- the number of attributes which singly distinguish between all the clusters (essential dimensionality), and
- the simplicity of cluster descriptions (number of selectors).

The names and numbers of criteria currently available appear in Figure 24.

The cluster operation is invoked by the following instruction,

```
cluster (events,parameters,results)
```

where "events" and "parameters" represent the names of relational tables within QUIN, and "results" is the name of a table which may or may not already exist (if not it will be created). Any legal table names may be used in the command. The events table must contain the descriptions of the objects to be clustered with each object occupying one row in the table. Each column represents an attribute of the objects in the table. The parameters table is used to indicate K (the number of clusters to be formed), the criteria to be used and other optional parameters. The optional results table is the table in the database to which the results of the clustering will be returned. If no results table is specified, the output of cluster can be found in a file in the user's working directory.

A simple example of clustering follows, using data similar to the previous examples in chapter four. In addition to the events table, a parameters table and at least one criterion table must be prepared before issuing the cluster command. Figure 25 illustrates a parameters table and table 14 illustrates a criterion table.

The parameters table (Figure 25) has two tuples (rows). The cluster algorithm will therefore be run twice, once for each row in the parameters table. The first time it will split the events into three groups (k=3) and the second time it will create only two groups (k=2). Criterion "crl" (found in table 13) is defined in the criterion table called "crl_criterion" (Figure 26). Criterion "1" is *sparseness*, (see Figure 24). It is the only·

criterion number	brief description
1	sparseness
2	degree of intersection
3	number of events occurring in more than one complex
4	share of events (evenness of cluster size)
5	number of selectors (simplicity of cluster descriptions)
6	essential dimensionality (dimensionality of differences)
7	relevant–variable sparseness
8	relevant–variable–set sparseness

Figure 24 : Clustering Criteria

parameters	
k	criterion
3	cr1
2	cr1

Figure 25 : Parameters Table

cr1_criterion	
criterion	tolerance
1	0.0

Figure 26 : Criterion Table

events		
mcv	hgb	mchc
0	1	0
2	2	0
1	1	1
3	4	3
3	4	3
4	1	4
5	2	4
4	1	4

Figure 27 : Events to be Clustered

criterion which will be used by the program in this example. The tolerance is a measure of the degree of error allowed in fitting the clusters to the criterion. The events table for this example is shown in Figure 27.

The values in the events table must all be integers. Attributes, such as those represented here, which ordinarily have continuous linear values must be made discrete before cluster can deal with them. The meanings of the values in the events table are given in Figure 28, with the values from the events table in the "#" column followed by the range of real values which have been assigned to each value.

When the sample given in Figures 28–30 is run, cluster splits the events into three groups as in Figure 29.

This is a particularly simple example, but it gives the flavor of the clustering operation. In this case, cluster has discovered three groups which can be interpreted as being cases of microcytic anemia (group one), normal blood counts (group two), and macrocytic anemia (group three). For further examples of the use of cluster see [22].

4.3.3. Diff

Diff (differentiate) takes a number of classes of events that have already been categorized, and attempts to find the conceptually simplest rules that will predict the category of each event, i.e., discriminate between the categories. The algorithm invoked by the command is called *Aq* and is incorporated in the program called *GEM* [15].

The following is an example of the use of the diff instruction to create rules for differentiating the groups of objects represented in three tables named grp1, grp2 and grp3. There are a number of differences from the cluster operation:

(1) No criterion tables are needed.

(2) The parameters table, an example of which is shown in Figure 30, has a different format from the cluster parameters table which was illustrated in Figure 25.

(3) The values in the events tables need not be integer only. Discrete nominal values are allowed in addition to integers. An example of the way an events table might appear is given in Figure 31.

Note that there still must not be real-valued attributes (e.g. 50.2) but nominal attributes are allowed. In addition, the type and domain of an attribute can be declared or the use of "diff." In the table in Figure 31, the "day" attribute clearly can take on seven values which are ordered and cyclic. Only three of these appear in the table and they are not in order. To define the domain of this attribute one must first prepare a relational table with one column containing all possible values which the attribute may have. The values should be listed in order, as in Figure 32.

Given such a table, the following command will set up a permanent domain for the attribute "day" which will automatically be referred to whenever the system needs to prepare "day" as an attribute or the "diff" operation:

```
domain (day) := weekdays
```

The "diff" operation recognizes three types of attributes :

- nominal (discrete unordered)
- linear (discrete ordered, such as "rainfall" in Figure 32), and
- cyclic (discrete with cyclical ordering, such as days of the week).

#	mcv	
0	<60	
1	60 to 69	
2	70 to 79	
3	80 to 94	(mcv normal = 80 to 94 cu microns)
4	95 to 104	
5	>104	

	hgb	
	<8 = 0	
1	9 to 10	
2	11 to 12	
3	13 to 14	
4	15 to 16	(hgb normal = 14 to 18)
5	17 to 18	
6	19 to 20	
7	>20	

#	mchc	
0	<27	
1	27 to 32	
2	33 to 38	(mchc normal = 33 to 38 %)
3	39 to 44	
4	[illegible]	

Figure 28 : Meanings of Values in Events Table

Group one : events 1,2,3
Group two : events 4,5
Group three : events 6,7,8

Group one is described as:
mcv<80 and hgb=9..12 and mchc<33
Group two is:
mcv=80..94 and hgb=15..16 and mchc=33..38
Group three is:
mcv>94 and hgb=9..12 and mchc=39..44.

Figure 29 : Results of Clustering

params	
echo	maxstar
pcve	10

Figure 30 : GEM Parameters Table

grp1		
day	rainfall	hours_sunlight
Monday	light	6
Saturday	none	12
Wednesday	heavy	2

Figure 31 : GEM Events Table

weekdays
names
Sunday
Monday
Tuesday
Wednesday
Thursday
Friday
Saturday

Figure 32 : Domain Values or Days of the Week

The system assumes that integer values are linear and that alphabetic values are nominal. When the opposite is true or when the attribute is cyclic, the following instruction can be used to define the type of the attribute for use by "diff:"

```
type (day) := cyc
```

The abbreviations for nominal, linear and cyclic are **nom**, **lin** and **cyc**, respectively.

The instruction format for invoking "diff" is as follows:

```
dif(grp1, grp2, grp3; params, results)
```

The "params" and "results" tables are optional. The system provides default parameters to GEM if a parameters table is omitted. If the "results" table is included, the discrimination rules produced by GEM will be placed in it. A variable number of groups (event tables) may be submitted. A semicolon indicates the end of the list of event tables, as after grp3 above.

4.3.4. Esel

The operation **esel** invokes Esel [17], a program that takes a large number of examples and selects a small subset of examples that is most representative of the larger group. The smaller sample will require less execution time in inference programs such as CLUSTER/paf or GEM. Very large numbers of examples (more than 200) would probably require inordinate amounts of processing time, making it useful and efficient to choose a representative subset.

4.3.5. Varsel

The **varsel** instruction invokes a program called PROMISE [16] which selects the most "promising" attributes for differentiating between classes of events. Its output is therefore intended for use with GEM. The elimination of irrelevant attributes is a horizontal reduction of the database somewhat comparable to the vertical reduction accomplished by esel. The reduction results in reduced execution time in GEM but also results in the elimination of attributes from consideration by the inference process.

4.3.6. Varcon and Varcont

The **varcon** instruction (variable construction) invokes a program called NEWVAR [18] which attempts to use mathematical operations (multiplication, addition) to create new attributes from combinations of existing attributes. The use of ratios or differences of existing attributes sometimes provides simpler and more accurate rules for distinguishing one class from another.

The command **varcont** is used to access a program named CONVART [19], a system for inducing time-dependent information from data. Multiple measurements of an attribute over time can be changed into a single attribute based upon its time-dependent characteristics. The induced description of the time-dependent attribute can then be used in data or input to other inference routines.

4.3.7. Other Operations

The **apply** * operation tests the performance of induced rules on new events. It currently a part of the AQ11 [20] program. The output is a confusion matrix that gives the percentage of alse positive and false negative decisions for each decision category.

Another inference operation, **treecon** * uses program OPTREE [21] to produce optimal decision trees from extended entry decision tables [23]. It performs the conversion of VL rules to decision trees (branching logic) for the convenience of the user.

There are three low-level inference operations that are used in CLUSTER/paf that also could be invoked separately.

(1) **Sim** * (similarity) takes any two events and calculates a syntactic similarity measure. The similarity of two events is the inverse of the syntactic distance measure used in CLUSTER/paf.

(2) **Reun** * (reference union) takes the values of attributes and "collapses" several events into one event with multiple-valued attributes. For example, the events

(12, medium)
(13, large)

could undergo reference union to become

(12 v 13, medium v large).

(3) **Gen** * (generalize) * planned operation not currently implemented goes one step further to take the events that result from reference union and generalizes the results into more intuitively succinct values. Thus

(12 v 13 v 14 v 15, medium v large v verylarge)

would become

(12..15, >small).

There are other inference programs that may be useful tools or the generation of knowledge from examples, and they too have the potential to be integrated into the system.

4.4. Macro Language

A macro processor is available to the QUIN user. This is simply a modified version of the standard preprocessor (/lib/cpp) for the C language compiler (/lib/ccom) which runs under Berkley standard UNIX. This handles macro expansion and include file copying for the C compiler. The significant modifications are a change to the #define directive to allow multiline macros (the original cpp allowed escaped newline characters in definitions, but they were essentially deleted from the macro as soon as processed) and a change to the I/O to allow the preprocessor to communicate with QUIN over a pair of sockets (a standard UNIX message passing system for concurrently running tasks or processes).

A macro definition begins with #define and ends with the symbol "@". Thus,

```
#define x(y) sqrt(y) @
```

is a macro which does not contain any embedded lines, and

```
#define x(y,z)
  print("y*z = %d",y*z);
@
```

contains embedded lines.

The other constructs (#ifdef,#ifndef,...) are allowed within macros, and [illegible] processor is noticeably more powerful than the original cpp. For full details, refer to documentation on the C language or to the UNIX documentation for "cpp". Note that arguments may be omitted from a macro call with the effect that they become instantiated to null strings and returns TRUE for "#ifndef".

4.5. Program Description

QUIN is written in Berkeley PASCAL for the UNIX operating system. It consists of three major segments of about 2000 lines of code each. The files containing these segments are named qqmain.p qqparsr.p and qqex.p. Qqmain.p contains the initialization routines, the session handling routines, and the utility routines. Qqparsr.p contains the command parser, and qqex.p contains the command executor.

Flow of control through the code follows the pattern of:

1) start in the session routine,
2) parse a command into PT (the parse table).
3) go to the executor and execute the command,
4) cycle

There are also three other small pieces of code, in files named qqprocs.h, qqconst.h and qqcunc.c. Qqprocs.h contains the external declarations of procedures which are accessed by more than one segment. Qqconst.h contains the constant, type, and variable declarations as well as the definition of the qqstatic area. Qqcunc.c is written in the C language and contains the system dependent operating system calls or process communication that are not available directly from PASCAL.

When inference commands are invoked, there are two options for the invocation of the inference program. If the session is interactive and the user specifies a [illegible] the inference program is forked and QUIN waits for it to finish before [illegible] circumstance, (not interactive or no results table specified) the inference program is [illegible] as a separate process independent of QUIN. The 'qq' prefix is attached to every procedure in QUIN to avoid name conflicts with other ADVISE modules.

The modified macro processor "cpp" is also spawned as a separate process, but input is only directed into that process when the $sma directive has been given. In fact, the process is never spawned until the first time $sma is issued.

CHAPTER 5

Rule Acquisition and Refinement

5.1. A Paradigm for Rule Base Development

A standard method for forming an expert system's knowledge base is a generate–and–test process. There are difficulties, however, in both the generation and testing of knowledge bases. The source of these difficulties is twofold. First, the expert is trained to *make* decisions, not to explicitly state his knowledge. Second, the expert is provided with virtually no aids in either stage of the process. He must generate his knowledge base from scratch with only the knowledge engineer's guidance to help him. He must then produce test examples which show faults in the knowledge base he himself just constructed.

Some relief is provided by expert system development systems, which establish a framework for expressing knowledge. Such systems give the expert a pre–defined knowledge representation method, and therefore make the knowledge acquisition process somewhat easier. However, they may also force the expert to channel his knowledge into a format which does not fit it. The knowledge representation problem will not be dealt with here. Instead, we will carefully delineate an area of applicability, and describe new tools for knowledge acquisition within that area.

Many different knowledge representation formalisms, each applicable to a range of domains, have been developed in the last twenty years. Unfortunately, some of these formalisms have been used in areas for which they are not really acceptable. In order to avoid this trap, the knowledge representation to be used will be exactly defined. Such a presentation will naturally suggest certain problem types.

The methodology described in this chapter deals only with rules. In a variety of application areas, an expert's knowledge can best be expressed in the form of if–then rules. With some extensions to the if–then format, a rule formalism can deal with uncertainty in information, with weighted conditions and with multiple decisions and associated confidences. A detailed discussion of the syntax and semantics for rules is presented in [Reinke84].

In this chapter, we are restricting discussion to rule based knowledge. Rules will be written in terms of discrete, finite attribute values. If a rule specifies a decision, that decision will be one of a known set of decision classes. If the expert is to present examples of his decisions, the examples will be presented in terms of the same attributes, and each example will have a defined decision associated with it. We develop a method which will provide, within this restricted framework, useful tools for building and debugging rule bases.

5.2. The Standard Rule Acquisition Paradigm

Figure 33 shows a flow chart of the standard knowledge engineering process. In the figure, circles represent processes and blocks represent objects (both humans and computer programs) which participate in the processes. The rule base specification process shown consists of two major subparts. First, the knowledge engineer must obtain from the domain expert a list of the variables that are relevant to the problem area. In medical diagnosis systems, for example, this would be a list of relevant symptoms, patient data and laboratory data. Once the

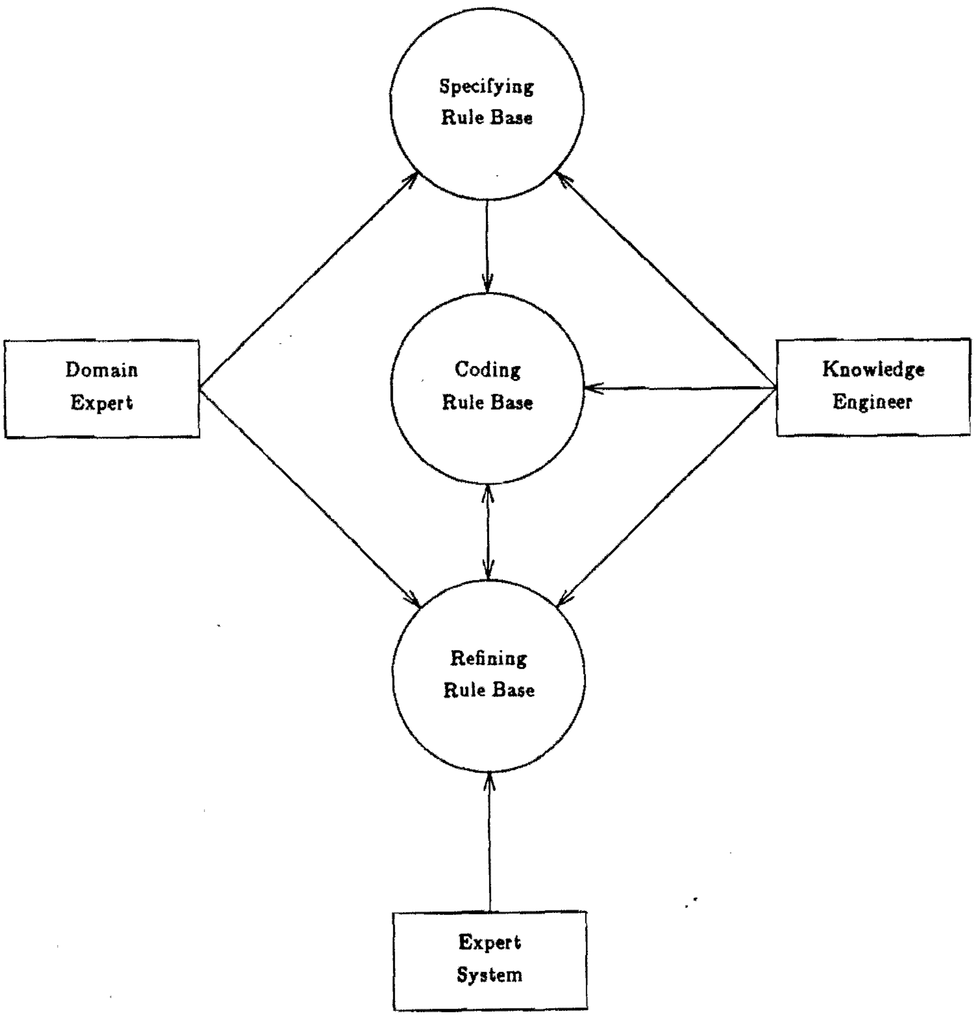


Figure 33: The standard paradigm for rule base development.

attributes are defined, the expert may write the rules for the initial knowledge base. At this stage, in consultation with the domain expert, the knowledge engineer must decide exactly what needs to be represented and how to represent it in the form of rules. He must consider, for example, how to deal with uncertainty, with weights on conditions, and with how the rules should be evaluated.

Once this process is completed, the knowledge engineer must proceed on his own to encode the rules and the inference mechanism which will use them. Due to the complexity of the next stages of knowledge acquisition, the engineer must be certain that his system is easy to modify and that he has provided sufficient explanatory facilities so that the expert, when debugging the knowledge base, can find the causes of problems.

This leads to the third, and most difficult, stage of the expert system development process. During the rule base refinement stage, the domain expert must test his "pupil" on pre-classified examples. This process often involves several domain experts using the systems over a period of months. Once enough difficulties have been noted, the domain expert must go back to the rule base and make additions and changes to it and possibly to the list of relevant attributes.

5.3. A New Paradigm for Rule Acquisition

The problem with the standard paradigm is that the process relies very heavily on the time and effort of the very expert whose job should be eased by the system. The entire process also depends on the domain expert's ability to elucidate and explain his knowledge. All of this suggests that the expert needs help in building and refining a rule base. Figure 34 shows a new paradigm for knowledge base construction, aimed at giving the expert help in those areas in which he is weak. The tools aligned with the expert are intended to work with *examples* of expert decisions, as well as with explicit declarations of an expert's knowledge. These tools should also aid the expert in producing examples that will be of importance.

Under the new methodology, the development of a rule base begins with the expert specifying the attributes relevant to the problem. Some work has been done in aiding the expert here through a program that picks important attributes out of an exhaustive list [Baim 82]. At this point, the expert has two options. He may proceed in the standard way, aided only by a rule editor, or he may choose to present the induction tools with a set of tutorial examples. The tools will produce a rule base which is guaranteed to work correctly for the examples given. In either case, the initial knowledge base is constructed, and the expert enters the knowledge refinement stage.

Here, the expert needs to produce examples that will demonstrate problems in the rule base. The testing tools shown in Figure 34 really consist of two parts: a mechanism to suggest areas where the rule base may not work correctly (i.e. it should suggest testing examples) and a mechanism that rapidly tests examples provided on the knowledge base and presents the results in a usable format to the domain expert.

If problems have been revealed in the knowledge base, it must be refined to deal with those cases which it handled incorrectly. Again, the expert is given the option of doing the work himself. However, he may present the examples which caused problems to the induction tool, which will refine the knowledge base so that it deals with these new examples correctly.

Note here that the new paradigm completely subsumes the old one. Within the context of the new method, the expert may still, if he chooses, do all the work himself, aided by the testing and editing tools. The most desirable course is probably a hybrid, wherein the expert may define some knowledge which is used to guide the induction process.

Given this paradigm, we can create a description of the software tools that should be available to the expert system builder. First, we need an efficient, correct method for generating and refining a rule base using examples. Next, we need tools that will help the expert generate testing examples and run those testing examples on the knowledge base. Additional tools to aid the expert in attribute definition would also be desirable. All these tools should work in the context of a powerful rule language which will be of use in a wide variety of

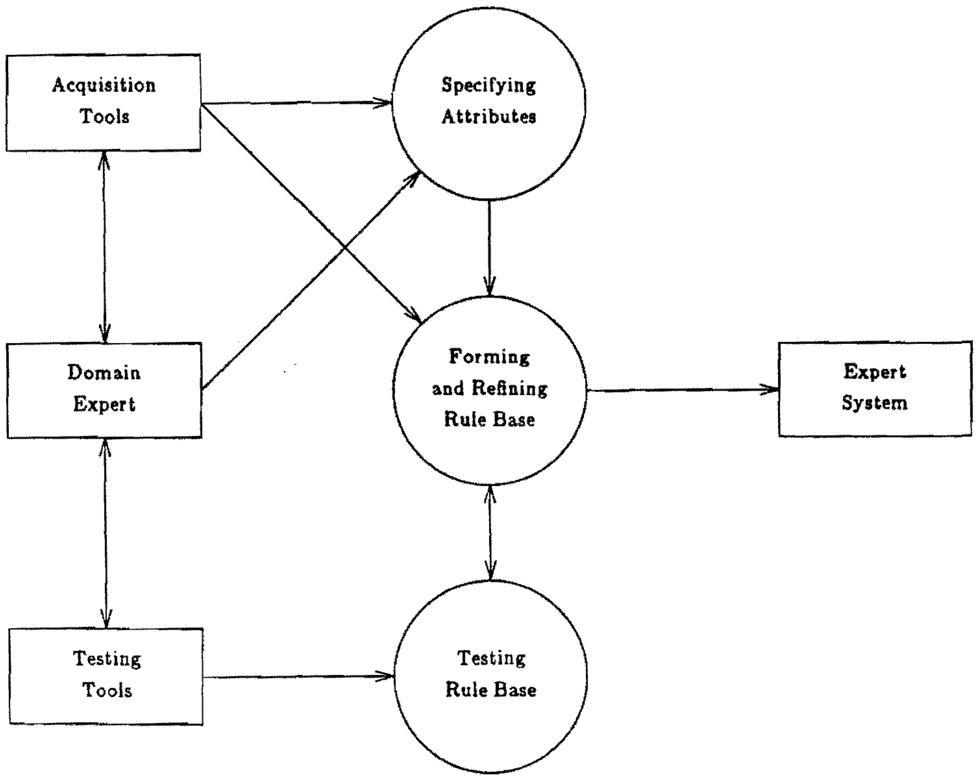


Figure 34: Paradigm for rule base development using automated refinement and testing

domains.

The next section presents a program which partially fills the and testing tool slot in the new paradigm.

5.4. The ATEST Tool for Rule R[illegible]nement

For the new rule base acqu[illegible]on paradigm to be effective, the domain expert must be able to produce testing examples [illegible] his knowledge base and apply those examples in order to assess rule base performance. ATEST is a tool developed specifically for that purpose. It provides the domain expert with two new capabilities. First, ATEST allows the expert to rapidly test a rule base on numerous examples under a variety of evaluation schemes. These evaluation facilities provide information about the overall performance of the rule base and about the performance of specific rules on specific examples. Second, ATEST provides routines that check a rule base for consistency and completeness. These routines can be used to point out problem areas in the rule base and to help the expert generate new examples.

Section 5.4.1 presents an introduction to the rule testing terminology used throughout the rest of this thesis. Section 5.4.2 presents the evaluation parameters available in ATEST and describes the program's evaluation and trace abilities in detail. Section 5.4.3 presents a discussion of the consistency and completeness problems and describes the algorithms used by ATEST to test consistency and completeness in a rule base.

5.4.1. Terminology

ATEST views rules as expressions which, when applied to a vector of attribute values, will evaluate to a real number. This number is termed the *degree of consonance* between (the left hand side of) the rule and the event. The method for arriving at the degree of consonance, given a syntactically correct rule and an event, varies with the settings of the various ATEST parameters (see next section). When ATEST is run on a set of pre–classified testing examples, it simply applies each rule to each example and reports the degree of consonance. However, with a large number of testing examples, and a large number of rules, output of this sort is likely to get unwieldy. Therefore, ATEST has the ability to summarize the results.

Rule testing is summarized by lumping together the results of testing all the events of a single class. This is done by establishing equivalence classes among the rules that were tested on those events. Each equivalence class (called a *rank*) contains rules whose degrees of consonance were within a specified tolerance (called *tau*) of the highest degree of consonance for that rank. When ATEST summarizes the results, it reports, for each rule, the number of testing events for which that rule was a first rank decision.

The only remaining term to be defined is *satisfication*. Satisfaction applies to disjunctive normal form (DNF) expressions. A DNF expression is said to be satisfied if some complex in it is satisfied. A complex is satisfied by an event if every selector in the complex is true for the event. In other words, satisfaction is a boolean logic conditional, and therefore applies to selectors and DNF expressions, but not to modules or rule groups (which may have weights associated with their conditions).

5.4.2. The ATEST Evaluation Routines

ATEST takes as input a set of attribute definitions, a set of rules (and an optional structuring on the rules), a set of testing events, and a set of parameter values. The parameters control what ATEST does with the rules and how it evaluates the rules on the testing events. There are nine different parameters involved with rule testing. Six of these determine how rules are evaluated. The remaining three control which of ATEST's capabilities will be used during a given run. This section presents a discussion of the six evaluation parameters.

Three evaluation parameters provide definitions for the logical operators "and" and "or". The operator "and" ("$\wedge$") may be evaluated as *minimum* or as *average*. The operator "or" ("$\vee$") may be evaluated as *maximum* or as *probabilistic sum*. The final evaluation parameter controls the the definition of the elementary conditions, called selectors. A selector may be treated as a boolean conditional (i.e. it may evaluate to 0 or 1), or as a function which when applied to an event evaluates to a normalized real number between 0 and 1. Given a selector in some attribute x whose domain is the ordered list $(a_1, a_2, \ldots, a_n)$, and an event where $x = a_k$, the normalized value for the selector $[x = a_j]$ is

$$1 - (| a_j - a_k | / n).$$

If the selector has several values on its right hand side, the value closest to a_k is used.

The *tau* parameter mentioned in the previous section controls the assignment of rules to equivalence classes when testing on a single event. This parameter allows the user to determine what kind of range in degree of consonance he may expect when actually using the rule base for consultation. Increasing tau will increase the number of first rank decisions, and therefore increase the number of (possibly conflicting) actions associated with a given testing event. By varying the tau parameter, the expert can determine how robust his rules are in discriminatory terms.

The *dropa2* parameter controls the use of the α_2 weight on rules. It specifies the truth threshold a module must exceed before that module can be included in the weight of cumulative evidence.

The remaining parameter, *threshold*, controls the degree of consonance threshold for a rule. ATEST reports, for every class, how many testing events caused the correct rule to have a degree of consonance greater than *threshold*. Figure 35 shows a sample problem input to ATEST and the resulting output if all of ATEST's evaluation capabilities are being utilized. The output shown consists of two parts. The table is a confusion matrix showing the performance of the rules on class B events. The numbers in the matrix are the degrees of consonance; numbers surrounded by asterisks indicate correct first rank decisions. If ATEST is told to summarize the results, only the first and last rows of this table will be output. The second portion of the output is a trace of evaluation for those cases where the rule base did not perform correctly. The selectors surrounded with question marks are those which were not satisfied. Selectors in double brackets are those which were satisfied. In a structured rule base, this trace is considerably more complex, as it details the paths taken to reach the final degree of consonance.

5.4.3. Consistency and Completeness

In some domains, it is essential that no two rules in the rule base conflict, i.e. that the rule base is *consistent*. Inconsistency occurs if there is a situation (event) in which two rules would indicate different, mutually exclusive actions. In the terminology of Section 5.4.1, an inconsistency exists if there is an event which causes two rules of different class to evaluate to first rank decisions.

There are also cases in which it is necessary for some conclusion to be reached for every possible input. We say a rule base is *incomplete* if there is an event for which no rule has a degree of consonance greater than *threshold*. The threshold used in ATEST is defined by the user, but has a default value of 0.50.

Testing consistency and completeness in a rule base are relatively easy if we are dealing with unweighted, non-structured rules and applying a boolean logic scheme for rule evaluation. However, the rule bases in Advise allows weighted, structured rules which may be evaluated in multiple ways. Therefore, ATEST does consistency and completeness checking under more general conditions. The routines in ATEST use a generate and test method for recognizing consistency and completeness problems. This methodology takes advantage of the speed and flexibility of the evaluation procedures already present for testing examples.

[illegible]onsistency and completeness are handled in essentially the same man[illegible] [illegible]irst, A[illegible] calls routines that apply logical and set theoretic operators to the rules [illegible]uce "[illegible]omplexes". The test complexes are fed through the evaluation routin[illegible] the [illegible] are examined to determine if there is indeed a problem.

The generating routines for consistency operate by forming the intersection of the left hand sides of the rules that are to be tested. A standard logical intersection will not work

Rule A : $[x_1 = 0,3]$

Rule B : $[x_1{=}2][x_3 = 1,2] \vee [x_1 = 0][x_3 = 1]$

Testing Events for class B:

	x_1	x_2	x_3	x_4
B_1	1	1	1	0
B_2	0	0	1	1

Parameters:

Operator	Interpretation
AND	average
OR	maximum

ATEST OUTPUT :

TEST RESULTS FOR CLASS B

EVENT	#TIES	A	B
B-1		0.00	0.50
B-2		0.00	*1.00*
#1st rank events		0	1

Number of events satisfying rule for correct class : 1

The rule for class B was evaluated as follows for testing event B-1:

$$??[x_1 = 2]??[[x_3 = 1,2]] \vee ??[x_1 = 0]??[[x_3 = 1]]$$

Figure 35: Sample input and ATEST output for a toy problem.

- If rules R_1 and R_2 are being tested for consistency:

$$R_1 : [x_1 = 3][x_2 = 4..6][x_3 = 4][x_5 = 7][x_8 = 9] : 0.8$$
$$+$$
$$[x_6 = 0..3] : 0.4$$
$$::> [d_1 = 0]$$

$$R_2 : [x_1 = 0][x_2 = 6..8][x_3 = 4][x_5 = 4][x_8 = 9] : 0.9$$
$$+$$
$$[x_6 = 4..6] : 0.05$$
$$::> [d_1 = 1]$$

- Then ATEST will generate the test complexes:

$$[x_1 = \text{FALSE}][x_2 = 6][x_3 = 4][x_5 = 7][x_7 = 4][x_8 = 9]$$

$$[x_6 = 4..6]$$

$$[x_6 = 0..3]$$

- These complexes, if "and" is evaluated as average, will cause ATEST to report:

The complex : $[x_2 = 6][x_3 = 4][x_5 = 7][x_7 = 4][x_8 = 9]$
produces a dc of 0.88 with rule R_1 and a dc of 0.91 for rule R_2.

Figure 36: An example of consistency testing.

for two reasons. First, there are cases where such an intersection will be empty even though, under certain evaluation schemes, the rules will produce conflicting decisions. Second, the number of intersections to be performed grows exponentially with the number of complexes in the rules.

The first problem is dealt with by changing the definition of intersection. The consistency testing routine multiplies rules together in the standard fashion except that the existence of non-intersecting selectors in a conjunct does not reduce the intersection to the empty set. Instead, a special selector, which always evaluates to zero, is inserted. In this way, events that may satisfy two rules to a high degree of consonance may be generated.

The second problem is handled in two ways. First, the consistency checking routines accept a parameter (*dweight*) which specifies a minimum weight for modules. If a module has an α_1 weight below *dweight*, the module is simply not used when forming the intersection of two rules. Second, the fact that the knowledge base is structured should tend to decrease the number of test complexes produced. Since consistency checking is only done between children of the same parent in the rule base structure, the number of rules that are involved in consistency checking is reduced. Figure 36 shows an example of how the consistency and completeness routines work.

Completeness checking is done by taking the union of the left hand sides of all rules that have the same parent in the rule base. Again, the dweight parameter is used to exclude modules whose weights may be too low. Once the union is formed, it is subtracted from that portion of the event space which should be covered. If the rules being tested are at the top of the knowledge base structure, then the union is subtracted from the entire event

- Given four boolean variables x_1, x_2, x_3, x_4 and the rules:

$$\begin{gathered} R_1 : [x_1 = f][x_2 = t][x_3 = t] : 0.80 \\ + \\ [x_3 = f] : 0.60 \\ ::> [d_1 = 0] \end{gathered}$$

$$\begin{gathered} R_2 : [x_1 = t][x_2 = t] \\ ::> [d_1 = 1] \end{gathered}$$

- The union of all complexes is subtracted from the entire event space yielding the test complexes:

$$[x_1 = f][x_2 = f][x_3 = t]$$

$$[x_1 = t][x_2 = f][x_3 = t]$$

- Causing ATEST to report that neither complex satisfies any rules.

Figure 37: An example of completeness testing.

space. Otherwise, the union is subtracted from that portion of the event space covered by the parent node. Figure 37 shows an example of the steps involved in completeness testing.

This process again generates test complexes. These complexes are applied to every rule used in the union. If none of the rules have a degree of consonance greater than the defined threshold, then the test complex is reported as an area of the event space that the rules should cover but do not.

5.5. Future Work

The ADVISE system provides an excellent framework for research in this area to proceed. The ATEST tool will be attached to the QUIN relational data base system, which, with associated editors for modifying knowledge, will provide an integrated interface for the domain expert building a knowledge base. Similarly, the ADVISE architecture provides a strong foundation for the addition of further learning and testing tools.

CHAPTER 6

The Rule Parser

6.1. Introduction

This chapter describes the GVL_1 rule parser. The parser takes a knowledge base written in GVL_1 and puts out a network representation compatible with the tuple manager. The parser was originally coded by Robert Stepp. Carl Uhrik has made numerous additions to the original. This documentation was prepared by Carl Uhrik. Bob Reinke contributed the sections describing the language for representing rules.

The network output by the parser is simply a stream of parent nodes and descendant nodes. The basic unit sequence is a parent followed by a list of descendants. This list is internally a vector, called a TUPLE. Hence, the input to the PARSER is a specification of variables, constants, rules and functions, and the output is a series of tuples which are subsequently assigned an interpretation in the context of a control scheme during execution of an application system. This interpretation is partly fixed by a convention of predefined symbols called PARMARKs (See appendix A).

6.2. Language for Rule Representation

This section outlines the language provided by ADVISE for describing and entering rule-based knowledge.

6.2.1. Rules

Rules have two major components: right hand sides (RHS) and left hand sides (LHS). LHS are conditions to be satisfied, and RHS initiate actions or decisions based upon the values of variables. The LHS and RHS have weights (α and β respectively) that correspond to the strength of the assertion in either a backward or forward direction (See Section 2.2.2.2).

6.2.2. Right Hand Sides (RHS)

A RHS is a concatenation (conjunction) of one or more of the following constructs:

[variable = value]
[variable = variable]
[variable = expression]

An expression is an integer, real, symbolic value, variable, function or any arithmetic combination of these. The action caused by evaluation is to take the expression value on the right of the equal sign and assign it to the variable on the left of the equal sign. The strength associated with the implication is attached as a confidence to the value assigned to each variable.

6.2.3. Left Hand Sides (LHS)

The structure of the LHS features a wider variety of constructs than the RHS. These constructs are listed at increasing levels of detail below:

(1) A **LHS**: consists of one or more linear modules. Linear modules are separated by disjunctions (V).

(2) A **Linear Module**: consists of one or more linear module parts. Linear module parts are separated by sums (+). An optional weighting coefficient or pair of coefficients may be placed before each linear module. In the former case, the coefficients must sum to one. In the latter case, the coefficients represent Bayesian ls/ln pairs as described for the BABY System (see section x.x.x).

(3) A **Linear Module Part**: consists of one or more selectors. Selectors are separated by one of the following logical operators: 1) OR (V), 2) AND (no symbol), 3) implication (->), 4) equivalence (<->) or 5) exception ().

(4) A **Selector**: consists of an expression, a relational operator and a reference surrounded by square brackets ([]). The relational operator is one of {<, >, =, <>, <=, >=}.

(5) An **Expression**: can be either a value, integer, real, variable, function or an expression separated by arithmetic operators. This operator is one from the set {+, -, *, /, %}. The symbol (%) denotes modulus.

(6) A **Reference**: consists of one or more reference values separated by commas. Each reference value can have a weight associated with it. The value/weight pair is separated by a colon. Each weight can be one or two real numbers. In the second case, the first number is the truth weight and the second number is the falsity weight (i.e., how much the selector's failure contributes to the falsity of the condition containing it). A reference can be an expression, and a weight can be an expression.

6.2.4. Rule Groups

A rule group consists of a named set of rules. Rule groups provide a mechanism for focusing the evaluation of rules toward a particular problem solving strategy or subproblem area. Each rule group references a block of variable declarations and, optionally, a block of function declarations.

Examples of the use of multiple rulegroups can be found in the PLANT/ds expert system (see Chapter 13) and the ALFALFA expert system (see Chapter 16). In the first, one set of rules (derived inductively by machine) focuses the consultation on a short list of candidate soybean diseases, while a second rulegroup (written by a human expert in plant pathology) performs a more detailed evaluation of the plausible diseases. In the second system, twelve distinct rule groups are employed to descend through various levels of identification of insect pests found in alfalfa fields, using dynamicly changing goals, preconditions and postconditions on rule groups expressed in the rule language to direct the control scheme in execution of appropriate rule groups.

6.2.5. Variables

Variable definitions are parsed independently of the rules and define each variable's domain. Variables in ADVISE can be of two types:

(1) **Nominal**: The values are simply symbolic names and no ordering is implied between the names. For example, the colors "blue", "green" are might be values of a nominal variable.

(2) **Interval**: The values of the variable can be a range of integer or real numbers, or symbolic names. In the case of **interval** variables, an ordering is implied.

Variables are declared in blocks, and each block is assigned a name. If a variable is declared from the special GLOBALS block, it is implicitly known to all of the rule blocks following.

6.2.6. Functions

Since the ability to parse functions constituted a major impetus for this project, fuller details of the syntax and semantics are given here. Functions come in two varieties: 1) **trap** functions or 2) **memo** functions. Both the bodies and calls to memo functions are parsed by the parser, but only the calls to trap functions are handled by the parser, not their definitions. **Trap** func[illegible] correspond to procedural knowledge and are handled as jumps to specific pieces of PA[illegible] code. An example of the use of **trap** functions is described in Chapter 12. **Memo** fu[illegible]s correspond to the classical notion of functions, except that two simultaneous speci[illegible]ons of their definition may be active: 1) a tabular definition consisting of a table of domain/range values or 2) a formula definition from which function values can be computed. When a function is called, a check is made to see if a table exists. If the table does exist, and the values for the arguments are found in the table, the function value is simply retrieved from the table. If no table is present or no entry for the function arguments is found, the formula definition is used to calculate the value and a new table (or table entry) is added.

Different rule groups can share the same function or variable blocks. In general, it is the responsibility of the user to verify the compatibility of the variables and functions between their definition and their use in the rule group.

A function in ADVISE is a mapping of values of arguments to a (value,confidence) pair. The confidence here is a default which may be alternately specified by a control scheme override in the evaluation of a rule set. To represent the description of the correspondence $F(arg_1, arg_2, \ldots)$ = (value,confidence), we have in tabular form:

Funcname $[arg_1, arg_2, arg_3, \ldots]$

$(varval_{11}, varval_{12}, \ldots)\ (funcval_1, conval_1)$

$(varval_{21}, varval_{22}, \ldots)\ (funcval_2, conval_2)$

.
.
.

$(varval_{n1}, varval_{n2}, \ldots)\ (funcval_n, conval_n)$

Where...

Funcname is the name of the function;
var is a variable name;
varval is the value of the variable;
funcval is the function value for some argument values and
conval is the corresponding confidence.

Note that for the use of weights, a convention was adopted to set the function value to the weight and set the confidence to unity (1.0) if no confidence is explicitly given. This also serves the purpose of functions used as a reference value.

Imposing an outer structure to allow for multiple function definitions in a block, consistent with the block structure of variable declarations and rule definitions, we have the function grammar specification indicated in Appendix B. Note that there is no provision for type specification. This is due to the fact that basically two types of domains exist in ADVISE :

(1) NUMERIC - real and integer which can take on any of an infinite number of values which are in common with other variables,

(2) SYMBOLIC - identifiers which are unique to a variable by virtue of its declaration (even when two ids have the same printname, they have separate internal names) .

In the latter case, a function defined with one set of arguments is bound to those arguments. In the former case, the generality of the internal representation allows the liberal interpretation desired. The responsibility is left to the control scheme to verify that a rule utilizing a function is calling the function with proper arguments. This is facilitated by the elements of the function tuple, which indicate the number of arguments, argument characteristics, etc. .

Functions can take one of three possible forms which are distinguished both by their declaration syntax and their use in rules. The 3 forms are illustrated in skeletal form below to give the abstract notion:

1) numeric for integer/real values in weights, number variables, etc.
which have the declaration,

```
function name ( arg1 , arg2 , ... )
                [ n11    n12  ... funcval1]
                [ n21    n22  ... funcval2]
                         •
                         •
                         •

                := arithmetic expression of arg1 , arg2 , ... ,
```

where the arguments, the table of values, and the expression are optional;

2) boolean for the representation of selectors or logical components of
a rule's LHS which have the declaration form,

```
function name ( arg1:type1 , arg2:type2 , ... ) : BOOLEAN
                [ val11    val12  ... funcval1]
                [ val21    val22  ... funcval2]
                         •
                         •
                         •
                := VL expression of arg1 , arg2 , ... ,
```

where the table of values or the expression are optional, (but types are explicit, or implicitly assumed to be integer/real if omitted;

3) symbolic for the representation of variable values within selectors,
having the form,

```
function name ( arg1:type1 , arg2:type2 , ... ) : ftype
```

```
[ val11    val12  ... funcval1]
[ val21    val22  ... funcval2]
              •
              •
              •
```

where the table of values is mandatory and types are explicit,
or implicitly assumed to be integer/real if omitted.

Note that the expression forms are functions that return either the reserved type BOOLEAN (TRUE/FALSE) or numbers. No expression can return a symbolic value. The user is encouraged to do as much type specification as possible, as the parser does little in this area. Any variable which is declared in the variable block assigned to this function block may appear in the expressional definition of the function (or even a global) not just the argument "dummy" variables. Note that a variable is first checked for a possible local context and failing that, the variable is assumed global. Further, any use of a global in a function declaration temporarily makes it local in scope. A GLOBAL block is intended to affect all the blocks to follow it by entering symbols permanently into the symbol table. The syntax is similar to PASCAL. An example follows (note however that the TYPE keyword is unreliably implemented).

```
GLOBALS
 TYPE
  BINARY = ( PRESENT, ABSENT ) ;
  COLOR = ( RED, BLUE, GREEN );
 VARS
  RULEGROUP : (INDUCTION, EXPERT, TREATMENT) ;
  DAMAGECOST: INTERVAL (0..1.0) ;
  USER     : (INEXPERIENCED, EXPERIENCED, SUPERUSER) ;
 END

VARSX VARS
  X1 = ( DRY, WET, NORMAL );
  X2 : BINARY ;
  X3 : BINARY ;
  X4 = ( BIG, SMALL ) ;
  T  = ( 0.0 , 1.0 )  ;
  Z  = ( 0.0 .. 10.0) ;
 END
```

```
FUNCX FUNCS
 VARS = VARSX;
 F1 [X1:PRES_ABSENT,Z3965,W235] : COLOR
   (ABSENT , 25.3 , 0.01 ,  RED  , 1.0)
   (PRESENT, 0.23 , -6.7 ,  BLUE , 0.9)
   (ABSENT , 0.0  ,  0.0 , GREEN, 0.8)  ;
 F2 [Z3966,W236]
   (PRESENT, 0.1 , 0.1 , 0.5 , 1.0)
   (PRESENT, 0.2 , 2.5 , 0.7 , 0.1)
   := 3.0 * Z3966  -  2.3 * W236 * Z3966  +  8.789  ;
 END


 RULESX RULES
  VARS = VARSX
  FUNCS = FUNCSX
      •
      •
      •
   [X1=PRESENT][X2=ABSENT:F2(ABSENT,23.1*12.6,Z*8.2)] :> [T=1.0];

 END
```

Note : *The VARS declaration in the function block is optional unless a function requires an implicit parameter for a functional expression computation. The type of a function or arguments not specified are assumed to be integer/real. The only predefined type is LHS, and it is reserved for function typing (ie., it may not appear on a variable). Further, a function of type LHS may not have any predefined tabular values. There is a local override in effect if a variable is declared to have a symbolic value already possessed by a GLOBAL type. Possible local context of a symbolic value is checked before it is deemed GLOBAL. Both variables and the symbolic types that occur in the GLOBAL block are global. This means that a global variable will be entered into the dictionary for the network. Also, a global need never be used as a variable, i.e., it may exist solely for the purpose of sharing a type between 2 or more variables that are local (but wish to pass their symbolic values into functions or back from functions or test for equality of symbolic values.*

6.2.7. Properties

Properties can be attached to rule groups, rules, variables or functions. These properties are used by the control scheme to perform various tasks. For example, in the PLANT/ds expert system (Chapter 13) uses properties to:

1) provide text for asking questions,

2) determine whether, for a particular variable, the user should be asked to provide a confidence in their response,

3) to provide a detailed description of variables and

4) to bias a variables importance.

Properties are treated as simple pieces of text and are not involved in rule evaluation.

6.3. Parser Construction

Some of the code that makes up the compiler was generated by the YACC compiler compiler. YACC provides a general tool for imposing structure on the input to a computer program. The Yacc user prepares a specification of the input process. This includes grammar rules describing the input, code to be executed when these grammar rules are recognized as applicable, and a low level lexical routine to do basic input. Yacc then generates a procedure in the from of a C-program to control the input process. This is in fact the PARSER. When compiled and executed, it calls the low level input routine (lexical analyzer) to detect the basic input symbols (tokens). These tokens are organized according to the input rules; when one has been recognized an applicable grammar rule, the user code supplied with the grammar rule is invoked, returning values and using the values returned by previously executed such rules.

This allows the PARSER to be specified by a number of production rules involving nonterminal symbols and terminal tokens. Precedence of operators may be specified to resolve any ambiguities in the grammar and certain error actions can also be invoked. The nature of the PARSER as consequence of YACC, specifically that it is a left-accept left-reduce (LALR) shift PARSER, restricts the form of many constructs. For instance, recursion is preferably left-recursive : $A \rightarrow Aa$, rather than $A \rightarrow aA$. For a full discussion of YACC, the reader is referred to the YACC user manual available through Bell Labs [* ref *].

6.4. Basic Features

All parser input is free-format. Blanks between lexical entities are ignored. Line boundaries are not significant, but the user should be aware of a limited print buffer. Use of wide line input is consequently not recommended. In the case of reading an empty file, the PARSER does nothing. Some information regarding input format and error handling is presented in Appendix A.

6.4.1. The PARSER Production Cycle

The YACC compiler takes as input a context free grammar with calls to semantic action routines supplied among the production rules. These routines are designed and coded by the implementor and ultimately produce any output apart from duplication of the input symbols. They accomplish the unit operations of the PARSER based on the current input symbol in the context of the particular current state of the parse tree. One of the most important of these routines is the lexical analyzer which recognizes the surface forms (terminals) of the grammar and is called somewhat implicitly (ie., it does not occur within any production rules of the grammar).

YACC output is a file called y.tab.c, which is intended to feed the C-compiler to generate a load module containing a simple automaton which executes an LR parsing algorithm whenever a parse is desired and in effect has two components :

(1) Parser State Table - an integer representation of the states needed in execution for maintaining the status of a parse. It is similar to the states in a deterministic finite automata.

(2) Parser Semantic Invocation Code - the core of the interpreter which actually calls the semantic routines given the proper states as they arise based on the input stream and the given grammar. It is essentially a case statement indicating which semantic actions to call at any point in execution.

Normally, YACC generates C–code for use by the standard compiler supplied with the UNIX system, but the semantic actions are more naturally expressed in PASCAL routines which draw on the rich library of the existing ADVISE system, especially the TUPLE MANAGER module which places and manipulates tuples in a network. Since the code implanted in the grammar is functionally only a specification of calls to procedures, the C–compiler is easily displaced with a PASCAL PREPROCESSOR which edits the C–code to conform to Pascal code.

This is accomplished by splitting off the state table to be read by our Pascal program and editing the executable C–code to look like Pascal. Part of this code is static for all generations of the PARSER and remains untouched, hence the program that does the conversion is somewhat simplified. The files "edparsem" and "edpartab" contain edit commands to extract the constituents (1) & (2) from the file y.tab.c and produce the files "parsem.i" and "partab" respectively. Then, partab is instated in the ADVISE "kbtext" library, and parsem.i in "kblib", reduced to a case statement as to what semantics to invoke, is automatically transplanted into the file "prsourc.p" upon compilation by a "#include" statement . The lexical analyzer and semantic action routines are already resident there and remain relatively static as they are completely oblivious to the YACC compiler (see Figure 38).

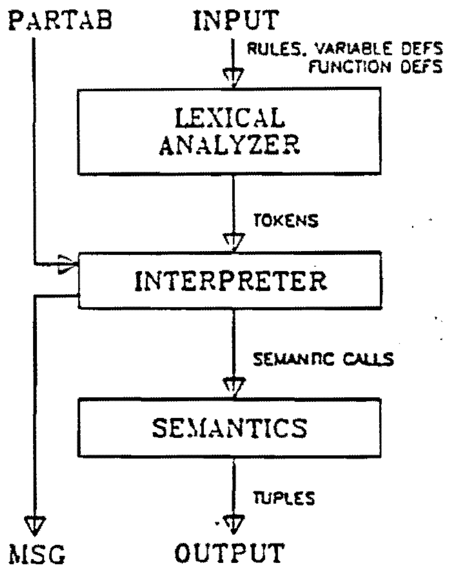


Figure 38 : Relation of Compiler Components.

In general, this system succumbs to two types of errors. One is in the grammar and the mechanics of grammatical parsing devoid of the semantic routines. The grammar can be ambiguous or allow undesired language constructs. The other type of error is in the coding of the semantic action procedures. These can be changed directly without touching the interpreter code installed from PARSEM. Usually, fair consideration should be given to interaction between the two types of errors.

6.4.2. Operation and Use of the Parser

The file prsourc.p is compiled to produce a load module which reads in the PARTAB file as its first priority. Subsequently, it reads input from the file specified as standard input, generates tokens, parses these tokens, generates tuples, and writes to the assigned OUTPUT file. Additional textual information, mainly diagnostics, is written to the file 'msg'. This process is illustrated in Figure 38.

On the VAX11-780, the current host computer for ADVISE, the parser is executed by typing the following:

```
$ADVISE/parser/prsourc  <input  >output
```

where the following files are involved...

input is a set of variables, functions, and rule knowledge bases;
output is a trace of the input file with error messages;
msg contains program debugging and performance information and
backup contains a network representation of the knowledge
base in a form that can be read by the TUPLE MANAGER.

The knowledge base can at this point be examined by running the "tmtestr" program as below.

```
$ADVISE/kblib/tmtestr
 ? os                    open standard network
 ? rb                    read backup file
 backup file : backup
 ? wt                    write text file
 text file name : net
 ? q               exit
```

At this point, a text format of backup file "backup" will have been written to "net", and this is very useful for debugging.

6.5. Updating the PARSER

The process of updating the PARSER is outlined as follows :

(1) Assess the need for any new tokens, symbols, or PARMARKs. Modify the lexical analyzer to accept these and return a valid token.

(2) Derive a set of grammatical productions which unambiguously parse the desired constructs.

(3) Determine the desired convention for the structure of a tuple to represent the construct in network form. This will depend on the intended use in the rule evaluator or control scheme.

(4) Write any new semantic action routines that are required to build the network of (3). These routines should ultimately go into "$ADVISE/kblib/prsourc.p".

(5) Insert the semantic action routine calls in the proper points in the grammar of (2). The current grammar is in "$ADVISE/parser/gramf".

(6) In the directory "$ADVISE/parser", type the UNIX command, "YACC <infile>", where <infile> denotes the name of the file containing the grammar. The file "y.tab.c" results which contains the compiler written in the "C" language.

(7) This step and the following two steps edit the "y.tab.c" and extract portions that are inserted in the PARSER. If the shell script "pyacc" can be executed successfully (w/o errors), these steps can be eliminated. First a portion of the grammar, represented by a large "case statement", is generated by typing: "ed <edparsem y.tab.c". The file parsem.i results.

(8) The state table is extracted by typing: "ed <edpartab y.tab.c".

(9) This step searches for labels in "y.tab.c" in order to construct the "OTHERWISE" portion of the code that encapsulates the case statement. Type

```
prlabels > prlabels.i
```

to collect together all the allowed labels that occur in the case statement of "parsem.i". Both "parsem.i" and "prlabels.i" are automatically transplanted into "prsourc.p" at compilation by "#include" statements. The case statement portion (parsem.i & prlabels.i) should be installed in the ADVISE library "$ADVISE/kblib".

(10) Install the partab file back in the library "$ADVISE/kbtext",

(11) Remake the prsourc file (i.e., compile prsourc.p and load prsourc.o), according to the file "Makefile" in kblib.

To assist users in making changes to the parser, the current grammar definition as seen by YACC is presented in Appendix B. Note that steps 6–9 can be built into a convenient shell script.

CHAPTER 7

The Rule Evaluator

7.1. Introduction

This chapter describes the some aspects of the Rule Evaluator, that portion of the ADVISE system that combines the evidence represented as a rule. The Parser module parses rules into a tree structure in pre-order form. The rule evaluator recursively descends into this tree in order to determine the "truth value" of some portion of it. In its simplest form, the rule evaluator returns the "truth value" of the left-hand side of a rule. Another user procedure, the rule interpreter, executes a rule's right-hand side if such action is called for (these decisions are made in the Control module). The rule evaluator was originally coded by John Davis. Kent Spackman has made significant additions to this original work and is the author of this documentation.

7.2. User Procedures

The rule evaluator is accessed via three procedures. A description of these three procedures follows :

reinit (schema,schematuplen)

Where...

schema is a tuple where the user specifies the evaluation scheme to be used (please see the next section). Each address in this tuple corresponds to a user selectable option that specifies how certain rule structures are evaluated,

schematuplen is an integer value corresponding to the number of options specified in the schema tuple above. There are 15 possible options the user might specify, if fewer than 15 are selected, those not selected are set to their default values.

The reinit procedure must be called before using the rule evaluator. It can be called multiple times if the user wishes to use different evaluation schemes within a single consultation session.

evaluate (lhs,val,errnode,error)

Where...

> **lhs** is a rule's left-hand side or some structure within a rule's left-hand side (down to a single selector). It represents the item to be evaluated;
>
> **val** returns the result of the evaluation as a real number (val). It corresponds to the *truth value* of the rule part passed to the evaluator. In the current implementation, val will range between 0.0 and 1.0;
>
> **errnode** returns the internal name of the node in which an error (if any) occurred and
>
> **error** is the error type encountered above. These errors may correspond to unexpected conditions that arose during evaluation, but might also contain information useful to the Control module. For example, the error that a rule was not completely evaluated may prompt the Control module to gather more information form the user.

As mentioned earlier, the schema tuple determines how various rule structures are evaluated. Another mechanism for controlling the behavior of the **evaluate** procedure is via accessory control (ACCTRL). The variable ACCTRL is a Pascal set type which can take on none or more of the values listed below :

- **storintres** : This instructs the **evaluate** procedure to store intermediate results obtained during evaluation.
- **useintres** : This instructs the **evaluate** procedure to use the results stored above. **Storintres** and **useintres** are most commonly used together. They can significantly speed up the time it takes to evaluate a rule, but are not appropriate in certain cases. For example, if the both of these values are added to the ACCTRL set, intermediate results are stored and used at all levels of the parse tree descent. If the Control module has changed the value of a variable in a rule already evaluated (for example, if the user has asked to change the answer to a question), then the evaluator will not descend into the parse tree deep enough to detect this fact.
- **continue** : This instructs the rule evaluator to continue evaluating even if it encounters a variable that has never been assigned a value. The evaluator will still return the error that the rule is not completely evaluated. Variables who have no value assigned are given a "truth value" of 0.5.
- **min** : Used in conjunction with continue, this causes the truth value 0.0 to be assigned to variables that have no value. Useful in determining a worst case evaluation of a rule.
- **max** : Used with **continue**, causes the "truth value" 1.0 to be assigned to variables that have no value. Determines the best case rule evaluation.

interpret (rhs,strength,reset,errnode,error)

Where...

> **rhs** is the rule part you wish to interpret; normally
> a rule's right-hand side;
>
> **strength** is a real number corresponding to the degree
> of truth returned by the **evaluate** procedure
> combined in some fashion with the strength of the assertion
> of the decision symbol (α).
> This value is control scheme dependent;
>
> **reset** is a variable which no longer has a function;
>
> **errnode** is the node that caused an error (if any) during
> interpretation and
>
> **error** is the name of the error (if any) that occurred.

In the current implementation, the **interpret** procedure will function correctly only if the **rhs** consists of a simple selector or conjunction of simple selectors.

7.3. Configuring the Evaluator

As mentioned before, how the rule evaluator evaluates a rule is specified in the schema tuple. Each position in the schema tuple corresponds to some rule structure and can be assigned values from several available. The meaning of each position in the schema tuple and available options is listed below.

(1) Linear module (evaluation) : **default.**

(2) Conditional statement (evaluation) : **default.**

(3) Disjunction of rule parts other than selectors (evaluation) : **default,max,suppes.**

(4) Conjunction of rule parts other than selectors (evaluation) : **default,min,prod,ave.**

(5) Disjunction of selectors (evaluation) : **default,max,suppes.**

(6) Exception (evaluation) : **default,excpt1.**

(7) Equivalence (evaluation) : **default,equivmaxmin,equivmaxprod, equivmaxave,equivsuppesmin,equivsuppesprod,equivsuppesave.**

(8) Implication (evaluation) : **default,impmax,impsuppes.**

(9) Conjunction of selectors (evaluation) : **default,min,prod,ave.**

(10) Selectors (evaluation) : **default.**

(11) Conjunction of rule parts other than selectors (interpretation) : **default.**

(12) Disjunction of rule parts other than selectors (interpretation) : **default.**

(13) Selectors (interpretation) : **default.**

(14) Conjunction of selectors (interpretation) : **default,min,prod, ave.**

(15) Functions (evaluation) : **default.**

(16) Behavior (evaluation) : **default.**

(17) Functions (interpretation) : **default.**

The definitions of the possible options are listed below :

- **min** : minimum.
- **max** : maximum.
- **ave** : average.
- **prod** : product.
- **suppes** : x + y - (x * y)
- **excpt1** : x / y (if y = 0 then the result is the truth value of x).
- **equivmaxmin** : value = max(min(x,y),min(1-x,1-y))
- **equivmaxprod** : value = max(x*y,(1-x)*(1-y))
- **equivmaxave** : value = max(ave(x,y),ave(1-x,1-y))
- **equivsuppesmin** : value = min(x,y)+min(1-x,1-y)-min(x,y)*min(1-x,1-y)
- **equivsuppesprod** : value = x*y+(1-x)*(1-y)-x*y*(1-x)*(1-y)
- **equivsuppesave** : value = ave(x,y)+ave(1-x,1-y)-ave(x,y)*(ave(1-x,1-y)
- **impmax** : value = max(1-x,y)
- **impsuppes** : value = (1-x)+y-(1-x)*y

CHAPTER 8

Knowledge Base Paraphrasing

This chapter describes the paraphrasing capabilities in Advise. Section 8.1 describes the design of a general paraphrasing mechanism that has yet to be implemented. Section 8.2 describes a pre-existing implementation of a rule paraphrase module based on the rule evaluation module.

8.1. Design of a General Paraphraser

A general paraphrase mechanism has been designed to paraphrase any tuple in a network. Remember that internally, every rule or table can be represented as a tuple in the low-level Advise network. Given a tuple, the paraphraser first locates a paraphrase program for that tuple, then executes that program to produce the appropriate paraphrase e.g. a GVL rule, an English rule, or a fancy table display. The paraphrase program for that tuple may be located in one of several places. First, it may located directly under the main node of the tuple to be paraphrased. Second, the program may be found under subnodes (nodes other than the main node) of the particular tuple. Finally, it may be at another node in the network, locatable through an inherit relation or indirection mechanism from nodes in the tuple. For example, the paraphrase program for a selector in a rule may be found directly under the main node of the selector, under a subnode of the selector (e.g. a marktype that determines the type of selector), or under the rule or rule group in which the selector appears.

The paraphrase program consists of a series of tuples under a given node. The second node in each tuple (the first node would be the main node) is a keyword that identifies the tuple as being part of a paraphrase program. This identifier will be one of MKPARAPHRASE, MKPROG, and MKPROGEND. These are defined below. Subsequent nodes in each tuple will determine a specific paraphrase action. Commom actions are finding a new tuple to paraphrase, printing text associated with a node, and setting up a means to paraphrase the tuple iteratively.

The following are the definitions of the keywords recognized by the paraphraser.

MKPARAPHRASE	Denotes the start of a paraphrase program. Optional arguments denote the style of paraphrase (i.e. rules, networks or tables) and may also denote a restriction on the tuples that can be paraphrased by this program.
MKPROG	Identifies statements in a paraphrase program.
MKPROGEND	Marks the end of a paraphrase program.
MKLOOP	Marks the beginning of a loop in a paraphrase program.
MKPARAINDX	This serves as a "program counter" in the sense that it denotes what node in the current tuple is being paraphrased
MKSHIFT	Assigns a specific node to the "program counter" relative to the current position. Default is the shift one node. Further shifts may be specified by an additional argument.

MKABSHIFT	Assigns a specific node to the "program counter" absolutely.
MKLOOPEND	Marks the end of a loop.
MKPRINT	The printname of the node argument which follows is output.
MKPARAPRINT	Paraphrase the tuple that matches the following left context of this tuple.
MKPRINTPOS	Output the printname of the node found at the postion in the current tuple specified by a position argument
MKPARAPOS	Paraphrase the tuple that matches a tuple constructed by adding the remaining left context of the MKPARAPOS tuple to the node at the position in the current tuple specified by a position argument.

Figure 39 shows a sample paraphrase program. The first tuple in the program is the MKPARAPHRASE tuple. It marks the start of this particular program. (There may be other programs under the main node RULEGROUP.) The MKPARAPHRASE tuple also says that it can only paraphrase tuples with left context MKEXEC MKAND, which translates to conjunctions of selectors in rules. Note that this program is located under a RULEGROUP node, a likely place to be inherited by all rules in the rule group.

If this paraphrase program has matched the tuple to be paraphrased, then that tuple becomes the current tuple and must be a conjunction of selectors from a rule. With this in mind, the paraphrase actions can easily be understood. The first MKSHIFT causes the current position to become 3 in the current tuple. This is always a node representing the first selector in the conjunction. The next step (MKPARAPOS) is to paraphrase the node at the current position followed by the remainder of of the MKPARAPOS tuple (i.e. MKEXEC). In other words, paraphrase the tuple matching (<selector node> MKEXEC). The paraphraser then recursively finds this tuple, makes it the current tuple, and paraphrases the selector. Assume now that the first selector has been paraphrased and the paraphraser has returned to this program.

```
(RULEGROUP (
   (MKPARAPHRASE MKEXEC MKAND)
   (MKPROG MKSHIFT 3)
   (MKPROG MKPARAPOS MKPARAINDX MKEXEC)
   (MKPROG MKLOOP)
   (MKPROG MKSHIFT)
   (MKPROG MKPRINT " & ")
   (MKPROG MKPARAPOS MKPARAINDX MKEXEC)
   (MKPROG MKLOOPEND)
   (MKPROGEND) )
```

Figure 39: A Sample Paraphrase Program.

The next tuple in the program is an MKLOOP. This begins an iteration of the instructions from here until a matching MKLOOPEND. The loop terminates when an MKSHIFT falls off the end of a tuple. The steps in the loop are easy to follow. The first is an MKSHIFT which makes the next selector (node) in the conjunction (tuple) the current node (position). If this succeed an "and" sign (&) is printed and the tuple corresponding to the selector is paraphrased as before. This continues until there are no nodes (selectors) left in the tuple (conjunction). Here the loop terminates and this paraphrase program completes.

Implementation of the general paraphraser is pending decision on the adoption of an object-oriented environment. The paraphraser's notion of inheritance would be well supported by an object-oriented approach. The only existing paraphrasing mechanism in Advise is a rule paraphraser which is described in the next section.

8.2. The Existing Rule Paraphrase Module

The existing paraphrase module is designed to "unparse" rules. It is capable of converting rules in their network form to the GVL_1 form. The rule evaluator was modified so that could also paraphrase rules. The rule evaluation function was retained.

There are two user callable procedures, PAINIT and PARAPHRASE. PAINIT is used to initialize the module and has the same calling sequence as REINIT, namely:

PAINIT (schemetuple,schemetuplelength);

Where...

schemetuple is the tuple specifying the rule evaluation schemes as in REINIT and

schemetuplelength is the length of the above tuple.

PARAPHRASE was adopted from procedur [illegible]UATE in the rule evaluator module and is called thus:

PARAPHRASE (**rulepart,width,textfile,value,errornode,error**);

Where...

> **rulepart** is the part of the rule to paraphrase
> and can be a whole rule down to a selector,
>
> **width** is the width for the text to be placed in
> **textfile**,
>
> **textfile** is the text file to place the results of
> paraphrasing in,
>
> **value** is the value of evaluating the rule part and
> is not defined for whole rules,
>
> **errornode** is the same as in procedure EVALUATE, and
>
> **error** is the same as in procedure EVALUATE.

The internal structure of the paraphrase module is the same as the rule evaluator module. The modifications done to the rule evaluator procedures are marked with the comment, (*PA*). This is only a preliminary version of the PARAPHRASE module. Beware of undocumented features.

CHAPTER 9

The Tuple Manager

9.1. Introduction

The Tuple Manager is an implementation of a generalized network manager similar to that described by Baskin [Baskin 1979] in his PhD dissertation. By offering a variety of high level primitives with which to manipulate the network, it allows the user considerable abstraction from the Pascal data types actually used to store the network. The user works directly with n–tuples (n < 256) which are arrays of symbols to be manipulated. There are actually three networks simultaneously active which allows for separation of public and private knowledge, and which enables one to experiment with a scratch network. The TM also supports procedures that will write out backup files and text files to re–create the network state.

9.2. The Data Types

A tuple is represented by a Pascal array of symbols, which in turn are represented by a variant record. This is analogous to lists in LISP with the exception that the list elements cannot themselves be lists, but must be atoms. Another difference is that the tuple manager's list elements can be accessed directly rather than having to traverse the list with compositions of 'cars' and 'cdrs'.

There are four types of symbols supported by the tuple manager; integers, reals, textnodes, and general symbol nodes. The most general type of symbol is allowed to have attributes attached and manipulated. These attributes are similar to LISP properties, however the attributes are referenced and stored by keying on as many of the left most symbols as desired, rather than one. This will be made clearer in the discussion of some of the tuple retrieval procedures. The textnodes are designed for the efficient storage of text and therefore, like the integer and real symbols, are not allowed to have attributes. From the user's perspective these n–tuples of symbols are just entities that can be stored, retrieved, and modified in a variety of ways. The semantics of tuples is defined by the user program, but the capabilities of the tuple manager allow for representation of any specialization from, and including, a generalized graph. So far use of the tuple manager has been limited to rules, tables in a relational data base, and a directed acyclic graph.

For efficient storage and retrieval of the tuples, they are indexed by their first symbol. A symbol consists of a node and its (possibly empty) set of attributes. A node is represented by a Pascal variant record which contains its printname, internalname (a unique node identifier), a pointer to its set of attributes, and various housekeeping variables. The attributes are stored as a linked list of linked lists of subnodes, each subnode consisting of the internalname of the node that it is representing. By referencing other nodes in the attribute list using only their internalname rather than a pointer, the TM is more easily able to make disk versions of the networks and reread them into main memory.

The tuple manager supports a dictionary for retrieval of a symbol given its printname. When a network is read in from a backup file only the symbols in the dictionary, and any symbols reachable from those, are accessible to the user. The function of the dictionary is similar to the function of the LISP ob–list. During a session, though, not all of the network's symbols may be reachable from the dictionary due to local creation and storage of symbols. The LISP analogy is a 'gen–sym' atom. The tuple manager implementation of the dictionary is a hash table that uses an intable collision resolution scheme. The procedures for entering, removing, and looking up a symbol are discussed in the next section.

9.3. The User–Visible Procedures

The user–visible tuple manager procedures are listed in alphabetical order below.

Procedure ADDATTRIBUTE. ADDATTRIBUTE takes a tuple as a parameter and adds it to the existing network. This is done by first finding the parent node of the tuple using FINDNODE. The proper place for the remainder of the tuple (the attribute of the node) is determined by a parameter passed to the procedure. This slot is then located and the incore subnode structure of the attribute is created.

Procedure ASCIIINT. This procedure converts the ASCII representation of an integer into the machine representation of that integer. This is a machine independent algorithm.

Procedure ASCIIREAL. The real number counterpart of ASCIIINT. Also machine independent.

Procedure CLOSENETWORK. CLOSENETWORK saves the state of all three levels of networks in the user's files. See OPENNETWORK. The dictionary is saved in the global level. The housekeeping pointers and variables are saved in each of the files. If one closes a network, signs off the system, and then opens the network, the state of that network will be unchanged.

Procedure CLOSENODE. This procedure takes as parameters the internalname of a node, a flagword to store with the node, and a level on which to find the node. It then locates the node with a call to FINDNODE, stores the flagword with the node, and then decrements the open counter (opencount) of the node. It does not alter the status of the node. A node with an opencount of zero is considered to be closed, and unavailable for access until opened.

Procedure CREATENODE. This procedure takes a flagword as a parameter and a level on which to work, and creates a new regular node, assigning a unique internalname to the new node. The node is not opened – it is just created. The opencount, usagecount, and attributecount are all set to zero. The printname is set to the null word so it will need to be filled in by calling the procedure SETPRINTNAME.

Procedure CREATETEXTNODE. This is a simple procedure that will create a new text node and assign it a unique internalname to it. An integer flagword is passed to this procedure and this is placed in the new text node. The internalname is returned by CREATETEXTNODE. This procedure does not open the node – it just creates the node. The new node is initialized with the opencount, currentline, and number of lines of text all set to zero.

Procedure DELETEDICT. DELETEDICT removes an entry from the dictionary. If it is not found then it does nothing. The stringpool is unaltered by this procedure, but its information is made unusable as is its storage area occupied by the printname. Therefore repeated calls to this procedure will create wasted space in the stringpool that cannot be recovered in the present implementation.

Procedure DELETESLOT. This procedure is the inverse of ADDATTRIBUTE. Given a particular attribute to be removed, it just deletes it from the in–core representation. It does this by first locating the node using FINDNODE, and then traversing the linked list of attributes until it has traversed as many as passed in the parameter slot. The subnode structure of the attribute is then removed. The value for slot that is passed as a parameter must be found by using the procedure GETATTRIBUTE.

Procedure DELETETUPLE. This is also the inverse of ADDATTRIBUTE. Unlike deleteslot, however, it takes a tuple as input. DELETETUPLE locates its parent node using FINDNODE, locates the slot under the parent node containing the tuple, and then deletes the tuple using DELETESLOT.

Procedure DESTROY. DESTROY takes as parameters the internalname of the node to be destroyed and the level on which to destroy it. It will then wipe out the node by first finding the node with FINDNODE, and then returning the node structure to the free node pool. This procedure will not remove a node from the dictionary. This is because a node can exist simultaneously on different levels. An error is returned if a request is made to destroy a real or integer node.

Procedure ENTERDICT. This procedure takes as input an internalname and its printname and stores it in the dictionary if it is not already in the dictionary.

Function EQ. This boolean function takes two internal names as parameters and returns TRUE if they are equal or FALSE if they are not. It first checks the type of internalname(node, text, real, or integer) and then checks for equivalent values depending of the type. In the case of a real node the numbers must match exactly, there is no allowed error. This can create problems if any arithmetic is done with a real number and comparisons are made using that number.

Procedure GETATTRIBUTE. This procedure takes a tuple and its length as parameters along with a location to begin the search, and returns the complete tuple and the slot under which it was found. The tuple passed to GETATTRIBUTE can be a left context tuple or a complete tuple. If a left context tuple is given then only the first matching complete tuple will be returned.

The procedure works by first finding the node using FINDNODE. It then counts down the attribute list looking for the attribute at which to begin the search for the particular tuple. From there it searches the attribute list in order looking for a tuple that matches as much of the tuple that was passed for the search. As soon as a matching tuple is found, the entire tuple is loaded into the return tuple and the slot under which it was found is loaded into the return slot.

Procedure GETPRINTNAME. This procedure takes as a parameter the internalname of a node and returns either its printname or its value, depending of the type of node. If it is a textnode or a regular node then the printname is returned. If it is a real node or an integer node then its ASCII representation is returned. For the latter two types of nodes the procedure converts the node value to the ASCII representation with calls to either ASCIIREAL or ASCIINT. In the case of a text node or a regular node the procedure first has to find the node with a call to FINDNODE. It then packs the printname into the return parameter.

Procedure INHERITATTRIBUTE. Like GETATTRIBUTE, this procedure takes a tuple and its length as parameters along with a location (slot) to begin the search, and returns the complete tuple and the slot under which it was found. The tuple passed to INHERITATTRIBUTE can be a left context tuple or a complete tuple. Unlike GETATTRIBUTE, however, the search is not restricted to tuples under the main node of the given tuple. INHERITATTRIBUTE also follows inheritance arcs to other nodes to match tuples (ignoring the main node, of course). INHERITATTRIBUTE also looks under subnodes of the tuple (by substituting the subnode for the main node) for the desired attribute (tuple). The search is exhausted vertically (along inheritance arcs) at each subnode before beginning recursively from the next subnode (horizontally). Additional parameters specify the maximum numbers of inheritance arcs and subnodes to search. The number of inheritance arcs and the number of subnodes searched are also returned. INHERITATTRIBUTE calls GETATTRIBUTE with the appropriate substitutions for the main node.

Procedure INTASCII. This procedure is a machine independent algorithm that converts an integer into its ASCII representation.

Procedure INTERINT. This is a bidirectional conversion procedure that converts to/from internal name representation from/to the Pascal integer representation. Presently there is no differenct between the two and the procedure just outputs the proper part of the internalname record passed as the parameter, or fills the proper part of the record depending on the direction of conversion.

Procedure INTERREAL. This is the real number counterpart of the INTERINT procedure.

Procedure LOOKUP. LOOKUP is the dictionary access procedure which takes a printname as input and returns an internalname and nodetype. If a real node or an integer node is passed to LOOKUP, then the ASCII representation is returned. LOOKUP works by searching the dictionary hash table for a match of the printname.

Function NTYPE. This function takes as input an internalname and returns as its value the nodetype of that node. The function is very fast and should be preferably to opening a node just to find out its type.

Procedure OPENENTWORK. OPENNETWORK opens three user networks at the three different levels (global, local, private). It creates the lists of free nodes and subnodes, and arranges all of the housekeeping pointers and variables. The dictionary is also read into the memory.

Procedure OPENNODE. Opennode takes as a parameter the internalname of a node and the type of access desired and opens the node if the access matches the allowed type of access for that node. The node is opened at a particular level, depending on what level is requested, also a parameter. Values returned by the procedure are the number of attributes, the flagword, and the type of node. If one is opening a node merely to determine its nodetype, then a better option would be to use function NTYPE.

OPENNODE works as follows. If the node requested is a regular node or a text node then FINDNODE is called to locate then node and bring it into the core memory if it is on disk. If the node was not located, and if the level requested was not global, this procedure will look at progressively higher levels for the node and copy it to the requested level if the node is found. If the node is located then its opencounter is incremented and the return parameters are set. If the node is not located then an appropriate error message is returned.

Procedure READBACKUP. READBACKUP takes a backup file and re-creates the network exactly as it was when the backup file was written.

Procedure READTEXT. This procedure takes a text file of the network and creates a new network based on the contents of the text file. Every node in the network is entered into the dictionary, making this procedure of very limited utility except for small networks. The procedure will have problems if one attempts to load more nodes than will fit in the dictionary . Currently the limit is 499. This procedure is in need of some modification in the future.

Procedure REALASCII. This is the real counterpart of INTASCII. It is also machine independent.

Procedure SETPRINTNAME. This procedure is the inverse of GETPRINTNAME. This procedure does different things for different types of nodes. For real or integer nodes it sets the value of the node to the Pascal implementation of that value. This is done with a call to either ASCIIREAL or ASCIINT. For regular nodes the node is first located with FINDNODE. Then the node's printname is assigned the printname that was passed as a parameter. For text nodes the node is located and then the printname, passed as a parameter, is interpreted as a line of text which is added to the end of the existing text for that text node.

Procedure WRITEBACKUP. This procedure writes out a backup file that will allow the exact state of the network to be preserved. The dictionary is included in the writeout procedure. Nodes having the same printname are not merged, as in WRITETEXT below.

Procedure WRITETEXT. This procedure will write a text file of the network to a specified filename. The algorithm used will cause nodes having the same printname to be merged. The dictionary is not saved.

9.4. Important User-invisible Procedures

Procedure FINDNODE. By far the most frequently used procedure in the Tuple Manager, FINDNODE is designed to be as fast as possible given the limitations of a linked list representation of the network. It takes as a parameter the unique node identifying number and returns a pointer to the internal memory representation of that node. It works as follows. All of the nodes in the memory are hung onto a hash table using a linear chaining collision resolution scheme. The proper hash table entry is determined from the node identifier and that particular linked list is searched sequentially for the node.

In an earlier implementation, the tuple manager was directly responsible it for virtual memory management i.e. ensuring that memory used for nodes did not exceed the core limits, and swapping nodes from disk to core when core memory was full. In that implementation, if FINDNODE did not find the node in core then the area on the disk that should be occupied by the node was examined. If the node was on the disk then it was brought into the core network. A return pointer was then set to the node. If the node was not in memory and not found on the disk then nil was returned.

In the current implementation, all virtual memory management is performed by the Unix operating system. From the user's point of view all of the nodes are in core at the same time.

CHAPTER 10

General Utilities

This chapter describes two utilities availabe for use in Advise. The first is the Tester Program which can be used as a low-level network debugger for Advise knowldege bases. The second utility is a set of trap functions, hard-coded functions available for reference from rules in the knowledge base.

10.1. The Low Level Network Debugger

The Tester program was originally developed as a tool for testing the tuple manager. It has evolved into a program that can be used to perform tests on the rule evaluator, the paraphraser and the tuple manager. In addition, it allows the user to debug or otherwise manipulate a knowledge base after it has been parsed. This section describes the functioning of the Tester module. The program was coded originally by Heinrich Juhn. Lance Rodewald and Albert Boulanger have supplied additional enhancements.

10.1.1. How to Use the Tester Program

The Parser reads in a rule base and outputs a network or *backup* file. The Tester program allows the user to examine the *backup* file and edit it. Before looking at an example of a portion of the *backup* file some definitions are in order:

(1) node: A node is simply a symbol. Each node has an internal name that is hidden from the user and is accessed via a printname. A printname is simply a string of characters that represents a unique identifier for a node. These printnames are collected into a dictionary that is manipulated by the tuple manager.

(2) tuple: A tuple is a vector of nodes, integers or real numbers. A knowledge base is represented internally as tuples. The node in the first position (slot 1) in a tuple has a special significance. It represents the place where information about the node is stored. This same node may appear in other tuples (but not in the first position) in which case it can be viewed as a pointer back to that tuple in which the node appears in the first position.

(3) slot: A tuple's slot corresponds to its vector address. For example, a tuple is declared as:

```
tuple: array [1..tuplelength] of internal_names;
```

Slot number n (1 <= n <= tuplelength) is the nth element of the vector (tuple[n]).

(4) attribute: An attribute is a tuple representing a property about that node that appears in position 1. A node may have several properties "hung under" it.

For example, consider an attribute in a knowledge base called TEMPERATURE. It can take on the values BELOW_NORMAL, NORMAL, or ABOVE_NORMAL. It would appear in the following form when viewed via the Tester program:

```
(TEMPERATURE (
  (MKDOMAIN MKNOMINAL BELOW_NORMAL NORMAL ABOVE_NORMAL)
  ))
```

The node TEMPERATURE (its printname) has under it a single attribute that specifies the possible values for the node. The identifiers MKDOMAIN and MKNOMINAL are semantic markers used internally by the program to identify this attribute as representing the domain of the variable TEMPERATURE, and that domain is scaled nominally.

10.1.2. Tester Commands

This section contains a list of commands available in the Tester program. Each command is one or two letters, and the user may be prompted for additional information after requesting a particular operation.

Basic Commands

These commands perform the basic network manipulation functions.

h: The (h)elp command displays a list of commands available to the user.

os: The (o)pen (s)tandard command prepares the program for (r)eading a (b)ackup file. In general, this is the first command a user should issue. More than one *backup* file can be manipulated in a single interactive session with the Tester program. In this case, the user should issue the (c)lose command before another (o)pen (s)tandard command.

rb: This command (r)eads a (b)ackup file. The user is prompted for the name of that file. The user should not issue another rb command in the same interactive session without issuing the (c)lose command first.

wb: Used to (w)rite out a (b)ackup file. The user is prompted for the name of the file to create for storing the network. This is useful when the user wishes to keep changes that have been made to the network.

wt: This command will output the entire network in a readable form. It is useful for hand-checking parser output and gaining some insight into how a knowledge base is stored.

rt: This command reads a file in the readable form that is output by the wt command. It is particularly useful for adding new rules to a network without going through the trouble of re-parsing.

c: The (c)lose command frees internal storage used by the Tester program. It should be issued before reading another *backup* file in the same session.

or: This command functions identically to the os command in the current implementation.

b: This command allows the user to set the level of tuple manager debugging information. This information is always placed in the file named "msg" which can be examined at the end of a session.

n: Display a (n)ode and all of its attributes. The user is prompted for the name of the node to be displayed. The command may fail if the node's printname is not in the dictionary (initially, very few nodes are in the dictionary). A nodes printname can be entered in the dictionary using the (m)ark command.

g: This command can be used to (g)et an attribute hung under a node. It establishes this attribute (if the command does not return an error) as the *current tuple*. A *current* *tuple* is assumed to exist when using other commands (See, for example, the (m)ark command). The attribute tuple is accessed by specifying node printnames beginning with the node in slot 1. The user is asked to provide a "left context" for identifying the attribute he wishes to access. This "left context" is simply one or more printnames in the order they appear in the tuple, beginning with slot 1. The user is prompted for the number of printnames he wishes to use as a "left context" and then is asked to enter those printnames. For example, in the TEMPERATURE tuple presented earlier, this tuple could be accessed by entering the number "2" when prompted for length and then the names "TEMPERATURE" and "MKDOMAIN" when prompted for the printnames. remember that the printnames must be in the dictionary for this command to succeed (you may have to use the (m)ark command to enter them). Also note that the case of the letters is significant when matching printnames. A simpler mechanism for looking at the network is provided by the "s" commands (sw,sp,etc.).

gi: This command also gets an attribute from the network as does the g command. The fi command, however, uses an inheritance mechanism to find an attribute. The inheritance mechanism is described in the chapter on the tuple manager.

a: This command (a)dds a tuple to the network. As in (g)et, the length of the "left context" is requested and printnames of that context. The tuple is hung under the node in slot 1 of the "left context" if that node exists in the dictionary, otherwise the node is created.

d: This command is used to (d)elete a tuple. It functions just like (g)et and (a)dd.

m: Used to (m)ark a node (i.e. enter its printname into the dictionary). The user is prompted for which slot (element) in the *current tuple* he wishes to mark. These slots are referenced one of two ways: either by its slot address as a positive integer (counting from the left) or by its slot address as a negative integer (counting from the right). For example, if the *current tuple* has length 3, its last slot can be referenced by either 3 or -1.

l: This command causes a (l)evel change. Three copies of each knowledge base are maintained: the global, local and private level copies. Initially, the global level copy is manipulated by the Tester program. For more information on levels, see the tuple manager chapter.

i: This command no longer has a function.

p: Used to (p)urge a printname from the dictionary. The user is prompted for that name.

x: The x command deletes a node that has no attributes. If the node has some attributes hung under it this command will fail (the d command should be used first to delete all attributes).

tr: Retrieves and displays a line of text from a textnode.

ta: This command will retrieve and display all the lines of text in a text node.

ts: This command will store a line of text under a textnode. The user is prompted for that line of text.

Network Traversing Commands

The group of commands that follow have been added in order to simplify the process of descending into a knowledge base network. In particular, they allow the user to look at parts of the network without having to enter a series of (m)ark commands followed by (g)et attribute commands to descend into the network.

sg: This command gets the first tuple in the network. The user is prompted for its printname and it becomes the *current tuple.*

sw: Prints all of the attributes under the *current tuple.*

sn: This command is followed by a space and then an integer. It prints the n-th attribute under the current tuple.

sd: This command is followed by a space and then an integer. It descends to that node in the current tuple as specified by the integer.

sr: This command goes back one descent level.

sa: This command will add an attribute under the current descent level.

st: This command is used to transfer the *current tuple* as seen by the "s" commands into the current tuple as seen by the "d" command. It is useful for deleting tuples.

Module Testing Commands

The commands below are used to test the rule evaluator and the rule paraphraser. All of these operations affect the node in slot 1 of the *current tuple.* This node in most cases corresponds to the printname of a rule.

js: Initializes the rule evaluator. This command must be issued before attempting to evaluate or interpret a rule.

jg: Used to put a value/confidence pair under a rule. Before attempting to evaluate or interpret a rule, the variables involved in the left-hand side of that rule should have values. These values can be inserted by using this command.

jg: This will get the value/confidence pair under a node (if it exists). For example, the user may want to see if a value/confidence pair was placed under the rules right-hand side after interpreting that rule.

je: This command will evaluate the current node (usually a rule).

ji: This command will interpret the current node.

ju: Used to initialize the rule paraphraser. Must be issued before attempting a jt command.

jt: Used to paraphrase the current node.

10.2. The Trap Module

This section describes the 21 TRAP functions used in PLANT/cd. These functions implement the *deep* model of black cutworm damage (BCW) as developed by Steve Troester [Troester82a,b,c,d]. The BCW development model by Kimpel [Kimpel78] and used in Steve Troester's programs [Troester82c,d], was not used in PLANT/cd. Instead, a simplified simulation was developed. The TRAP module and this documentation was written by Albert Boulanger.

The rule evaluator uses the Special Functions Module (also known as the TRAP module) to evaluate TRAP functions that are in the rules. A TRAP function has the form:

TRAP(number,p1,p2,...,pn)

Where...
number is the TRAP number, and

p1,p2,...,pn are the parameters to the trap function.

The rule evaluator passes the TRAP number and the parameters to procedure TRAPFUNC in the TRAP module. Procedure TRAPFUNC has a case statement in which the TRAP numbers serve as case labels. Upon branching, several operations are performed. The TRAP parameters are converted from their network representation to a Pascal representation. Parameters that are nominal are usually mapped into a Pascal scalar variable. Next the semantics are executed. This is usually a call to a procedure or function. Finally the outgoing parameters are converted from their Pascal representation to their network representation. These procedures are lexically scoped within procedure TRAPFUNC, although there are several utility procedures outside. One procedure that is outside is procedure TRINIT that the backward control scheme code calls to initialize the TRAP module. Each of the current TRAP functions is described briefly below:

- *TRAP 1.* This was used for developing the TRAP module and is no longer used.
- *TRAP 2.* This calls TRASKSTATION which asks for the closest weather station from the user, by a special protocol. This procedure was necessary because STACODE (the station code) is a nominal type variable with too many domain elements to be handled by creating a set of touch targets.
- *TRAP 3.* This calls TRASKTRAP to obtain the moth trap counts over a span of 11 weeks beginning March 17. The user can enter *unknown* for any of the entries and the system will assume a value of 0. It will also set the certainty of the first parameter to the TRAP function to 0.5. Also provided is a check for proper number format. If something entered was not a number, the user is asked to reenter his data. This type checking is performed for all the user input routines in the TRAP module.
- *TRAP 4.* This calls TRASKATTR to obtain the field attractiveness rating for the same 11 week time span. Unknown values are handled in the same way as in TRASKTRAP.
- *TRAP 5.* This calls TRASKBCWPOP to get the larval age spectrum in the field. This works like TRASKTRAP and TRASKATTR. TRASKTRAP, TRASKATTR, and TRASKBCWPOP use TRDSPWEEKS and TRDSPLCNTS to produce the appropriate column headings. They also use TRGSTUFF to get the user input.
- *TRAP 6.* This calls TRCTOEGGS to convert the moth trap counts to an egg population. Egg population is equal to 5.7 times the moth trap counts [Troester82a].
- *TRAP 7.* This calls TRCTOFLD to convert the eggs laid in the region to eggs laid in the consultation field. This is done by multiplying the egg population by the attractiveness rating.
- *TRAP 8.* This calls TRDSPEGGS to display the egg population in the consultation field and the surrounding area.
- *TRAP 9.* This calls TRDSPTAB to display the results of the cutworm development model. This is in the form of a transition matrix which shows the dates when different instars will undergo age transitions.
- *TRAP 10.* This calls TRDSPLTAB to display the results of plant development.

- *TRAP 11.* This calls TRDSPPOPVSSTAGE to display the results of putting cutworm development in terms of corn development. This is called matrix K in [Troester82a].
- *TRAP 12.* This calls TRGETDDTABLE to get the degree day data necessary for the corn and cutworm development models. The two incoming arguments, STACODE and OBDATE, are used to specify the location and start day of the data respectively.
- *TRAP 13.* This calls TRPLANTDATE to backward develop the corn in order to estimate the planting date (PLANTDATE) given the observed fractional leaf stage (FRACT), the corn variety (VARIETY), and the observation date (OBDATE). This relies on work described in [Troester82a]. This procedure calls TRLEAFLOOKUP.
- *TRAP 14.* This calls TRCORNDEVELOP, the corn development model. Inputs are the planting date (PLANTDATE) and the corn variety (VARIETY). This also relies on the work referenced above.
- *TRAP 15.* This calls TRBCWDEVELOP, the cutworm development model. Inputs are OBDATE and PLANTDATE. This model has two different [illegible]. One section is used only if eggs are forward developed from an observation date less than planting date. This section is bypassed if actual larval counts are input. In Steve Troester's work, eggs are developed with a model built by Kimpel [Kimpel78] and simulated using GASP 5. For PLANT/cd, another approach was used. The egg population was forward developed until planting date. Then the different aged larvae are classified into the closest instar category. The simulation from there is the same as described in [Troester82a] and is the same one that simulates cutworm development given actual larval counts. This procedure calls TRAVERAGE as a utility procedure. The procedures TRSMOOTH and TRSURVIVE are provided for experimenting with smoothing the egg distribution, and simulating larval mortality. Currently these are not used.
- *TRAP 16.* This calls TRPOPVSSTAGE to put the results of cutworm development in terms of corn development. This is based on the work described in [Troester82a].
- *TRAP 17.* This calls TR1DAMAGE to estimate cutworm damage without recovery and without regrowth. Input to this function are MUCHWEEDS, VARIETY, MOISTURE. The parasitism rate is set to a constant. Output of this function are the corn yield without insecticide treatment and without recovery (YIELD1) and the percent damaged corn (CORNDAMAGE). This and the following three TRAP functions rely on work described in [Troester82a].
- *TRAP 18.* This calls TR2DAMAGE to estimate cutworm damage without recovery but with insecticide treatment. This function uses FRACT and MOISTURE (soil moisture) to compute YIELD2 (yield without recovery and with insecticide treatment).
- *TRAP 19.* This calls TR1RECOVER to estimate corn recovery without insecticide treatment. This function uses MOISTURE and HOTWINDY (whether it is hot and windy) to compute YIELDINC1 (yield increase due to recovery without insecticide treatment) and TOTRECOVER (percent total recovery of the corn).
- *TRAP 20.* This calls TR2RECOVER to estimate corn recovery with insecticide treatment. It uses FRACT and MOISTURE to compute YIELDINC2 (yield increase due to recovery with insecticide treatment.)
- *TRAP 21.* This is used to prompt for and obtain the value for the date variables used in PLANT/cd. It returns the number of the day entered in *mm/dd/yy* format. To obtain the date from the user, it calls TRASKDATE. TRASKDATE checks for proper date format. The year is stored internally in the TRAP module.

- *TRAP 22.* This calls TRGETLSTAGE which is used to calculate the fractional leaf stage (FRACT) given PLANTDATE and OBDATE.
- *TRAP testnum.* This is used to call the trap module exerciser routine, TRTESTR.

The TRAP module also has a driver program that is used to run it in test mode. In this mode, the major functions are exercised, and damage estimates can be obtained without the use of the knowledge base (i.e., it runs in stand alone mode.) The main program calls TREXERCISE to do the exercising functions. This procedure calls TRAPFUNC and has it branch to *testnum* in the case statement.

CHAPTER 11

Rule Based Inference Control (PLANT/ds)

11.1. Introduction

The PLANT/ds consultation program is an experimental expert system used to advise farmers on diseases common to soybeans in Illinois. The program acts as a diagnostician, by asking the user questions regarding problems observed in the diseased crop and returning a list of the most likely disease candidates. A general description of the problem domain and an earlier program can be found in [Chilausky79]. This section describes the realization of PLANT/ds within the environment of the ADVISE knowledge programming system, with a particular emphasis on the control strategy employed. The program and this documentation was prepared by Mark Seyler.

The responsibility of the control scheme is to make the knowledge embedded in the program available to the user by conducting a consultation. The search space represented by the PLANT/ds problem domain is of sufficient size that the control strategy utilizes search heuristics that attempt to focus the consultation on only that knowledge relevant to the user's problem. An approximate reasoning method found useful in this particular domain is selected (from the several available in the ADVISE system). The control scheme is also responsible for explaining some aspects of its reasoning process and providing access to the knowledge it contains. Each of these aspects of control will be discussed in turn.

11.2. The Knowledge Base

Knowledge in the PLANT/ds system is represented as decision rules in the GVL_1 formalism [Michalski80]. There are two types of rules, those that represent hierarchical relationships among variables (candidate rules) and those that reflect the relationship between the variables and the SOYBEAN DISEASE goal variable (goal rules). An example candidate rule is:

```
[LEAF_SPOTS = ABSENT]
          ::>
[LEAF_SPOTS_MARGIN = DOES_NOT_APPLY]
[LEAF_SPOT_SIZE = DOES_NOT_APPLY]
```

In this case, the variable LEAF_SPOTS represents a grosser level of detail than the other two variables. This use of two levels of detail is one mechanism by which attention can be focused as early as possible on that class of diseases relevant to the problem at hand. An example goal rule is:

```
0.8[TIME_OF_OCCURENCE = AUGUST..SEPTEMBER]
  [CONDITION_OF_LEAVES = ABNORMAL]
  [CONDITION_OF_STEM = NORMAL]
  [LEAF_MILDEW_GROWTH = ON_UPPER_LEAF_SURFACE]
                +
0.2[PRECIPITATION < NORMAL]
  [TEMPERATURE >= NORMAL]
                ::>
  [SOYBEAN_DISEASE = POWDERY_MILDEW]
```

There is one rule of this sort for each of the possible diseases (currently 20). All of the variables in the rule's left hand side are those deemed relevant to that disease. They are grouped together and weights assigned to each group (linear module) according to the importance of that variable to the disease in question. The weights sum to unity and evaluating a rule of this type can be viewed as accumulating positive evidence that the disease in the rule's right hand side is present.

There are two sets of goal rules (rule groups): those output by the inductive learning program AQ-11 [Michalski78] and those compiled by the expert plant pathologist. The AQ-11 program attempts to find the minimum number of of variables that successfully discriminate the various classes of soybean disease. These rules are used to reduce very quickly the number of disease candidates considered by the program. Once the number of candidates is reduced to 5 or fewer, the expert compiled rules are evaluated and used in the remainder of the consultation.

It was recognized early that knowledge regarding the consistent diagnosis of soybean diseases was not complete. For this reason, a method of representing and combining approximate reasoning is employed. Furthermore, confidence in a particular observation may be prone to error and for this reason the user is asked to select a confidence in his answer. Details of the evaluation scheme used in PLANT/ds can be found in [Michalski82].

Aside from the candidate rules, which are used to reduce the search space, the PLANT/ds knowledge base is two-leveled. This does not lend itself well to classical chaining (backward or forward) control strategies that establish intermediate goals. Instead, the problem is one of selecting among one of many possible terminal goals (soybean disease). The primary PLANT/ds control loop is outlined in a Pascal-like pseudo code below:

```
repeat
   select the most useful variable;
   if the value is not known ask the user for it;
   find all those rules in which this variable occurs;
      (in the left-hand side)
   for all of the rules found above do begin
      evaluate the rule;
      if its value is below the threshold then
         eliminate it from consideration;
   until all of the variables have been selected;
```

The control scheme attempts to minimize the number of questions asked of the user. In this respect, it acts in much the same fashion as the human expert, who eliminates those aspects of the problem irrelevant to the task at hand and focuses on what is most relevant. PLANT/ds uses two mechanisms for focusing attention to the most likely disease candidates. The first is by the use of a hierarchical variable structure (the candidate rules). The second is rule elimination by thresholding. Any time a goal rule falls below a certain threshold (determined by the knowledge engineer and domain expert) it is eliminated from consideration. The algorithm for selecting the most useful variable can then be formulated as follows:

```
select a variable that may satisfy one of the
   candidate rules;
if none of these are available then
   select a variable with the maximum utility where utility
   is defined as the number of rules in which the variable
   occurs;
```

By defining utility in this fashion, the program will attempt to eliminate as many goal rules as it can as early as possible. The viability of a rule in the PLANT system is defined as the degree of truth of its left hand side. This degree of truth cannot be calculated exactly until all of the variables on the left hand side have a value. However, a best case truth value can be calculated at any stage by assuming those variables that do not currently have a value are satisfied. If a rule's best case truth value falls below the threshold, the rule can also be eliminated from consideration. By eliminating goal rules, any variables they involve can be eliminated, thereby reducing the number of potential questions. In experiments done to date, of a possible 40 questions possible only about 15-20 are asked by the program.

Another aspect of control embodied in PLANT/ds is that of allowing the user access to its knowledge and some aspects of its reasoning. This aspect of transparency is highly desirable in expert systems both because it increases user acceptance and can be used as a tool for testing new knowledge bases. During the variable value request portion of the program a number of options are made available to the user:

(e) Provides assistance in clarifying the question being asked.

(v) Lists those diseases still being considered and their best case confidence.

(w) This option displays the change that would occur in the confidence in each disease for each possible response.

(r) Displays those rules in which the current variable is found.

(b) Allows the user to return to the previous question.

(m) Allows the user to modify his answer to the current question.

After the program has displayed its conclusions, the user can make further inquiries of the knowledge base:

- Program execution statistics can be examined.
- Any rule in the knowledge base can be displayed.
- For any goal rule, a list of those selectors that failed can be displayed. This can be used to determine why a particular disease was ruled out or how the confidence in the most likely disease might be improved.

In addition to the capabilities mentioned above, the control scheme can be reconfigured prior to entering its consultation phase. The user can elect to use only the machine generated or expert rule groups. The breadth of the search can be adjusted by choosing to gather packets of information before evaluating. These packets represent groups of variables whose values are asked of the user prior to evaluating any rules. The thresholds used for rule elimination can be set as a means of balancing the performance of a particular rule set. A final option allows the user to select a novice or experienced mode of consultation. In the novice mode, additional help and guidance is given throughout to consultation as a means of training new users in its function and operation.

11.3. Using the PLANT Program

The PLANT program resides on the VAX-11/780 at the University if Illinois, Urbana-Champaign. It represents one of the earliest experiments in expert systems to be developed within the ADVISE environment and is still undergoing improvement. In parallel, the PLANT program was being "downloaded" onto a small computer (the IBM PC). A sister system TURF was subsequently developed by Greg Smith, and later Bob Reinke and Jiarong Hong readapted this for the vax-sun Unix environment for rapid compiled execution.

The PLANT program can be executed on the VAX by typing **$ADVISE/kblib/plant.** It generates diagnostic and performance messages which can be examined after the session in a file called msg. The program can be configured to run on a particular terminal by re-loading the program with the appropriate device driver or loading the "gkuniversal" and "gktermcap" routines developed to support UNIX termcap conventions (in which case the shell TERM variable should be properly initialized).

11.3.1. Data Structures

The architecture of the Pascal modules is such that each should remain active throughout the life of program execution. This means that a static memory area is set aside for each module. In the case of the control scheme modules, such as PLANT/ds, this area contains a number of useful data structurespertinent to the regulation of rules and variables. This section elucidates the various elements to the PLANT/ds control scheme static area as defined in "csconst.h".

The following constants are available:

esc	ascii escape character (note: UNIX cbreak/raw mode required to detect this),
bs	ascii baskspace character,
sp	the space or blank character, also available as the constan "blnk"
qm	the character "?",
e	the ascii character "e",
o	the ascii character "o",
maxnumvars	the maximum number of variables = 500, simply to set array dimensions,
maxnumrules	maximum number of rules = 1000, also determines array size,
mnblocklen	refers to the total number of blocks (rule groups + var defns + function defns) = 14.

The following types are declared:

byte	a single byte quantity,
intype	a half byte quantity,
foldtype	for possible options (min,prod,aver,full) of *folding* together truth value weights, (noprotect is delete old valcons, protect is save them)
updatetype	for specifying what to do with old value/confidence pairs of variables, *noprotect* is delete old valcons, *protect* is save them,
pktypes	specifies question packet options (pkone = one at a time, pkall = all at one, pkhalf = more important half of the questions first),
rwtype	form generation options = (readin,writeout).

Within the master record type, csstatic, the folowing fields are declared:

error	main error indicator, there is an extensive errortype declared to indicate which of multiple errors have occurred
answers	array of variables' state values,
goodrules	list of the currently viable rules,
frmenbl	a boolean array indicating whether or not a predefined frame (screen image) is enabled or not (to be asked); certain frames or forms are preconstructed, but exactly which ones should be filled in are a function of the state of the consultation
backflg	whether or not the current state is *go backwards*, i.e., the option to go back to a previous state has been requested,
fastexit	whether or not to immediately exit consultation,
iplflg	whether or not to reinitialize the session, i.e. completely reset system and start over
earlyexit	boolean flag, whether or not a premature exit is being taken, not exactly the same as immediate exit,
exitmsg	what to print out as we exit session,
rg	pointer to current rule group,

viablegoals	current # of viable goals,
expert	intnamerec of expert rulegroup,
machine	intnamerec of machine rulegroup,
stop	number of viable goals to stop with,
escexit	boolean condition which indicates ESC exit of form,
changed	boolean array of variables, indicates if a variable value was changed/updated,
unpropogateable	boolean array of variables, indicates if a variable can not propagate
currform	number indicating the current form in the consultation,
maxform	number indicating the maximum form number, including dynamically constructed forms at a particular point in the consulation
lastform	number indicating the form asked in the consultation, not the same as currform-1, and useful to the "back" operation
scrn8in	file pointer to the scrn8in file, which is used to dynamically construct new forms beyond the static forms,
scrnout1	file pointer for a work file, used in dynamic form construction
scrnfil	file pointer for a work file, used in dynamic form construction
scrnout2	file pointer for a work file, used in dynamic form construction
startslot	csget-getattribute startslot, cstools global
trerr	trap function error-unused here, cstools global
dummy	dummy intnamerec parameter to cstools
debug	boolean flag indicates whether to spit out debug messages,
evalenable	boolean flag (true = turn on evaluator)
thresh	machine/expert rules confidence threshold, optional to erthresh/mrthresh
erthresh	expert rules confidence threshold
mrthresh	machine rules confidence threshold,
usemachine	boolean flag, if true use machine rules,
useexpert	boolean flag, if true use expert rules,
firsttime	used to convey 1st variable in consultation,
level	indicates one of 3 network levels: global, local, private,
backup	text file pointer to backup file to be read/written,
paraf	text file pointer to paraphraser scratch file,
noopen	boolean flag tells if any nodes open,
dspname	boolean flags, if true dump printname else dump property,
memavail	param to szestimate, gives available memory (on stack),
elapsedtime	time since last call to plreport,
jobtime	total elapsed jobtime,
walltime	wallclock time at start of program,

wayback	boolean flag (if true back to beginning of a rulegroup),
waywayback	boolean flag (if true back from expert to machine rules),
approxeval	boolean flag (if true enable approximate evaluation).
packetoption	option as to number of questions to ask before sending a question, can be one, half, all,
newuser	if true, then is new users,
olduser	if true, then is old users,
confirmed	boolean flag, tells whether hypothesis is confirmed,
nqueries	number of questions asked
xintnamerec	a spare pointer, for development work,
vars	a record with the following elements: list – an array of records, one for each variable, giving following' id — the variable internal "intnamerec" reference asked — boolean flag, if true variable was asked of user propogated— 0 = unpropagated, 1..n = when propapagated tells whether all consequences of a variable value have been spread (number indicates which frame actually solicited the variable value) candidate— boolean flag, true = candidate for this rg freq — integer indicating lhs frequency of variable nvars – integer indicating length of variables list npropogated – integer indicating # of variables propagated
rules	a record with the following elements: list – array of records, one for each relevant rule with following name — the rule designation as an intnamerec viable — boolean flag, if true rule still viable *) nrules — integer giving length of rules list
erules	a record with rules to be evaluated after variable query with the following elements: list – tuple having intnamerecs of relevant rules cp – whether to use printname or blanks in printing nrules – number of rules in list
goal	status of goal node record, contains following items id – intnamerec representation of goal varaible val – array records pertaining specific goal variable values id — intnamerec representation of value conf — real number specifying confidence of value viable — boolean flag indicating whether value is viable nvals – integer number of goal variable values nviable – total number of viable goals
imk*xxxxx*	network is accessed by determining the internal names of the mark types of form imk*xxxxx*; allows convienent access to the tuples used by the control schema; procedure plinitmk determines the internal names of the necessary mark types as part of the control schema initialization by looking them up in the dictionary,

ics*xxxxx*	similar to imk*xxxxx*, but more control scheme use than general use

11.3.2. Control Scheme Tools Package

The code in "cstools.h" was felt to be of general utility to both PLANT/cd and PLANT/ds in writing control schemes. A brief description of each procedure follows. Note that each routine takes a pointer to a csstatic area as its initial argument.

csherror	This procedure is used to handle error conditions. Given an errortype and msgstr, it displays the error to the user and puts a dump in the message file.
cseqpname	Given 2 nodes, this function returns true if the printnames of the two nodes are equal.
csgetpname	This procedure gets the printname of a node. notice that it uses dynamic dimensions for the array that is holding the print name.
csput	Given a tuple and tuplelength, this procedure puts it in the network, however first checks to see if there is a tuple with the same left context up to a specified tuplelength (possibly of shorter length than the whole tuple). If there is one it deletes it, then adds tuple. Thus, this procedure can also replace.
csmakename	This procedure make a node with a print name in the dictionary if it is not there already.
csgetreal	This converts the network representation of a real number to the Pascal representation.
csputreal	This procedure puts the Pascal representation of a real number into network form.
csginteger	This converts the network representation of a integer number to the Pascal representation.
csputinteger	This procedure puts the Pascal representation of a integer number into network form.
csrealp	This function is used to check to see if the node represents a real value, generating real value if it is.
csintegerp	This function returns true if testnode represents an integer, generating integer value if it is.
csopen	This procedure is used to open nodes under a restricted protocall. This is meant to be used to mark the fact that a node should not go away through several closely placed (in time) calls to tuple manager routines that use the node. This assumes that a use counter is now implemented for nodes. One further note: most of the routines in cstools are node-open-or-close-status preserving if a use counter is implemented. Thus to keep the use count above 1 to state that a node will be around for a while, then do a csopen on the node at the beginning of transactions on the node, then do a csclose at the end of the transactions. This procedure and its companion are here for efficiency reasons.

csclose	This is the companion routine to csopen. It decrements open count.
cshasprop	This boolean function is used to check on the existence of a property (intnamerec) under a node.
csputvalcon	This procedure is used to store value (intnamerec), confidence (intnamerec) pairs under the variable, vari (intnamerec). It calls in turn the system wide procedure to do this. Assumes updatetype = (protect,noprotect), i.e., how to handle previous values, is defined on top of this procedure.
csgetvalcon	This procedure is used to get the tuple "duples" containing value/confidence pairs under a node. The returned tuple has its 1st elt the "node" intnamerec, its 2nd elt the "mkvalcon" intnamerec, and the following elts will be the value/confidence pairs. The boolean argument "novals" indicates whether no value/confidence pairs were found.
csdumptext	This is used to dump the text of a property under a node out to a textfile (to be later displayed on the screen).
csgetint	Given a marktype, this procedure returns its internal name by looking in the dictionary. If it isn't in the dictionary, a new node is created.
csrevaluate	Given a rule (intnamerec) to evaluate, this routine sends the necessary information to the evaluator and returns the rules truthvalue and a boolean flag indicating whether evaluation completed (e.g., whether all necessary variable values were present). If the rule lhs has been completely evaluated, complete is set to true.
cspresults	Prints to a file the confidence values of a variable which is assumed to be a goal variable. If no values are viable, a boolean flag is set.
csgetlabdata	This procedure is used to get a list of labdata variables for the ruleset (intnamerec). The tuple of labdata variables are asked for at the beginning of trying a rule group.
csget	Gets an attribute tuple under main node c1 by matching context (c1 c2 c3 c4). note that level is global to this and other procedures in this utility package. Accnotfound flag specifies whether to error out if not found.
csstrengthtofire	Given a confidence from the evaluator, this routine calculates the strength to fire the rhs from alpha. Four schemes for folding the confidence with alpha are available : 1) min (minimum of confidence and alpha) (default) 2) product (confidence * alpha) 3) average ((confidence + alpha) / 2.0) 4) full (alpha).
csrinterpret	Given a rule(intnamerec), its truthvalue and foldscheme, this routine invokes the interpreter with the necessary information after calculating its strength to fire.

11.3.3. PLANT/ds Tools Package

The PLANT/ds system was originally encoded simply in terms of the appropriate "cstools" constructs and a set of procedures and functions. Subsequently, these were modified to be of more general value in generating "PLANT/ds-like" systems. This package is referred to as "pltools" and is summarized here.

plgetstr	Gets a msgstr from file or terminal and determine length as integer value.
pldumptext	Dumps property under node to standard output.
plemptyvar	Clears avar (intnamerec) of all its valcons.
plrankresults	Sorts and prints results (i.e., goal variable value/confidence pairs) in descending order according to confidence.
pldispname	Puts inames (intnamerec) printname in iofile and returns its integer length.
plreport	Reports msgstr on some current job statistics.
plputbanner	Puts advise banner on screen.
plpage1	Displays a PLANT/ds specific introductory panel on screen.
pusers	Asks the user his name to check if he is a priviledged user, checking against the names file for number of times he has previously used the system (>5?). Update in nnames by incrementing his entry there.
plpage2	If a priviledged user, various options can be set as to the control scheme. This is meant to follow a check for priviledged users (pusers).
plresdump	Dump to msg the results data structure along with note msgstr.
plgrabresults	Assumes rule (intnamerec) has fired; looks under the goal node for results of firing and stores the results.
plresults	Print results of plant consultation. Print indicated diseases (within .2 of max confidence and > erthresh). Also print contra-indicated diseases (diseases ruled out).
plputdomain	Outputs the variable name, its domain and provides selection of items for each domain element. Also returns the domain tuple and its length: for integer-domain[1] - start of domain, domain[2] - end of domain domlength - negative of # of values in domain for real-domain[1] - start of domain, domain[2] - end of domain domlength - 0 *)
plparaf	Paraphrases item (intnamerec) which is a rule or rule subexpression and places text on the screen. It handles paging through text which is too big to fit on one screen.
plreqrule	Prompts the user for a rule option request, i.e., asks user which rule he wants to see, then calls *plparaf*.
plrelrules	Prepares display of all rules relevent to a variable (intnamerec).
plstatusofgoal	Copies all viable rules in the goal record onto a screen frame. If boolean flag pviable = true then prints viable goals, otherwise prints non-viable goals.
plagoalrule	Returns true if rule (intnamerec) has a rhs which contains a goal.
plisgoalviable	Check whether goal value of rule (intnamerec) is amongst the viable candidates.
plgetrhsval	Given a rule (intnamerec) and the goal variable (intnamerec) gets the internal name of the reference in the first selector of its rhs. If the selector found is not a goal selector plgetrhsval returns false.
plrulesdump	Dump to msg file the rules data structure, along with note msgstr.

plerulesdump	Dump to msg file the erules data structure, along with note msgstr.
plgetvars	Gets a lhs variable list for a rulegroup designated by *rg* in the control scheme static area and copies the information into the vars data structure.
plcandidates	Marks as candidates for network propogation every variable in *vars* that occurs in the rulegroup's lhs.
plgetrules	Loads the rules data structure with the rules in the current group (*rg*) and initializes that data structure.
plisruleviable	Returns plisruleviable = true if the rule (intnamerec) passed is currently viable.
plruleviable	Marks the rule (intnamerec) as no longer viable: if settrue = true then rule set to viable else rule set to not viable.
plgoalviable	Marks the goal value sought by specified rule (intnamerec) as no longer viable: if settrue = true then goal is set to viable else goal is set to not viable.
plvarunknown	Returns true if their are no values under variable *avar* (intnamerec) or its value is unknown.
plvarselect	Select a variable *avar* (intnamerec) that has yet to be propogated thru the network. Use precedenc: 1) select var whose value is known but not yet propogated(a rhs non-goal variable), 2) select the first biased variable encountered, 3) select the variable with the max lhs frequency. If avar has no value, *askforit* is set to true. If all the variables have been propogated, *found* is set to false. *loc* returns a pointer in the var vector to the variable selected.
plmarkpropogated	The propogated flag of *avar* (intnamerec) is set to *mark*.
plclearerules	Clear the erules data structure.
plmatchrules	Finds all the rules in rulegroup *rg* that have *avar* in their lhs's and places them in the erules data structure. It will only insert those rules that are not already there.
plselectrule	Select next rule from erules data structure. If none is available, *found* is set to false.
plbuildfreq	For each candidate, un-propogated variable in the vars record sets its frequency field to an integer value corresponding to the number of viable rules' lhs's in which it occurs.
plsmstats	Display some job statistics.
plsmfailed	Given a rule node and the location of its corresponding location in the goals list, displays all failed selectors.
plfailed	Prompts the user for the goal rule he wishes to examine, then calls plsmfailed to display it.
plsumm	Displays program summary information.
plinit	Initializes system, reading in backup file *backupfn*.
plgoalinit	Initializes the goal structure. This should not be so intimately bound as it is to the other initializations.

plexprep	Prepare expert rules for use.
plhypelim	Displays a frame listing all eliminated hypotheses since the last call. Also provides several user options similar to *plgetdomain*.
plgetdomain	Given a variable *varcurrent*, retrieves a value and confidence pair for it from the user. If *back* is true the user requested going back to a previous question.
plwhy	User option that looks at all the possible answers to the current question and reports to the user how they would effect the status of the goal.
plvarsdump	Dump to msg file the vars data values.
plevalall	Evaluate all the rules in the rules list using the threshold *thresh* regardless of current viability.
plcloseout	Perform various closing tasks.

CHAPTER 12

Rule Based Inference Control (PLANT/cd)

12.1. Introduction

This chapter describes the backward chaining control scheme used with the PLANT/cd knowledge base. The program was written by Albert Boulanger.

12.2. User Description

The PLANT/cd control scheme was patterned after the EMYCIN [vanMelle79] view of control. In addition to this basic control, PLANT/cd features antecedent rules (limited forward chaining), "labdata" variables (variables that are marked to be asked before any other variable), and multiple goals for a rule group.

This control scheme makes use of properties. Properties are pieces of text a rule or variable can possess. These are very much like LISP properties; i.e. they have a type and contents. (See description of the parser.) The control scheme uses the PROMPT property of a variable to ask for the value. The TRANS property of a variable is used to display the value(s) of the variable. This property is a better description of the variable than the variable's name.

ANTECEDENT rules allow for limited forward chaining in a backward chaining mechanism. Whenever a variable is asked for, or it is updated by the execution of a RHS (right hand side), all ANTECEDENT rules that refer to that variable on their LHS (left hand side) are tried.

GOAL variables are variables whose value/confidence pairs are displayed to the user at the end of a session. They usually represent the entities that the user seeks advice on. This present PLANT/cd control scheme allows for more than one GOAL variable.

LABDATA variables are variables that are used often and usually represent basic information. LABDATA variables are sought out (either by asking or inferring) before GOAL variables. Unlike EMYCIN, in which such variables were always asked, PLANT/cd allows these variables to be inferred.

12.3. Control Scheme Details

The most important parts of the backward chaining control scheme, a program called BWARD, are illustrated in flow chart form in Figures 40,41 and 42. The called procedures are in capital letters in these figures. The procedure names are idealized a bit since the actual names start with the module 2-letter prefix BC to abide with ADVISE module naming conventions. Also many of the low level procedures are in a set of utility procedures, called CSTOOLS, that is shared between PLANT/cd and PLANT/ds. These procedures are prefixed with CS.

The top level (Figure 40) contains a loop that enables multiple consultations to be performed within one session. The items that need to be initialized once across several consultations are initialized in procedure START. The initialization that is needed before each

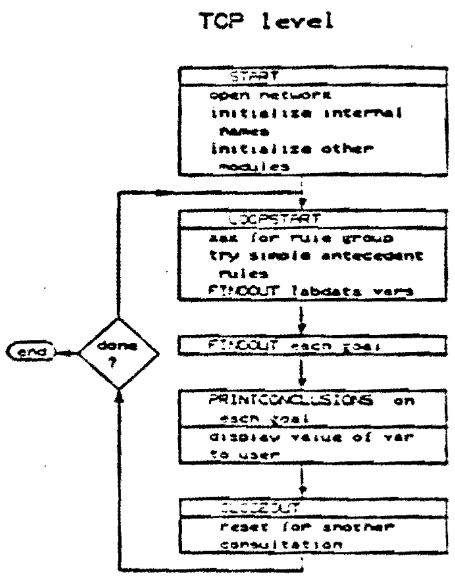

TCP level
START
open network
initialize internal names
initialize other modules
LOOPSTART
ask for rule group
try simple antecedent rules
FINDOUT labdata vars
FINDOUT each goal
PRINTCONCLUSIONS on each goal
display value of var to user
end
done ?
reset for another consultation

Figure 40: Flowchart depicting the top-level structure of PLANT/cd.

consultation is performed in procedure LOOPSTART. In LOOPSTART, the rule group (the knowledge base) name is requested, the GOAL variables for this rule group placed on a list, a list of ANTECEDENT rules obtained, a list of "simple" ANTECEDENT rules obtained, and the list of LABDATA variables retrieved from the network. The simple ANTECEDENT rules are next tried. Finally, values for each of the LABDATA variables are searched for using the FINDOUT procedure described below.

After this initialization, each of the GOAL variables is assigned a value using the FINDOUT procedure. This is the main part of the consultation. After the GOAL variable values are obtained, they are printed with their confidences using procedure PRINTCONCLUSIONS. The consultation is ended by cleaning up for a new consultation and calling LOOPSTART again.

The FINDOUT procedure (Figure 41) is responsible for finding the value of a variable; either by asking for it, or by using rules to infer it, or both. It first uses the ASKFIRST function to check if the current variable has the ASKFIRST property.

If it does have the ASKFIRST property, then procedure ASKFORIT is called to get the value from the user. After obtaining the value from the user, procedure CHKANTE is called to evaluate and possibly fire any ANTECEDENT rules that has the variable in their LHS. The SHOULDINFER function is then called to see if the variable also needs to be inferred. The decision to infer a value involves several considerations. In the most general case, there is the value/confidence pair requested from the user and there is the value/confidence pair inferred from the rules. The process of resolving any differences in these value/confidence pairs will be

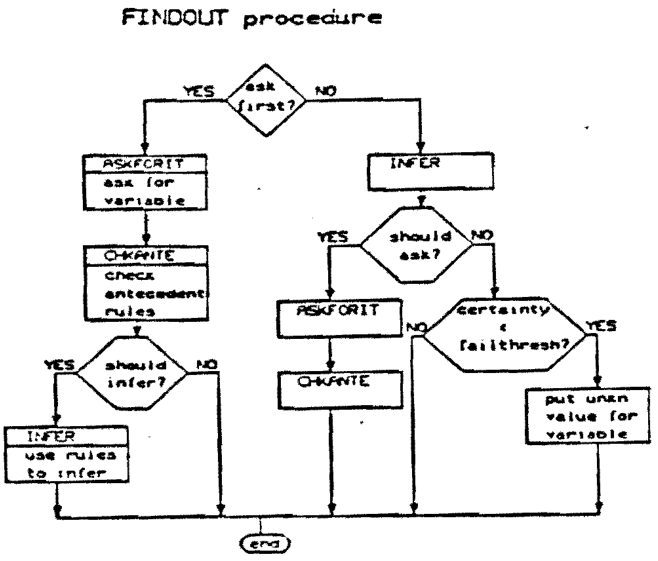


Figure 41: Flowchart depicting the FINDOUT procedure.

called voting. There is a scaler PASCAL variable, VOTESCHEME, that indicates the resolution method. The voting method used in this control scheme is to replace the current value/confidence with the more current one. In the general case, the decision to infer after asking for the variable is a function of the voting scheme used. In the case of this control scheme, the variable is inferred after asking for it if the current value/confidences are below SATISFYTHRESHOLD.

If the current variable should not be asked first, then the variable is first inferred. The SHOULDASK function is called to see if ASKFORIT needs to be called. To be asked, the variable has to have a PROMPT property. Also, the maximum certainty has to be less than SATISFYTHRESHOLD. If the variable should be asked, then ASKFORIT as well as CHKANTE is called. If the variable should not be asked and the maximum certainty is below the FAILTHRESHOLD, then the value UNKNOWN is assigned.

The INFER procedure (Figure 42) uses the rules to determine the value of a variable. INFER first gets the list of rules whose RHS update the current variable. This is done by procedure GETRULES. Next, RANKRULES is called to rank this list. This procedure is currently empty. At this point, a loop is set up to try the rules in the above list. SHOULDCONTINUE is called to check if the maximum certainty of the value/confidences for the current variable is above SATISFYTHRESHOLD. This is one terminating condition for the loop; the other is when all rules have been tried.

Inside the loop, the list of variables used in the LHS of the current rule is obtained by calling GETVARLIST. This list is ranked in procedure RANKVARS. A simple rule is one that

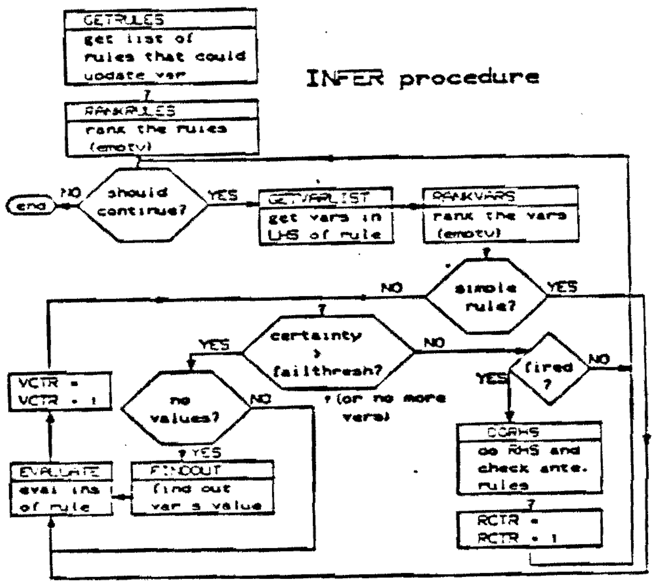


Figure 42: Flowchart depicting the INFER procedure.

does not use any variables in its LHS. There is a check after getting the list of variables for the current rule whether the rule is a simple rule. If it is, then the LHS is evaluated and the rule is checked to see if it fired. For rules that are not simple, then another loop is set up to use the FINDOUT procedure on each of the variables in the LHS variable list. For each variable value determined, the LHS is reevaluated to see if the certainty of the LHS falls below FAILTHRESHOLD. If it does, the loop is terminated, and the rule will not fire. The other terminating condition for the loop is running out of variables. Upon exiting the loop, the rule is checked to see if it fired, using the function FIRED. If the certainty of the LHS is greater than FIRETHRESHOLD, then DORHS is called to execute the RHS. Since executing the RHS may update variables, CHECKANTE is also called on all the variables that are updated in the RHS of the current rule.

12.4. Future Research Goals

There are a number of improvements that might augment the power of the present version of the control scheme:

- Self referencing rules.
- EMYCIN contexts and between context reference.
- Variable blocks. These are groups of variables that can be requested in a group. This could be done by setting up an empty table for the user to fill in – as in EMYCIN or by

multiple display module blocks on the same screen.

- Consultation typescript file.
- The ability to save and reload prior consultations.

CHAPTER 13

Context Driven Data Annotation (BABY)

13.1. Introduction

This section describes BABY, an expert system to aid clinicians who manage patients in a Newborn Intensive Care Unit (NICU). BABY was developed and partially implemented by Lance E. Rodewald. Throughout this section, 'user' refers to a clinician using BABY as a monitoring aid; 'expert' refers to a person designing the medical knowledge base; and 'programmer' refers to a writer of expert system software.

Overview of the Clinical Environment. BABY's task is to find clinically important patterns in the medical and demographic data about NICU patients. It is targeted specifically on the NICU for two reasons—there is a need for a system like BABY, and the chance for success is good due to peculiarities of neonatology. There are few areas in medicine where the amount of data, especially numeric data, is as great as in a NICU. The volume of information to be comprehended can be great enough to overwhelm the clinician, and much data is either within normal limits or changing slowly, creating the potential for a decreased index of suspicion of new findings. In contrast with adult medicine, the relative importance of the monitoring data to physical exam findings is greater because the babies often do not demonstrate obvious physical signs with serious disease. The vast majority of data can be made available on-line for a computer system [Frayer 80][La Gamma 80]. Machines already monitor many physiologic parameters and have been used for extraction of significant events from the stream of signals coming from monitoring equipment [Freedman 79]. Additionally, the past medical history of a newborn is much more concise than that of an adult. Because the number of diseases is limited, the amount of medical knowledge needed for interpretation of findings is reduced.

Overview of System Function The design philosophy behind BABY is that the system should metaphorically act as a neonatologist observing all on-line data in the nursery, keeping track of the clinical states of the patients, suggesting further evaluation for important findings, and answering questions about the patients. This places BABY in the relatively benign role of the observer, who answers questions, rather than that of the attending, who asks the questions.

BABY, although it uses a knowledge base, differs significantly from other medical expert systems in that mandatory human interaction is de-emphasized. This departure from the norm is done for two reasons. Most important, it was felt that the expert system, to have a good chance for success, should integrate itself into the daily routine instead of forcing a change in this routine. The second reason is that there are many inferences to be made from the automatically collected data that are either not attempted, or not done well, by current laboratory computer systems. In other words, there is an environmental niche for an expert system in the NICU to intelligently annotate the incoming data.

The role of BABY forces several requirements on the expert system structure. First, the man-machine dialogue must be primarily initiated by the user. This, in turn, requires that the the workings and current state of the machine be made as transparent as possible by the user interface. In particular, the system's current impression of the patient must be explicit and accessible, as should the means for inferring that assessment—the lab values and knowledge structures.

The automatic nature of the non-user input means that the system must be able to interpret information not specifically requested. To do this accurately the machine must assess the data in the context of global knowledge about the patient. A computer representation of the patient's state which is capable of conditioning the input interpretation is therefore needed. BABY represents clinical states as prototypic data patterns that are matched against current information in the patient's database. Embedded in these patterns is information indicating the clinical context required for an appropriate match so that interpretation will not be attempted with a pattern that is out of context.

Having BABY suggest further work-up to clarify problems identified in the automatic data implies that the system be able to identify the tests most likely to supply valuable information. Ideally, this ability should be derived from the machine's assessment of the patient's condition in order to use global knowledge for test selection. Pattern prototypes that can match partial or incomplete data and signal to the user the missing information provide BABY's solution to the problem.

Overview of System Structure. There were two guiding forces in the BABY design. Most important, the system was designed from the user interface inward to maintain the desired type of man-machine interaction. Second, it was integrated into the ADVISE system in order to use the knowledge engineering tools developed at the University of Illinois.

The previously mentioned metaphor for the system poses a number of engineering problems. A knowledge representation must allow data-driven interpretation; the control scheme has to be semi-autonomous; and the representation of the patient state must be made available to the user interface operators. The resulting BABY structure is shown in Figure 43. The patient state and user interface are central to the system since the other modules interact through them. The ADVISE system provides the software environment for both system development and operation.

BABY needs to interface with at least the hospital information system to obtain the lab values and demographic information. In addition, if monitoring input is to be used, the stream of raw data must be preprocessed to extract significant events. In other words, BABY is not a machine for data storage or signal enhancement; the existence of that capability is assumed. Rather, BABY is a knowledgeable interface between clinician and NICU computers that makes sense of the patient's data by putting it into a clinical context.

13.2. Clinical Perspective

As an aid to the neonatologist, BABY aims to help with the tedious tasks rather than those in which the clinician has the most individualistic approach and takes the most pride. Therefore, it was felt that BABY should intelligently follow the data about the patients and not concentrate on the differential diagnosis.

13.2.1. Role of BABY in Diagnosis

In their description of clinical problem solving, Eddy and Clanton identify four main tasks [Eddy 82]. They are: selection of a pivot, generation of a cause list, selection of a diagnosis, and validation of the selection. As mentioned previously, a pivot is a pathophysiologic state around which a differential diagnosis can be developed. BABY only addresses the first step—it is strictly concerned with finding pivots in the data. Selection, pruning, and validation are left to the clinician.

Sidestepping the medical diagnostic process has at least two advantages. Most important, false positives become acceptable because the burden of diagnostic proof remains on the physician. Having BABY only provide pivots also has the advantage of simplifying system architecture and knowledge base construction. The complexity and size of CADUCEUS's knowledge base testifies to the difficulty of computer differential diagnosis

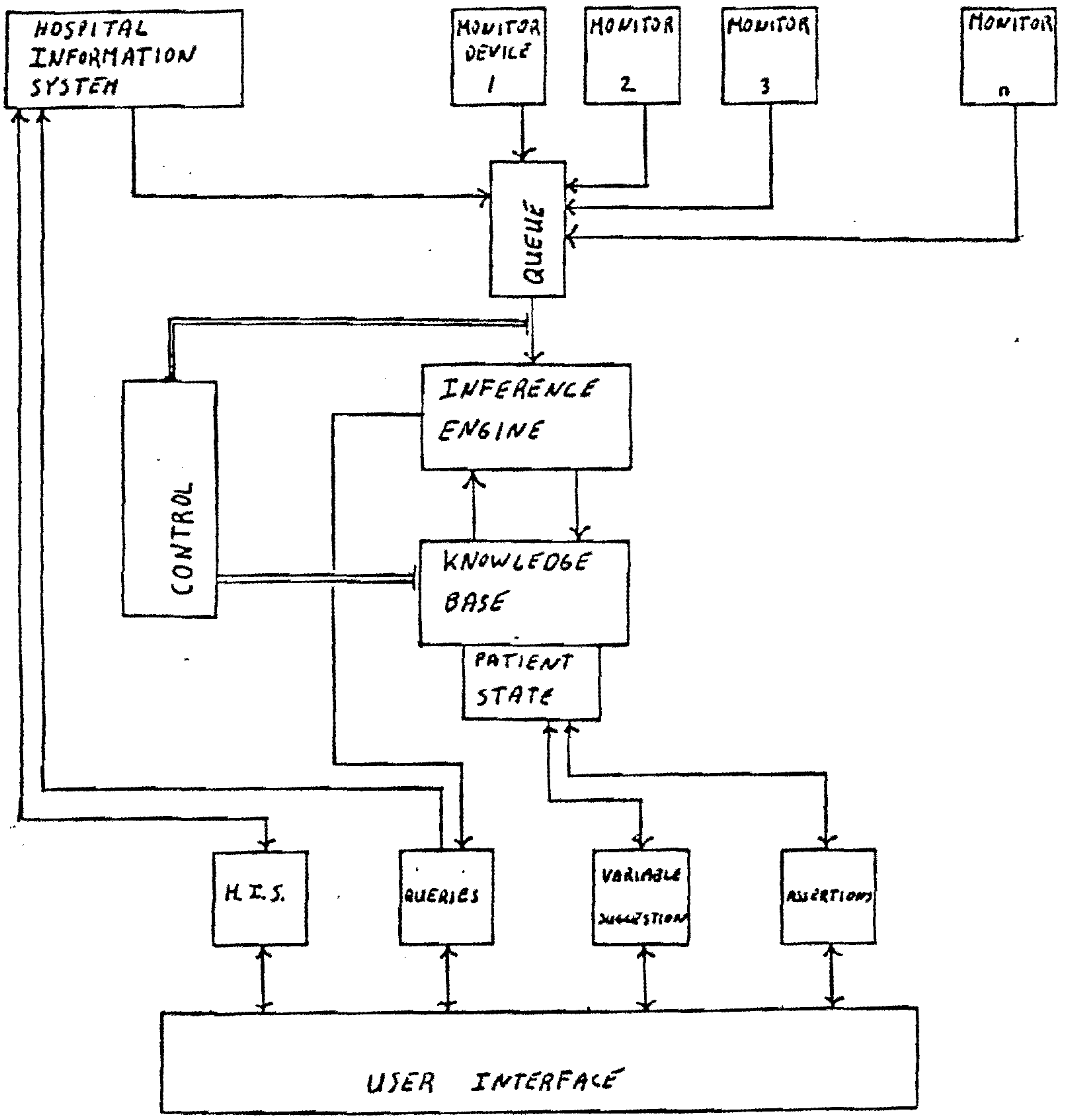


Figure 43: System Structure

[Pople 82].

13.2.2. Clinical Patterns

There are three pattern types that need to be distinguished: patterns annotating a single variable, patterns composed of more than one variable or subpattern, and patterns that assign risk value. The risk assessment pattern is a special case of patterns composed of other patterns, but its clinical usage is quite different.

Variable Annotation. Given a laboratory value or significant event from monitor output and the clinical state of the patient, an expert system should be able to decide if the value is low, normal, or high. Determination of the reference range for a single variable depends on demographic and pathophysiologic parameters of the patient. These parameters, embodied in the patient state, drive the variable annotation. For example, the relation of the serum sodium level to an appropriate normal reference range depends on the state of renal maturation, which itself depends on the age and length of gestation.

In order for a system to be accurate in its annotation, global interpretation of the variables is needed. In contrast, most computer systems that indicate a lab value's location in a reference range use a single range for all patients, regardless of other values known about the patient. Often the lab systems do not have demographic and clinical information with which to make inferences, and without a large amount of patient information any attempt at accurate annotation is bound to fall short. Neonatologists notice this problem often because adult normal values differ so markedly from newborn normal values. After some experience with inaccurate annotation, the clinicians tend to look only at the values while ignoring the computer's assessment of those values.

Global interpretation puts a large demand on the accuracy of the machine version of the patient's clinical state. If annotation could be done well, there would be much value to it. However, the problems of representing clinical information in machinable form is quite difficult. BABY approaches the problem of global interpretation by having appropriate pathophysiologic states condition the interpretation of incoming data. The portion of the knowledge base to use in annotating the data depends on the state of the patient.

Combination Patterns. Different lab values or monitoring events that must occur together to signify a finding comprise patterns of the second type. These groupings of data usually indicate pathophysiologic phenomenon in the patient. An example is the finding of metabolic acidosis, which itself depends on more primitive patterns such as acidosis, hypocapnia or normocapnia, and hypocarbia. The distinction between data annotation and combination patterns is that one should always be able to annotate a variable, while the presence of the latter type of pattern is less predictable. The combination patterns to expect depends on the clinical situation.

Risk Assessment Patterns. While the above combination patterns represent pathophysiologic states, another type of combination pattern could be used to assign a degree of risk for the occurrence of an event or complication of therapy. Although they do not strictly represent pathology, it is desirable to identify these patterns if they are evident in the automatically collected data. As an example, consider a data pattern that tries to predict the risk of an iatrogenic pneumothorax in a ventilator-dependent patient. Such a pattern would need data about the respirator pressures and rate, the patient's disease, his age, a measure of the lung compliance and its trend of change, the breathing pattern (fighting the ventilator?), and a history of prior pneumothoracies. A monitoring system that could accurately assess the risk in different patients might be able to prevent this catastrophic occurrence by raising the clinician's index of suspicion. This particular pattern probably could be built and tested in the clinical setting.

13.3. Clinical Context and Patient State

The clinical context within which the data is gathered presents a problem. Few values can be interpreted in isolation of other findings or parameter measures. Consider the value of the variable AGE. The actual age of the patient is really a statistic used to help assess the parameter of physiologic maturity of the patient. In a baby, knowledge of age is not enough since the length of gestation is also needed to determine the degree of physiologic maturity.

Therefore, a system to analyze lab data containing variables whose reference range varies with renal maturation, for example, should be prepared to take into account the patient's physiologic age.

Although this seems straightforward enough, the problem becomes less clear when one considers how the normal reference range is defined and used. The interpretation can vary from a gaussian distribution of lab values to an aesthetic ideal of the most perfect value for an individual [Galen 80]. In the former interpretation, the range is usually defined as those values falling within two standard deviations of the mean. While this is the most common derivation of "normal" and is easy to determine, it often is incorrect in a given clinical setting because heterogeneity of the target population is accounted for statistically rather than individually. More precise norms could be defined for smaller populations. This problem is seen in pediatrics where normal growth and maturation are constantly changing the normal range. In general, the creation of context-dependent normal ranges is difficult because of problems in defining the contexts. In BABY the reference ranges are defined by the knowledge base author, as are the contexts. Ideally, a system should allow clinicians to define their own contexts in order to tailor the system to meet their own specific needs.

Searching for these three pattern types within the clinical context of a patient is the primary purpose of BABY. The immune system provides a biologic analogy to the type of information processing performed by BABY. The animal's antigenic stimuli become the data, while the antibodies become the patterns to be matched against that data. Like the antibody waiting for its antigen, the pattern does nothing until a match is found in the data which then causes an action to take place. The clinical context of the patient is used to condition the activity of individual patterns in the set of possible patterns. As with the immune system, and unlike the nervous system, there is no centralized control for the patterns; it is distributed among its individual elements. In practice, of course, BABY has to simulate this decentralization because of its implementation on a non-parallel processing machine.

13.4. Knowledge Engineering Environment

13.4.1. Clinical Data

There are three sources of input to BABY: significant events extracted from monitor equipment output, information available on a hospital information system, and user input during an interactive session. BABY needs no user input at all; it will make whatever inferences it can from the automatically collected data. If a user wishes to interact with the machine, more inferences can be made with the additional information he or she supplies.

The data available in the NICU can be classified in two different ways—by function, or by collection method. Functionally, it is either automatically collected, or it is requested to answer a specific question. Distinguished by collection method, data is either obtained continuously by machine, intermittently by machine, or is observed in the process of a clinician's physical assessment. Continuously sampled physiologic indicators would need to have significant events extracted from the analog signals.

The significance of this classification is that it delimits the function and structure of BABY within the limits of the metaphor describing its purpose. Functionally, the standard input is automatic data, while the standard output is assertions about the patient along with new data to clarify clinical findings in the data. Structurally, the standard input only excludes physical signs. Often BABY will have to make its inferences within the scope of the allowable data.

13.4.2. Uncertainty in Medical Data

Certainty of medical data decreases with time; the more time that elapses since a measure was taken makes the value less reliable. The rate of certainty decline varies considerably from test to test, and within the same test, depending on the stability of the patient. To complicate matters further, the loss of certainty, although monotonic, can be non-linear. It is desirable for the knowledge representation to express temporal uncertainty, but to do it accurately is far from easy.

For a monitoring expert system, the NICU has the advantage that data is refreshed at frequent intervals. Temporal uncertainty is reduced most by this mechanism, but by using comparisons to previous values, uncertainty due to factors intrinsic to the test or collection procedure can also be decreased. BABY deals with uncertainty in a probabilistic sense. That is, certainty (and uncertainty) are explicitly represented as probabilities of truth in an assertion. Combining different sources of uncertainty into a single probability is done with a method similar to that used by the PROSPECTOR system [Duda 76].

13.4.3. The Knowledge Base

Two important aspects of a knowledge representation are its notational efficiency and expressive adequacy [Woods 83]. Expressive adequacy is concerned with what the representation is capable of stating about the world. Notational efficiency has to do with the ease with which it can be stated. Of the two attributes, expressive adequacy is probably the most important because it limits the potential of the representation.

The knowledge base often has a single representation format that limits its expressiveness, but makes inference engine development easier and facilitates knowledge base creation and modification. The representation method selected usually allows for some degree of domain independence. In addition, modularization is strived for in expert system design so that the component parts can be more easily modified. Therefore, control and knowledge ought to be developed separately, but in practice it is often difficult to completely remove elements of control from the knowledge base. For example, in MYCIN the antecedent ordering in a rule affects evaluation order in the backward chaining.

As mentioned before, the BABY knowledge representation consists of rules connected together by a network that guides the control scheme to a limited number of inferences. BABY has a large element of control in its representation which is expressed with context nodes that signal to the inference engine a portion of the knowledge base is usable for inferences. These context nodes act as keys, indicating that a pattern is potentially relevant and should be searched for. During knowledge base design the context nodes let the expert confine his or her reasoning to a smaller problem within the defined context, easing the creation task somewhat.

13.5. Baby Implementation

The current implementation of BABY consists of two Pascal programs situated within the ADVISE system on a Vax 11/780 computer at the University of Illinois. One program is a tool for knowledge base creation and is responsible for translating a text description of the rule network into a machinable form. The other program uses this machinable representation to interpret the NICU data and run the user interface.

At any point during runtime, BABY is either updating information, waiting for information, or interacting with a user. While updating information, the knowledge base is unstable and unavailable for user queries or input. As inferences about the patient are made, they are scrolled onto the appropriate output window where they remain until new information makes them invalid. Following knowledge updating, the variables most likely to influence the patient state are reported and the user has a chance to interact with BABY until new information is supplied by the laboratory computer or patient monitors. The result is a mixed-initiative dialogue with the user in control of the questioning phase and the machine intermittently supplying a summary of its findings.

13.5.1. User Interface

The user interface attempts to maximize the man-machine communication bandwidth, while at the same time minimizing the need for a specific communication language. Using windowing techniques and a pointing device, the number of verbs needed in the interface is kept to a minimum. Central to the user interface is a bit-mapped graphics terminal which communicates serially with the ADVISE computer. All non-numerical user input is done with a mouse pointer acting on pop-up menus.

There are five physical windows in the current implementation that correspond to four conceptual views of the system and one scratch window for interactive system output. Two windows deal with output, and two windows deal with variables.

BABY has two types of standard output—assertions about the patient state and suggestions for refinement of that state. Assertions are scrolled onto one window and any user queries concerning the patient state or list of current assertions takes place within this window. The suggested variables are scrolled onto a second window. If the user wants to supply any of these variable values, he or she would move the pointer into the window to select the proper variable. If the variable type is nominal, a pop-up menu with its domain appears and selection is again made with the mouse. The keyboard would be used only to supply numeric values.

The third window gives a view into the variables of the hospital lab system, and would be used as a regular interface with the lab. The other window gives a view into the BABY variables. Here requests can be made to see a variable's value or domain and values can be provided for variables that were not suggested by BABY.

The graphics terminal supports many primitive functions needed to manage windows, including window creation, clipping, saving contents, context switching, and pointer management. The programmer uses these procedures in routines which bind data base and knowledge base information to the windows. For example, a menu can be placed in an ADVISE textnode, which in turn can be executed by a user interface procedure. This procedure is textnode independent, and the user choice is returned as a small integer to the calling procedure where binding of the appropriate subroutine to that choice is made.

13.5.2. The Knowledge Representation

A BABY knowledge base provides a representation for a collection of prototypic data patterns that are to be searched for in the laboratory and monitoring input. Any prototype that matches an appropriate combination of data elements from the input will be asserted to the user. Each of these prototypes has a truth value representing how well the data substantiates the prototype, so an assertion is made only if the truth value is above the pattern's threshold.

The pattern prototypes of BABY wait for data to justify them in a bottom-up, data-driven manner. The pattern prototypes that are active and thus trying to match data from the input depends on the past history of the data. This is accomplished by having only patterns present that are in clinical context; thus only appropriate patterns will be available for matching.

The prototypes have the form of directed, acyclic graphs with unique roots. The graph consists of nodes connected by directed arcs. At one end of the graph is a root that represents a clinical or pathophysiological condition and always has a current truth value, or degree of belief in that condition. At the graph's other end are leaves to act as data entry points. The BABY leaves take the form of VL1 rules [Michalski 74] which, at the minimum, compare a variable's value to a reference value, returning a truth value as its result.

See Figure 44 for an example of a knowledge base pattern.

The BABY rules are used as predicates for matching a condition to a truth value. The ADVISE subset of the VL1 is the language that defines both variables and rules. For a description of variables and rules, see Chapter 6. Rules are connected to the graph structure with arcs that act as conduits for propagation of truth values. The variables contained within these rules may be used in a large number of unrelated rules, creating the problem of mapping variables to their respective rules, a necessity arising from the data-driven nature of BABY. The VL1 parser creates a symbol table for this mapping that is used by the inference engine to locate the pattern leaves currently in context and available for matching.

Patterns are recursive structures composed of nodes, arcs, and rules in a manner similar to a PROSPECTOR knowledge base network [Duda 78]. The information content of a pattern is summarized with a single number between zero and one, its truth value, representing the degree of confidence with which the pattern is believed to be supported by the input data. The recursive nature of the patterns arises because they can be used as intermediary nodes in other patterns, as their truth value is propagated upward to any patterns of which they are a part.

The truth values travel along arcs in the direction of leaf to root, being processed along the way at the intermediary nodes. These arcs are currently of two types, EVIDENCE and CONTEXT, having quite different semantics. Both arc types carry information which, when present, supports the truth of the parent node. However, the CONTEXT arcs have explicit control information that indicates whether or not the parent node is clinically relevant. If in context, the parent node is made a part of the active knowledge base and can be used to match input data. Otherwise it is essentially excluded from the collection of current patterns until the context changes. Thus, the CONTEXT arcs act as keys to their parent nodes, either locking them in or out. By this mechanism the size of the active knowledge base is reduced to a small subset of the global knowledge base, resulting in both storage and computational savings.

Every node in the network has a truth value ranging from zero to one, which represents both subjective probability and certainty of truth. Zero indicates certainty that the assertion is false while one indicates certainty that the assertion is true. Initially, no information about an assertion is represented by the node's prior value. As the truth values of the nodes change, increasing values represent rising certainty in the truth of the assertions, and vice versa.

There are five node types supported by the BABY inference engine. They are the logical types AND, OR, and NOT, the predicate type RULE, and a type responsible for folding evidence and uncertainty together, the type BAYESIAN. The RULE nodes are the leaves of the patterns and are evaluated by the ADVISE rule evaluator according to semantics set by the programmer. The three logical nodes have very simple semantics. The truth value of an AND node is the minimum of its children's truth values, while an OR node takes the maximum value of its children. NOT nodes invert their child's truth value by subtracting it from the maximum truth value. A high truth value of any one child will give an OR node a high value, but all children of an AND node must have high values to cause it

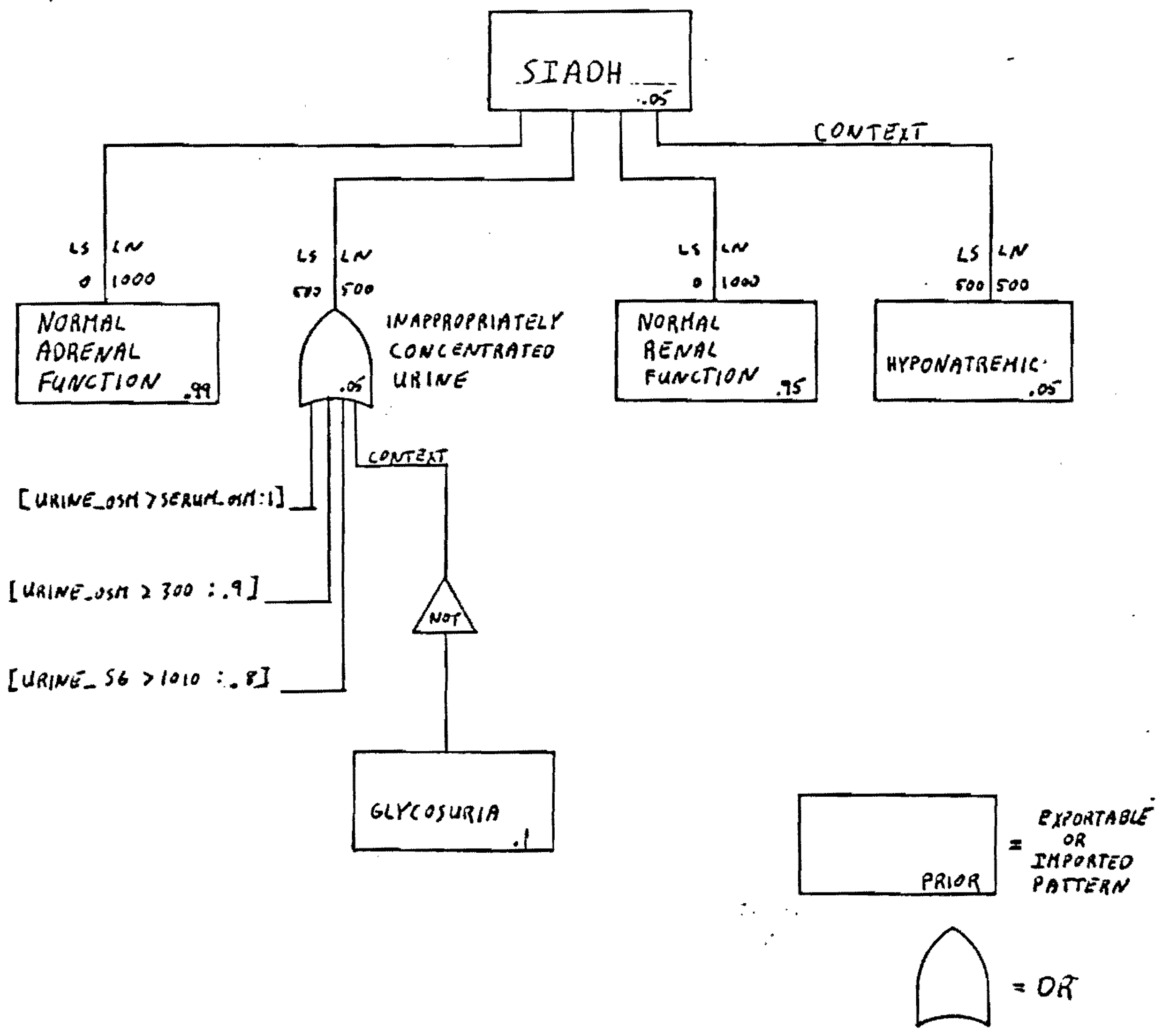


Figure 44: A Pattern to match SIADH

to also attain a high value.

The BAYESIAN node type is used to fold together independent pieces of evidence to calculate a truth value. These nodes can have an arbitrary number of children attached by EVIDENCE arcs, each with their own assertion strength that the child's evidence implies the parent's hypothesis. In addition, these child nodes must have a prior truth value that represents the probability of the evidence being true before anything is known about the patient. Associated with each connecting arc are two numbers representing the strength of the inference from child node to parent. The first number, LS, is the strength of the inference if the current child node probability is greater that that node's prior probability. Conversely, LN represents the inferential strength when the current child node probability is less than its prior probability. An entirely equivalent method of specifying LS and LN is to specify the maximum and minimum posterior probabilities that the parent node can attain, given maximum and minimum child node current probabilities. These numbers must be supplied by the expert and he or she can use whichever form is most convenient.

The truth values of all five node types can be calculated with information local to the node, assuming that the values of its children are stable. Implied, then, is that a single node can only affect the values of nodes between it and the pattern root, limiting the number of nodes whose values need propagation when new data arrives. By locking out portions of the knowledge base from activity, nodes connected by CONTEXT arcs also help reduce the list of node values to propagate.

13.5.3. The Inference Engine

The network structure of BABY's knowledge base makes the inference engine quite simple. It is a data-driven, forward-propagating algorithm that only needs a small planning phase because of the context links. This is quite different from Prospector in that the planning is minimized, propagation is a parallel process, and the context links are central to control rather than to question planning [Duda 78]. It is easiest to understand the algorithm by way of examples.

Initially assume that there are no context links in the knowledge base. When a burst of lab data comes into BABY, the appropriate system variables are bound to the lab data values. For example, when the serum sodium value comes in as 135 meq/l, BABY's variable for serum sodium is located and set to 135. Next, all rules using serum sodium in the currently active knowledge base are located via a look-up table and placed on a queue called the NODES-TO-PROPAGATE (NTP) queue. Each variable may be used by several predicates, all of which are enqueued. In other words, the serum sodium value may be used in several different patterns. The table managing the binding of variables to predicates is created by the ADVISE VL1 parser.

After the rules are enqueued, they are dequeued, evaluated, and their truth value is propagated to any reachable parent nodes. A node is reachable if there is a direct link to it and if it is in the currently active knowledge base. Propagation implies calculating the parent node's new value based on the value of the node just dequeued. After the new value is calculated, that node is enqueued onto the NTP queue. If the parent node is a pattern root, and if its new value is greater than its assertion threshold, its value is presented to the user. This cycle of dequeing and enqueing is repeated until the NTP queue is empty. The algorithm resembles a breadth-first graph traversal due to the use of a queue rather than a stack.

Context arcs complicate the algorithm slightly, but also add considerable potential. If, in the above example, a context link was crossed during an upward value propagation, then a check would be made to determine if either the context node's value changed from above the context threshold to below it, or if it changed from below the threshold to above it. In the former case, the parent node would then be in context, and should be added to the active knowledge base. A recursive algorithm is called that activates this new portion of the knowledge base. The situation where a piece of the knowledge base can be a part of different patterns, each with their own respective contexts, is handled by an ADVISE primitive.

The activating algorithm activates all children of the node that is now in context. It then calls itself to activate the children's children. If one of these nodes has a context link, only that link is followed by the algorithm's recursion, otherwise all links are followed. When a leaf is reached, a check is made to see if any of the rule's variables has a value. If so, the leaf is added to the NTP queue so that the rule can be evaluated and the value propagated to the now in context area of the knowledge base. If it were deemed desirable, this is where a goal-directed, backward-chaining algorithm could be added. Then, if a variable's value was not available a check could be made to see if that value could be inferred. Currently such a capability is not available in BABY.

13.5.4. The Patient State

At any given time, the system's model of the patient is contained in the patient state: that portion of the knowledge base that is in context and therefore has been activated. Included in the definition of the patient state are all the variable value bindings and the intermediate node values. The size of the active network will be much smaller than the entire knowledge base, since only a small portion will be in context at any time. This storage economy also results in the processor time economy because inferences are not made on any non-active portion of the knowledge base. Indeed, the inference engine cannot even access non-active knowledge.

The use of reduced portions of the knowledge base for individual patients could allow the system to keep track of more than one patient at a time by providing each with their own patient state. The ADVISE system facilitates this capability by having its storage divided into three levels: global, local, and private. Each lower level retains all the connectivity of the higher levels, but only those parts of the graph requested from a higher level will be explicitly stored at the lower level. Thus, an individual patient state could reside at the private level, while the entire global knowledge base would be stored in the global level. As the patient state is expanded by coming into context, it is stored at the private level. The converse must happen when graph areas go out of context.

Two other aspects of the patient state are facilitated by Advise features. Since the contents of the three levels are mapped onto three independent areas of secondary storage, switching from patient to patient can be easily done by swapping disk areas at the private level while leaving the global level alone. Also, any values belonging to a particular patient are stored in the patient state, so that data security can be maintained at the file level. ADVISE also supports security at a more primitive level during run time.

13.5.5. Variable Suggestion

In BABY there is a variable suggestion phase that follows propagation of the data and activation of the knowledge base. The variables selected are listed in one of the user interface's windows to indicate to the user that knowing these values is desirable. Ideally these variables would provide the most information to the patient state, or be able to effect the greatest change in the current context. Two different algorithms for scoring the variables are implemented; one is done during knowledge base instantiation, and the other requires a separate partial patient state traversal.

The latter algorithm will be discussed first. At each node, in addition to the current value, BABY stores the minimum and maximum possible values, given the minimum and maximum values of its children. If nothing is known about a RULE node's value its maximum is one, minimum is zero, and current value is its prior value, otherwise all three values are set equal to the current value. The differential, if any, between the three values will ripple upward during regular value propagation. The scoring algorithm makes use of all three values. A variable's score is roughly equal to the sum total of probability that could be added to or subtracted from the patient state if that variable's value were known with absolute certainty. To calculate this value the active network is traversed top down, keeping track of the difference between the maximum value and the current value, and using the assertion strength values, LS and LN, to determine the multiplier for the difference in odds. This algorithm is expensive for a large patient state.

The other scoring algorithm is much simpler, but it does not account for assertion strength. This one works during knowledge base activation upon reaching a leaf. If any of the leaf's variables has no known value its suggestion score is incremented. At the end of data propagation, all variables whose values were desired but unknown have a score. The variables that were inspected the most have the highest score, and are assumed to be the most desirable. This method, although fast, looses much of the knowledge base information; it only retains the physical layout of the graph while discarding the probabilistic elements.

In either case, the highest-scoring variables are mentioned to the user, who has the option of supplying any known values.

13.5.6. Network Parser

The creation of the knowledge base is entirely expert dependent. The BABY network parser, in conjunction with the ADVISE VL1 parser, facilitates transformation of a textfile description of a network into a machine usable form. BABY accepts any rule structure that is supported by both the VL1 parser and the rule evaluator. It is up to the expert whether to make a rule more complex in order to simplify a network, or vice versa. The programmer has the option of choosing among several different semantics for uncertainty evaluation within the predicates, extending the network expressiveness.

The network parser is a recursive descent parser that creates and links the nodes with their appropriate arc types, and calls the ADVISE parser as a subroutine to create the rule parse trees and a look-up table of rule to variable bindings. A limited syntactic check is performed also to insure that at least the newly created network structure will work in BABY. In addition, the network is printed out in an in-order, indented format so that the expert can see if the traversed prior values are in accordance with expectations.

The language accepted by the network parser is quite limited and rigid, but it is not difficult to translate from a picture of a network into the text format. If a node is to be either an assertion, or it is to be used by more than one pattern, it must be uniquely named. This name will be the one shown to the user. If a node does not need a name, the parser will supply its own unique one.

Figure 45 illustrates the mapping of the pattern of Figure 44 into the network language. Appendix C shows the corresponding mapping to the ADVISE internal storage format.

```
NEONATE_PATTERNS
EVIDENCE AND NEONATE_PATTERNS
 EVIDENCE BAYESIAN SIADH .05 .8
  [500 -500] CONTEXT .75 BAYESIAN HYPONATREMIC ;
  [0 -1000] EVIDENCE BAYESIAN NORMAL_RENAL_FUNCTION ;
  [0 -1000] EVIDENCE BAYESIAN NORMAL_ADRENAL_FUNCTION ;
  [0 -1000] EVIDENCE OR *
   CONTEXT .75 NOT *
    EVIDENCE BAYESIAN GLYCOSURIA ;
    ;
   EVIDENCE RULE * .1 .8 [URINE_OSM > SERUM_OSM : 0.1] :> MKNULL;
   EVIDENCE RULE * .1 .8 [URINE_OSM > 300 : 0.9] :> MKNULL;
   EVIDENCE RULE * .1 .8 [URINE_SG  > 1.010 : 0.8] :> MKNULL;
   ;
  ;
 ;
```

Figure 45: Network Description of Figure 44

13.6. Conclusion

The BABY project presented a description and partial implementation of an expert system for assisting clinicians caring for babies in an NICU. The current prototype version of BABY is part of a learning process attempting to identify the bottlenecks and difficulties that will be encountered during implementation of various ideas. The main difficulties in BABY center around the knowledge representation of the patient state.

The expressiveness of a knowledge representation sets an upper bound on the performance quality; if a type of knowledge cannot be made available, inferences and explanations based on that knowledge cannot be performed. Temporal, spatial, physiologic, and developmental relations between variables are not representable by the current knowledge base formalism. Explanations indicating supporting evidence for an assertion still could be provided for in the future.

Explicit temporal reasoning is not possible with the current knowledge representation. Trends and predictions of variable values are not calculated, even though a value is represented as a domain element and a time stamp. It was felt that rather than implement an ad hoc mechanism for handling time relationships, it would be better to develop a more complete theory of medical, temporal reasoning. Such a theory would have to include prediction of future values based on not only past trends, but also on the clinical context of the patient.

Although there is work to be done in improving the knowledge representation, the functionality of the representation should probably be preserved since it meets the data flow requirements of an NICU. The main improvement required of the knowledge base is the addition of semantics for handling temporal relations within the clinical context of individual patients. Prediction of future values and decrease in value confidence need explicit representation so that conclusions can be stated as accurately as possible, but without overstatement. Additionally, tabular representation and a graphics network editor are needed for better notational efficiency.

Following these changes, a non-trivial knowledge base needs to be constructed and debugged so that empirical testing in an NICU can determine the adequacy of BABY to contribute significantly to patient care.

CHAPTER 14

The ALFALFA Entomology Pest Identification System

14.1. Introduction

As a means of exercising various control scheme features in an expert system which actually requires more than one rule group with more than one control scheme, the alfalfa field pest identification system was undertaken by entomologists William Lamp and Lane Smith of the University of Illinois Natural History Survey (???) in conjunction with Jiarong Hong and Carl Uhrik of the University of Illinois Department of Computer Science. The meta-expert system development goals are the primary focus here, but the reader can get a better understanding of the general concerns of entomology by referring to [Borror, Delong and Triplehorn '76]. Further details of the ALFALFA System, particularly the rules and attribute descriptions, are recorded in [Hong and Uhrik '85].

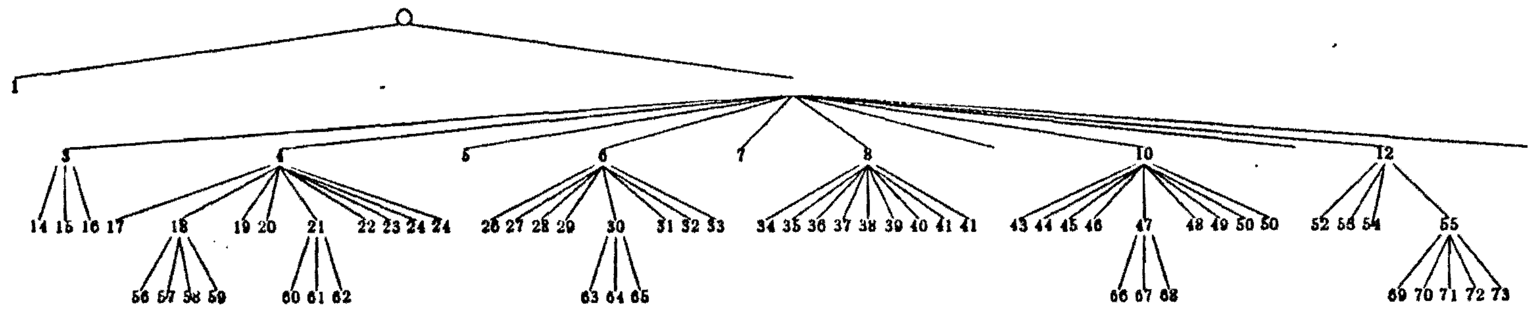
An automated key to insects should use descriptors which are easily observed, remembered and reported. Further, the key should proceed through a layered series of identifications, becoming more specific as more information is provided. The identification takes the form of the classical Linnean system at the higher levels (Class, Order, Family), but as often as not, the exact species is not critical and a common name is acceptably assigned (e.g., "thrips"). Incomplete data should result in, rather than no identification, a more general identification. Thus, the key targets different levels of identification using different sets of attributes for each stage of identification (Figure 46). Conceptually, different groups of rules apply to the various levels, each group possibly claiming its own uniquely important variables, pertinent to a particular stage of the consultation. Moreover, the rule group in use at a particular moment often requires its own special variation of a control scheme. Thus, one can see the inherent needs of the ALFALFA System for multiple rule groups, multiple control schemes, and dynamicly changing goals.

The desired approach to implementing the system called for minimal changes to existing modules. Modules changed are the parser and control scheme. Certain features of the rule evaluator were changed to be consistent with previous usage but allowed additional features. For example, the ?, *, $ patterns for matching various flavors of *unknown* values were not implemented consistently in the previous Rule Evaluator.

The general system development goals may be grouped according to the following:

1) Preconditions and termination conditions on rule groups,
2) Multiple non-homogeneous goal values or goal variables,
3) "OR" in the RHS of Rules,
4) Enhanced Data Acquisition features .

A description of each of these areas follow and is the focus of this chapter.



g1 Id = Spiders and Mites
g2 Class = Insecta
g3 Order = Neuroptera
g4 Order = Coleoptera
g5 Order = Collembola
g6 Order = Homoptera
g7 Order = Diptera , Id = Flies
g8 Order = Lepidoptera
g9 Order = Odonata, Id = Damsel Flies
g10 Order = Hemiptera
g11 Order = Thysanoptera, Id = Thrips
g12 Order = Orthoptera
g13 Order = Hymenoptera, Id = Bees & Wasps
g14 Family = Chrysopidae, Id = Green_lacewings
g15 Family = Hemerobiidae, Id = Brown_lacewings
g16 Generic_id = Lacewings
g17 Family = Coccinellidae, Id = Lady_bug
g18 Family = Curculionidae, Id = Weevils
g19 Family = Silphidae, Id = Carrion_beetles
g20 Family = Staphylinidae, Id = Rove_beetle
g21 Family = Meloidae
g22 Family = Lampyridae, Id = Lightning_bug
g23 Family = Cantharidae, Id = Soldier_beetle
g24 Family = Elateridae, Id = Click_beetle
g25 Generic_id = Beetles
g26 Family = Cercopidae, Id = Meadow_spittle_bug
g27 Family = Delphacidae, Id = Other_plant_hoppers
g28 Family = Aphididae, Id = Pea_aphids
g29 Family = Aphididae, Id = Spotted_alfalfa__aphids
g30 Family = Cicadellidae, Id = Leaf_hopper
g31 Family = Aphididae, Id = Blue_alfalfa__aphids
g32 Family = Membracidae, Id = Treehoppers
g33 Generic_id = Aphids_leafhoppers_and_spittle_bugs
g34 Family = Pieridae, Id = Alfalfa_caterpillar
g35 Family = Nymphalidae, Id = Fritillary
g36 Family = Nymphalidae, Id = Buckeys
g37 Family = Nymphalidae, Id = Vanessa_atalanta
g38 Family = Nymphalidae, Id = Morning_cloak
g39 Family = Danaidae, Id = Monarch
g40 Family = Noctuidae, Id = Cutworms_and_relatives
g41 Family = Pyralidae, Id = Webworms_and_relatives
g42 Generic_id = Butterflies_and_moths
g43 Family = Anthocoridae, Id = Minute_pirate_bug
g44 Family = Miridae, Id = Plant_bugs
g45 Family = Reduviidae, Id = Assassin_bug
g46 Family = Nabidae, Id = Damsel_bugs
g47 Family = Lygaeidae
g48 Family = Berytidae, Id = Stilt_bugs
g49 Family = Coreidae, Id = Leaf_footed_bugs
g50 Family = Pentatomidae, Id = Stink_bugs
g51 Generic_id = True_bugs
g52 Family = Tetrigidae, Id = Pygmy_grasshopper
g53 Family = Acrididae, or Family = Gryllidae
g54 Family = Gryllidae, Id = Field_cricket
g55 Family = Acrididae
g56 Id = Alfalfa_weevil
g57 Id = A_weevil
g58 Id = B_weevil
g59 Id = Blue_metallic_weevil
g60 Id = Grey_blister_beetle
g61 Id = Striped_blister_beetle
g62 Generic_id = Generic_id = Blister_beetles
g63 Id = Potatoe_leaf_hopper
g64 Id = Aster_leaf_hopper
g65 Id = Leaf_hopper
g66 Id = Big_eyed_bugs
g67 Id = Seed_bugs
g68 Id = Seed_bugs_and_relatives
g69 Id = differential_grasshopper
g70 Id = Red_legged_grasshopper
g71 Id = Two_stripped_grasshopper
g72 Id = Migratory_grasshopper
g73 Generic_id = Grasshoppers_and_relatives

Figure 46 : Goal Structure of the ALFALFA System.

14.2. Preconditions and Termination Conditions

Prior to the ALFALFA system, the only attributes of rule groups were variables blocks, functions blocks, and the rules themselves. There was a need for making explicit the various control information implicit in the PLANT/ds and PLANT/cd control scheme. This was especially required to enforce some sort of sequencing discipline among the rule groups representing the different levels of pest identification.

The parser was modified as follows: given a rules block of the form –

```
ruleblkname RULES
VARS = varsblkname ;
PRECOND = lhsnode1;
TERMINATION = lhsnode2;
PROP = CONTROL
{UTILITY,BACKWARD,FORWARD,INORDER}
%%

 lhs-rule :> rhs-rule ;
   .
   .
   .

END
```

then the following tuples are produced –

```
(rulesblkname  MKEXEC MKCS MKREF1 lhsnode1)
(rulesblkname  MKEXEC MKCS MKREF2 lhsnode2)
(rulesblkname  MKPROP  textnode)
```

where the lhsnode1 and lhsnode2 refer to items which are identical to left hand sides of rules and are directly evaluatable by the RULE EVALUATOR. Under our proposed control scheme, preconditions are applied for each rule group and if satisfied the rule group is entered (initiated), and rules will start to be executed using the type of control scheme specified by the text in the CONTROL property of the rule block.

Termination conditions are evaluated after each rule in the rule group to test whether the rule group should be exited. This continues until there are no more rules in the case of the sequential scheme or until the termination condition is satisfied.

14.3. Multigoals

PLANT/ds only allows a single variable on the RHS to determine the goal. Certain complications of goals might be imagined:

a) structured values of goal variable,
b) dynamicly changing sets or structure of values for goal variables,
c) dynamicly changing "goal" variable,
d) sets of goal variables,
e) dynamicly changing sets of goal variables.

As a minimum, an array of goals which will be determined in one of 2 ways is desirable.

Option 1 If there is a GOALS specification in the rules block, the goals will be taken to be that of a goals tuple. That is, given a rules block –

```
ruleblkname RULES
VARS = varsblkname ;
GOALS = (goal1, goal2, goal3, ...);
 lhs-rule :> rhs-rule ;
   .
   .
   .
END
```

produce a tuple of the form –

```
(rulesblkname  MKEXEC MKCS MKREF0  goal1 goal2 goal3 ... )
```

with the idea that goals occur in order of their priority.

Option 2 If this GOALS designation is not present for a rule group, then all right hand side variables will be used as candidate goals.

A special tuple modifies each rule group as it is read in to update the information about which rule groups have been defined. This tuple will appear under the special node GLOBALS where the global variables are already hung. Hence the GLOBALS tuples form is:

```
(GLOBALS MKVARS var1 var2 ... )
```

and

```
(GLOBALS MKRULES rulegroup1 rulegroup2 ...)  .
```

14.4. Disjunction on the Right Hand Side of Rules

Several cases arise in the entomology domain where it is desired to pursue one classification option but if it does not work out (leads to a contradiction or low confidence of decision), then it should be abandoned and another option should be selected to pursue. These points of backtracking can easily be recorded in rules and weights can indicate which options should be considered in what order.

For example, the rule :

```
[Mouth Parts = Chewing] [Hind Legs = Jumping]
          →
               [Order = Orthoptera : 0.9]
                    V
               [Order = Coleoptera : 0.2][Insect = Flea Beetle : 0.1]
```

has the interpretation "pursue orthoptera first, but if that does not work out, then try Coleoptera given there are no more promising options." This style of parallel reasoning assumes that the values of goals are mutually exclusive and is most easily effected by a priority queue. Another flavor of the disjunction on the right hand side of rules is for independent values of a variable each having the possibility of each satisfying LHS selectors simultaneously. This latter option was not undertaken in our system. We distinguish the 2 types of disjunction by allowing a special symbol for each type. No changes to the Rule Evaluator were proposed (allowed) for this distinction at present.

14.5. Data Acquisition

A special data acquisition method was proposed to operate as a expert system apart from the inference engine. The control scheme was to pass a list of ranked variables that would be of most use. The data acquisition system makes considerations based upon the following criterion as to what questions to ask and in what order (possibly on an automatically built form):

(1) hierarchies of variables - certain variable should be asked before other variables, that is, it does not make sense to ask confirmatory data before primary data (even though the confirmatory data has more apparent usefulness),

(2) flow of consciousness - certain questions seem too jumpy if asked out of sequence, semantic closeness should be taken into account,

(3) certain variables values imply other values - restriction rules which assign defaults and does-not-apply values should be used, a graph structure will be used for this,

(4) structured variables will be implemented so as to propagate uncertainty in a reasonable manner, more use of the mutual exclusive and independent values will be made,

(5) some distinction will be made between different type of unknown - that which is uncertain, that which does not apply, that which may not be asked for again, etc.,

(6) some values of variables need never be asked at some point in a consultation and this can be inferred from the remaining viable rules,

(7) restriction rules need not achieve threshold to fire but propagate uncertainty.

14.6. Additional Research Goals

In the course of this project, several additional interesting areas of research opened up. In fact, pursuit of these areas was unfortunately the cause of the some other ideas never being refined or completed. These are described here.

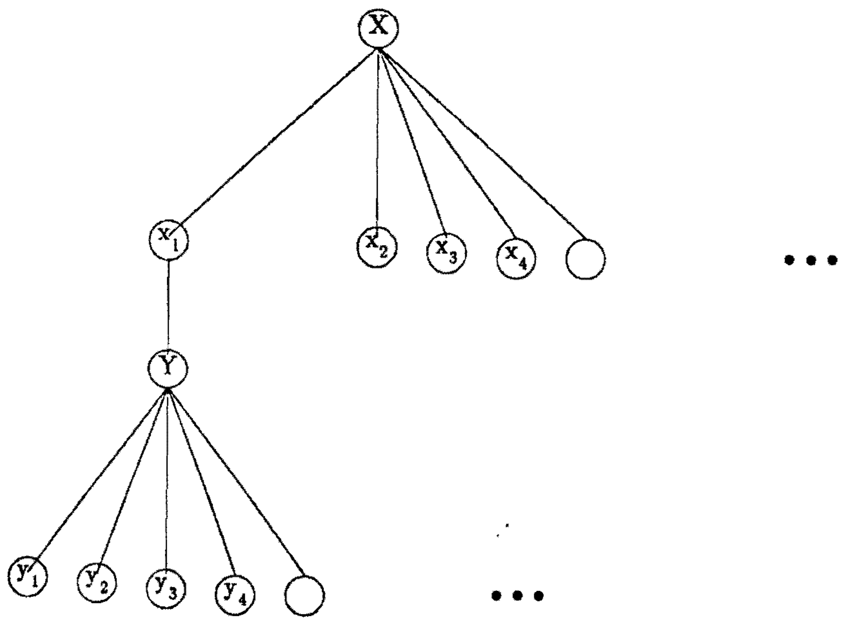
14.6.1. Describing Variable-Value Relations with Semantic Nets

In PLANT/ds, the instrinsic relationships among various variables and their values were necessarily represented by a series of restriction rules which dictated when values of some variable prohibited other variables from having semanticly inappropriate values. For example, there were a number of rules of the form:

```
[CONDITION_OF_LEAVES = NORMAL] :>
  [CONDITION_OF_LEAVES_BELOW_AFFECTED_LEAVES = DOES_NOT_APPLY]
  [POSITION_OF_AFFECTED_LEAVES = DOES_NOT_APPLY]
  [LEAF_DISCOLORATION = NONE][SHOT_HOLING = ABSENT]
  [LEAF_WITHERING_AND_WILTING = ABSENT]
  [LEAF_MALFORMATION = ABSENT][LEAF_SPOTS = ABSENT]
  [LEAF_MILDEW_GROWTH = ABSENT][SHREDDING = ABSENT] ;
```

```
[ROOTS = NORMAL] :> [ROOT_SCLEROTIA = ABSENT]
    [ROOT_ROT = ABSENT]
    [ROOT_GALLS_OR_CYSTS = ABSENT];
```

Such information indicates only one sort of behavior: whether or not the "normal" or "default" value of one variables value should preclude other variables from being asked [Chilausky and Michalski '80]. This information is more naturally expressed as a semantic network specifying connectivity between variables and values. Such a representation does not preclude the use of rules, and an interface algorithm was designed which converts such semantic nets into rules. Figure 47 illustrates the algorithm for an abstract graph. This is a simple matter of a tree traversal from top to bottom if there are no common subtrees.



Derived Rule :

$[X=x_2] \vee [X=x_3] \vee [X=x_4] \vee \bullet\bullet\bullet\ [X=x_n] \vee [X = \text{does\_not\_apply}] \rightarrow [Y = \text{does\_not\_apply}]$

Figure 47 : Abstract Outline of Algorithm Converting Variable/Value Graph to Rules.

Complications arise in the case of a DAG where there is a comon subtree. This is currently taken to mean that two variables simultaneously must be considered by an AND condition of the rule as shown in Figure 48. An option exists to specify an "independance" annotation for the common node allows the node to have the interpretation that *either* variable may influence the d.n.a. assignment to it.

A partial ordering is being produced in both the simple and latter case, and a consistent total ordering must be derived for the rules if they are to be fired sequentially. The rules can be made order independent by use of "OR" operands as in figure 49. Depending on the needs of the particular system, the graph traversal algorithm could be modified appropriately.

14.6.2. Dynamically Changing Value Sets for Variable

Much to the chagrin of the consultation user, the prototype system once querried the user as to which of 30 different values the variable COLOR should be assigned. This was extremely annoying, apart from the inability of the display routines to fit so many values on a single screen, because it was obvious at the point of querry that only a few of the defined

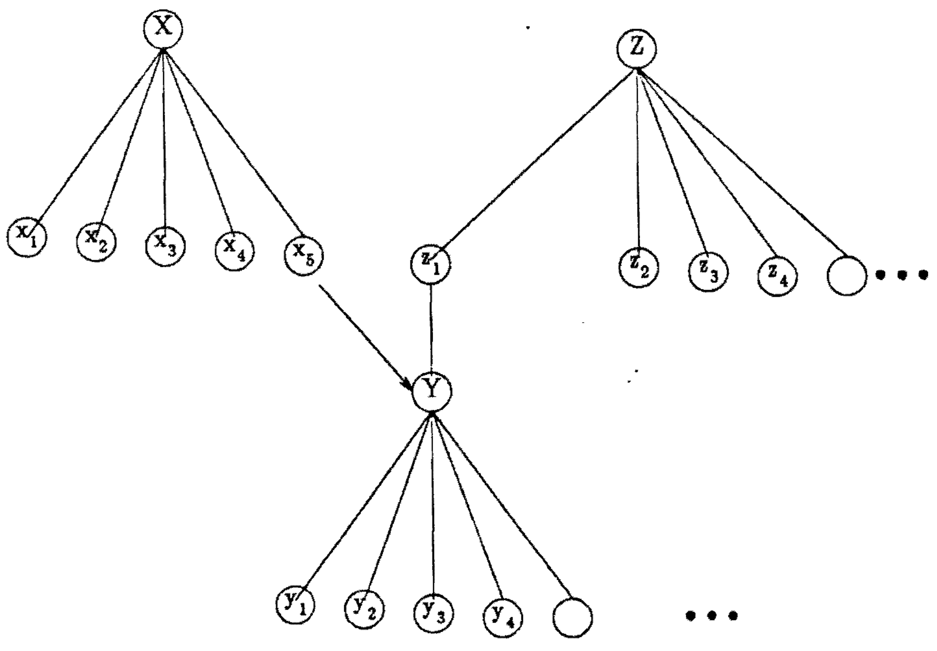
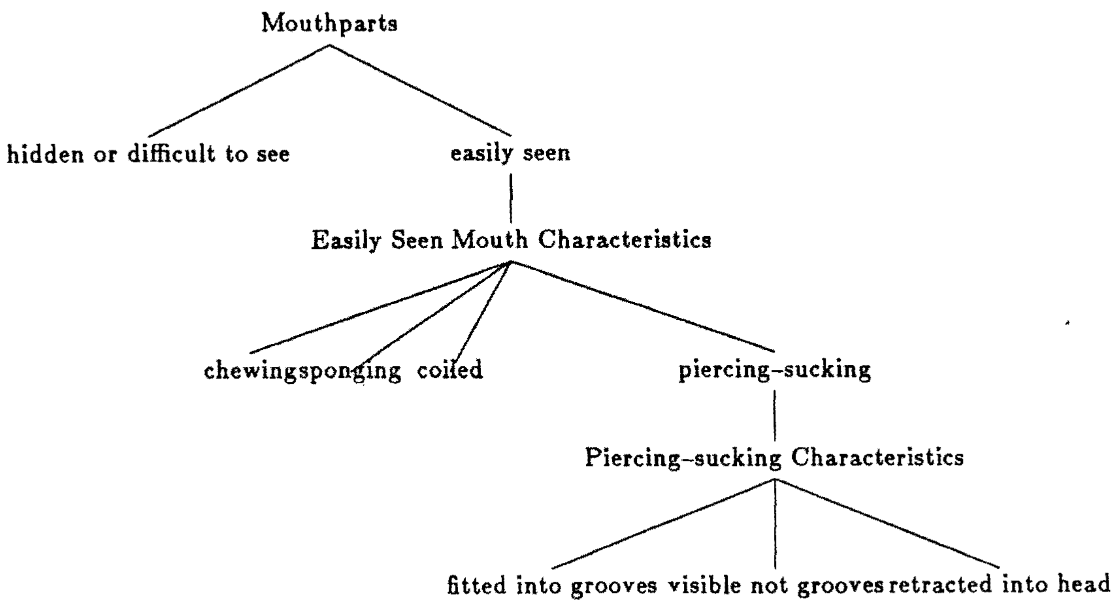


Figure 48 : The Case of a Common Subtree in Varible/Value Graphs.



Rules :

[Mouthparts = hidden or difficult to see]
∨[Mouthparts = does not apply]
→ [Easily Seen Mouthpart Characteristics = does not apply]

[Easily Seen Mouthpart Characteristics = chewing]
∨[Easily Seen Mouthpart Characteristics = coiled]
∨[Easily Seen Mouthpart Characteristics = sponging]
∨[Easily Seen Mouthpart Characteristics = does not apply]
∨[Mouthparts = hidden or difficult to see]
∨[Mouthparts = does not apply]
→ [Piercing-sucking Characteristics = does not apply]

Figure 49 : Typical Order Independent Rules Derived from Variable/Vale Graph.

values were either relevant or possible.

There are various mechanisms for achieving the dynamicly varying value sets for variables. One of these would dictate that after each querry, a computation might be effected to find all relevant domain values for any plausible conclusions supportable by the current state of the system. Another strategy might dictate that this only be done for particularly annotated variables, and then only when the variable is asked for (no sense in computing the value set until it is actually needed for a querry). Another strategy involves defining a series of variables which "inherit" values from previous variables as a rule group is started up, or defining rules that regulate the value of a single *structured* variable based upon an auxillary variable encapusulating state information.

Refering to Figure 46, the reader will be convinced that is an appropriate level of granularity for such computations. It is here that it is most relevant to talk about the possible current and subsequently-possible values of a variable based on the current state of the system. The dynamic nature of a consultation, with possible modifications to the state of variables necessitates undoing the conclusions drawn up to a particular point, and possibly revising the "possible-values" of such variables. This is currently accomplished by a complete traversal of all rule groups for which the precondition does not explicitly fail, and recording all values for the variable sought which explicitly occur in such rule groups. This is only an approximate solution (and costly even so) since some rules may be judged to be below threshold based on current state.

A better solution is possible though. A pretraversal of the rule group parse tree by a special compiler could generate a structure similar to that in Figure 50 which indicates the relative correspondence between GOAL state and the COLOR variable. This would ultimately be available by a simple table lookup or annotation to the rule group parse tree.

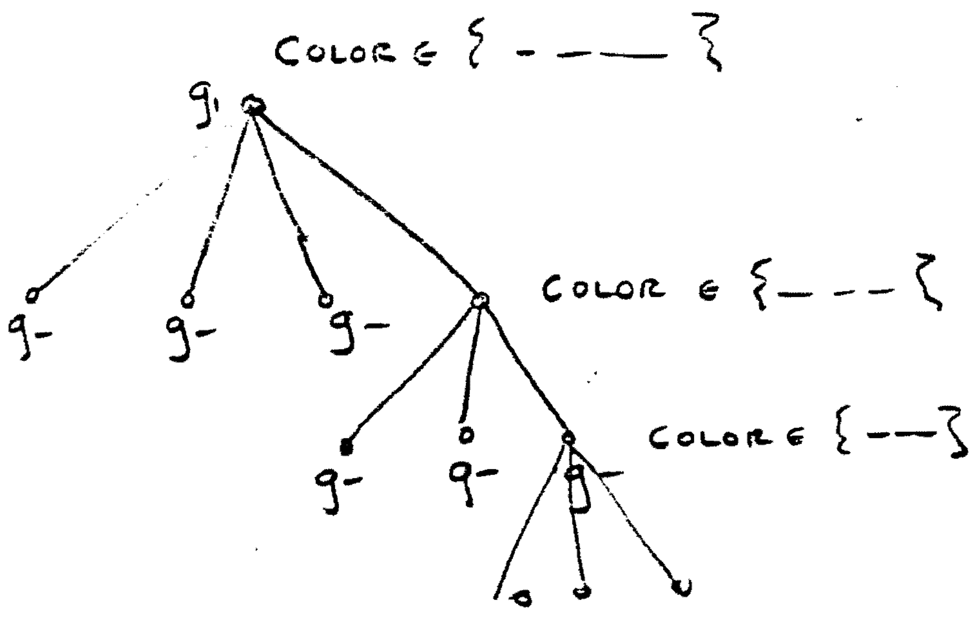


Figure 50 : Relevant Value Set of Variable COLOR at Various Points in Consultation.

14.7. Future Research Extension

Modifications to the existing ADVISE meta expert system to support the ALFALFA system. It is emphasized that these modifications built upon existing pieces – a rule evaluator, a database manager, an expert system building–blocks package, which enables more general expert systems to be built. These systems can have multiple, dynamicly changing goals, numerous rule groups, dynamicly changing control schemes, and variables with dynamicly changing value sets. A philosophy which separates the basic inference mechanism from the data collection process appears to justifiable.

In the course of this project, several additional interesting areas of research opened up. In fact, pursuit of these areas was unfortunately the cause of the some other ideas never being refined or completed. Time ,and resources ran out on this development segment. The idea of using GOALS, PRECONDITIONS, and TERMINATION CONDITIONS for planning and for optimizing the question–asking efficiency were never explored. POSTCONDITIONS were explicit conditions which would be forced to be true on exit from a rule group. This differs from termination conditions in that the later simply become true in order to exit the rule group. The graph traversal mechanisms were implemented as batch programs, but it would be interesting to make them interactive, allowing dynamic changes to the semantic network part of the knowledge base for enhanced debugging.

Enhancements to the current system include the following.

- inverse operation to converting semantic net to rules (rules to s.n.)
  for verifying human rule knowledge
- visual entry of the restriction information on vars
- more general relations over var–val semantic nets
  - value of one var sets another
  - probabilistic
- modifying the algorithm for traversing the vars graph to get
  restriction values dynamicly
- visual display of the tree of possibilities – allowing to select the
  most probable failure point or use a ranking of reliability over vars
- if a hi freq var occurs as RHS in restriction rule
  then all the LHS vars should be elevated to at least its value
  plus the value it has from other rules
  - what if it is in more than one restriction rule
  - what if more than one RHS var applies
  - what about redundant effects
- if a rule group fails
  - should run again
  - there should be a way of forcing a conclusion
  - there should be a way of cycling or back tracking to modify
    suspect values – eg., freq. mistyped or misperceived vals
- only relevant values should be asked
- restriction rules should be in a separate rule group with a lower
  threshold than other rules – change parser + RE to allow LHS fwt
  to be RHS conf – global RE option / syntactic in rule
  - a THRESHOLD prop on rule group
- straighten affairs among UNDEF, UNKN, ALL, NA

The biosphere of the alfalfa field is a complex structure. Once all the vectors present in the field are identified, it is no simple task to decide on the proper management procedures to be applied. For instance, there may be benificial insects as well as detrimental ones. Insecticide may be inappropriate for any of a number of reasons, prompting the introduction or enhancement of environment for beneficial insects. It may not even be worth the cost of applying insecticide if the alfalfa can be cut in reasonable time to ensure a good yield. These considerations make it clear that the management of alfalfa fields could be an expert system in its own right.

CHAPTER 15

Summary and Future Work

We have described the ADVISE meta–expert system at the conceptual and technical level. The system can be used for constructing and experimenting with expert systems in specific domains by:

(1) assembling knowledge about the problem,

(2) encoding the knowledge in some formal manner,

(3) possibly using the knowledge for computer inductive inference, and

(4) picking the inference mechanism(s) to be used on the encoded knowledge.

At present, we have experimentally implemented four expert consultation systems using the ADVISE meta–expert system, PLANT/ds for diagnosing soybean diseases, PLANT/cd for predicting extent of Black Cutworm damage to corn, BABY for monitoring infants in a neo–natal intensive care unit, and ALFALFA for identification and classification of insects.

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APPENDIX A

Rule Parser Details

This appendix contains additional information regarding the rule parser. Section A.1 describes some basic lexical notions concerning input to the parser. In section A.2 are details of error handling by the parser. Section A.3 defines the "mark" types currently handled by the parser.

A.1. Basic Lexical Notions

Format: All input is free-format. Lines can be as long as desired.

Comments: Comments may appear anywhere in the input, and are denoted by a leading !. The comment continues for the remainder of the line (i.e. terminated only by EOLN).

Identifiers: Identifiers must begin with a letter, and then may contain up to 39 other non-punctuation symbols including digits, ^ @ _ and '. Note that apostrophes are NOT used to enclose strings of otherwise-illegal characters.

Variables: A variable is (to the parser) an identifier which has been previously defined as a VL variable name.

Integer: A sequence of digits without a decimal point.

Real number: A sequence of digits with a decimal point. NOTE THAT A REAL MUST BEGIN WITH A DIGIT. ".9" IS NOT A REAL NUMBER.

The parser can process ASCII input files containing lower-case text, however because of the escape-code nature of lowercase material, the identifiers may be only 20 lower-case letters long. All parser keywords (i.e. RULES, VARS, etc.) are recognized only as upper-case characters.

A.2. Error Information

When a syntax error is detected the parser does four things:

(1) A ^ is written under the offending symbol.

(2) The message **** SYNTAX ERROR is printed.

(3) The list of symbols which would be acceptable is output.

(4) The parser skips to the next unit of information, e.g. skips to the next rule, next variable definition or next block.

The error return code given by the parser may be NOERROR when no errors have occured, or one of the following:

ERRPRNOPARTAB	:	The PARTAB file could not be read.
ERRPROSYNTAX	:	One or more syntax errors were detected.
ERRPROVERFLOW	:	Internal parser stack overflow.
ERRPRINTERNAL	:	The parser made a logic error which was fatal.
ERRPRUNSUPPORTED	:	An unsupported language feature was used.
ERR<other>	:	Any other fatal error code from supporting system (e.g. the tuplemanager) from which there is no recovery.

The parser writes additional messages to the MSG file to help diagnose some of these error types.

The parser writes additional messages to the MSG file to help diagnose some of these error types.

A simple parser driver program exists which utilizes two files of knowledge. Before parsing, a preexisting network is loaded from the file BACKUP. The parser is invoked on input file INPUT and giving output file OUTPUT. Subsequent to parsing, BACKUP is rewritten to contain the updated network (BACKUP is processed with READBACKUP and WRITEBACKUP directives). Also the file NETWORK is written via the WRITETEXT directive and gives a readable representation of the network.

A.3. Mark Type Definition

The parser generates a network of tuples for each block (i.e. for each RULES block and each VARS block). The name of the block (the group name) is the only handle for the network of tuples, whose head node is located via the directory, given the group name. From this node on in the block network, all tuples have a "parser mark" node in them located in the first node position, tuple[2]. The parser mark (or just "mark") indicates the functionality of the tuple for interpretation or decoding. The marks which are used this way are as follows:

A.3.1. Within a VARS Block

These mark types are generated from the VARS block definitions:

MKVARS: a list of variable-defn nodes in this tuple
MKDOMAIN: the nodes in this tuple define the domain
    [2]MKDOMAIN
    [3] domain type:
        MKNOMINAL: additional nodes give either
            – one integer: number of levels or
            – list of values
        MKINTERVAL: additional nodes give either
            – two integers: interval range or
            – ordered list of values
        MKSTRUCTURE: additional nodes give values for leaves and
            internal nodes in the structure tree
MKREFINE: gives the refinement structure of a
    structured variable tree

[2]MKREFINE
[3] internal node name
[4]... subordinate nodes to [3]

MKUNITS: gives the units of measurement for the variable

MKVALCON: gives the value of an identifier or rule component. The tuple contains pairs of numbers (value, degree of confidence), where value may be either real or integer and where deg. of conf. is always real. When multiple alternative values are to be represented, many (value, degree of confidence) pairs may be used. When space in one tuple is exhausted, another MKVALCON tuple is incorporated to hold additional data.

A.3.2. Within a RULES Block

These mark types are generated within the RULES block:

MKNULL: a "no-operation" indicator

MKVARDCL: for a group of rules, next node indicates variable definitions which are to be used

MKBEHAVIOR: the node in position [3] denotes the behavior
MKINCR: increasing (/)
MKDECR: decreasing ()
MKRMIN: has a relative minimum (/)
MKRMAX: has a relative maximum (/)

MKPAREN: indicates parentheses used around this unit

MKTVARS: indicates "target" variables used in the rule. A target variable is one which occurs to the left of the relation symbol in a selector.

MKRVARS: indicates "reference" variables used in the rule. A reference variable is one which occurs to the right of the relation symbol in a selector. In either theMKTVARS or MKRVARS tuple the following node (tuple[3]) contains eitherMKRHSV or MKLHSV to indicate whether the variables listed occur in the rule's right- or left-hand side, respectively. Tuple positions from tuple[4] hold variable node data. Each variable cited occurs one or more times in the right or left hand side (according to tuple[3]) as a target or reference (according to tuple[2]).

MKLHSV: indicates rules in a rule group which involve a specific variable in the left hand side part.

MKRHSV: indicates rules in a rule group which involve a specific variable in the right hand side part. Tuple[3] contains a variable node and tuple[4] on to the end contain rule nodes which incorporate the variable within the left- or right-hand side (as indicated by tuple[2]).

MKEXEC: indicates that the following node (tuple[3]) contains an "executable" code which can be one of the following:
MKFALSE: denotes the constant value false
MKTRUE: denotes the constant value true
MKRULES: a list of rule nodes in this tuple
MKRULE: rule lhs node and rule rhs node in this tuple
MKLM: the folling node is a linear module

MKCS: pairs of (lm-coeff, lm-node) in this tuple
MKOR1: nodes are lin-modules to be or-ed together
MKAND1: nodes are condition units to be and-ed together
MKOR2: nodes are condition units to be or-ed together
MKEXCPT: two nodes follow: node-a node-b
MKEQUIV: two nodes follow: node-a <=> node-b
MKIMP: two nodes follow: node-a => node-b
MKAND2: the nodes are selectors to be and-ed together
MKVAR: start of selector. there are five nodes plus optional nodes:

[2]MKVAR
[3] node for the variable
[4] node for the relation (MKEQ,MKGT,MKLT,MKNE,MKGE,MKLE)
[5] node for reference type (MKREF0,MKREF1,MKREF2)
if MKREF0: one additional node follows in position [6]
MKALL: entire domain (*)
MKUNKN: unknown (?)
MKUNDEF: undefined ($)
MKNA: not-applicable (NA)
if MKREF1: one or more nodes follow denoting a list of nominal values
if MKREF2: one or more sets of node triples of the form
(low-value, high-value, weight) used for interval values and
weighted values of both interval and nominal type
if MKREF3: one or more sets of node quadruples of the form
(low-value, high-value, weight$_1$, weight$_2$) used for interval values and
weighted values of both interval and nominal type

MKFUNC1: the nodes in this tuple indicate a function reference
similar toMKVAR above, except that the node for the name of the
function is "floating", i.e. it contains no parse tree.
To evaluate such a node, the dictionary must be consulted.
The relation and reference nodes may both be omitted. If
either is required, both are present.
MKFUNC2: the node in this tuple indicates the general function
MKTRAP: the node in this tuple indicates a trap function
MKARGS: the nodes are arguments to MKFUNC1 above

APPENDIX B

GVL$_1$ Grammar

This appendix lists the GVL$_1$ grammar at the time of this writing. Its format is as input to the YACC compiler-compiler available on Berkeley UNIX.

```
%token LP RP LSB RSB LBR RBR MOD IMPASGN IMP RMIN NE TO
/*      (  )  [   ]    {   }    %    ::>     =>   /   <> .. */

%token OR PLUS MINUS TIMES DIV EQUIV LE GE RMAX EQ COLON
/*      v  +    -      *    /   <=>   <= >=  /   =   :    */

%token COMMA DOT EXCPT GT LT SEMI TRUE FALSE UNKN UNDEF
/*      ,     .         >  <   ;    T    F     ?    $   */

 %token ID VAR INT REAL RULES VARS FUNCS END IN NA

 %token NOMINAL INTERVAL STRUCTURE UNITS PROP TRAP

 %%


 file    →   block
           | file block


block    →   blk


blk      →   idnode RULES vardcl funcdcl optprops rulebody END
           | idnode VARS optprops varsbody END
           | idnode FUNCS vardcl optprops funcbody END
           | error


vardcl   →   VARS EQ ID SEMI


funcdcl  →   FUNCS EQ ID SEMI
```

```
                | ε


rulebody   →   rule
              | rulebody SEMI rule


varsbody   →   vardefn
              | varsbody SEMI vardefn


funcbody   →   funcdefn
              | funcbody SEMI funcdefn


rule   →   optidnode lmsnode IMPASGN  strength lmsnode optprops
         | error
         | ε


optidnode   →   ID
               | ε.


optprops   →   prop
              | optprops prop
              | ε


prop   →   PROP EQ ID  END


lmsnode   →   lms


lms   →   linearmodule
        | lms OR linearmodule


linearmodule   →   quantifier LP lmsnode RP
```

```
                  | Imparts


quantifier  →  LT optint idnode inset GT
              | ε


optint  →  INT
          | ε


inset  →  IN ref
         | ε


Imparts  →  Impart
           | Imparts PLUS Impart


Impart  →  LP Imparts RP
          | optreal optreal condstmt


optreal  →  realnode
           | ε


condstmt  →  condstmt condition
            | condstmt OR condition
            | condstmt EXCPT condition
            | condition


condition  →  term EQUIV term
             | term IMP term
             | term


term  →  LP condstmt RP
        |  selectors
        | TRUE
```

```
          | FALSE


selectors  →  selector
             | selectors selector


selector  →  LSB exprnode rel refgroup behavior wfunc RSB
            | exprnode


wfunc  →  exprnode
         | ε


optrelref  →  rel  refgroup
             | ε


rel  →  EQ
       | GT
       | LT
       | NE
       | GE
       | LE


refgroup  →  ref


ref  →  valunit
       | ref COMMA valunit
       | set weight
       | ref COMMA set weight
       | TIMES
       | UNKN
       | UNDEF
       | NA


valunit  →  exprnode   ddval weight
```

```
val  →  intnode
        | realnode
        | ID
        | varnode optargs
        | TRAP optargs


args  →  arg
        | args
       COMMA
       arg
        | ε


arg  →  exprnode


optargs  →  LP args RP
            | ε


ddval  →  TO  exprnode
          | ε


weight  →  COLON exprnode optexpr
           | ε


optexpr  →  exprnode
            | ε


set  →  LBR vals RBR


behavior  →  DIV
             | EXCPT
             | RMAX
             | RMIN
             | ε
```

```
vals     →  val
          | vals COMMA val
          | ε


exprnode  →  expr


expr     →  aterm
          | expr addop aterm


aterm     →  afactor
           | aterm mulop afactor


afactor    →  MINUS afactor
            | LP expr RP
            | val


addop     →  PLUS
           | MINUS


mulop     →  TIMES
           | DIV
           | MOD


strength    →  LP intrealnode COMMA intrealnode RP
             | LP intrealnode RP
             | ε


vardefn    →  idnode dfields optprops
            | ε


dfields    →  dfield
            | dfields dfield
```

```
dfield  →  dfieldpart


dfieldpart  →  NOMINAL EQ  LP idsunique RP
               | NOMINAL EQ  inttuple
               | INTERVAL EQ   intrealtuple TO intrealtuple
               | INTERVAL EQ   LP idsunique RP
               | STRUCTURE EQ  LP idsunique RP LP refines RP
               | UNITS EQ  idtuple


funcdefn  →  idnode var LP functab RP


functab   →  funcentry
            | functab funcentry


funcentry  →  idnode intrealnode intrealnode


var          →  varnode


refines  →  refinement
           | refines refinement


refinement  →    idtuple EQ LP ids RP


idsunique  →   idsu


idsu  →  idtu
        | idsu idtu


idtu  →  idintnode
```

```
idnode  →  ID


varnode  →  VAR


intnode  →  INT


realnode  →  REAL


intrealnode  →  intnode
             | realnode


idintnode  →  idnode
           | intnode


ids  →  idtuple
     | ids idtuple


idtuple  →  idnode


inttuple  →  intnode


intrealtuple  →  intrealnode
```

APPENDIX C

Internal Representation of a BABY Network

```
(NODES_TO_PROPAGATE ( ))
(DATA_SET ( ))
(PATTERNS (
   (DOWNWARD NEONATE_PATTERNS ) ))
(ASSERTIONLIST ( ))
(NEONATE_PATTERNS (
   (MKVALTUPLE BAAND 0.1e1 0.0 0.163184079 0.099950124e1 )
   (DOWNWARD SIADH EVIDENCE 0.7968e-8 0.1631 0.09995e1 )
   (DOWNWARD HYPONATREMIC EVIDENCE 0.0 0.8 0.1e1 )
   (DOWNWARD GLYCOSURIA EVIDENCE 0.0 0.8 0.1e1 )
   (DOWNWARD NORMAL_ADRENAL_FUNCTION EVIDENCE 0.0 0.8 0.1e1 )
   (DOWNWARD NORMAL_RENAL_FUNCTION EVIDENCE 0.0 0.8 0.1e1 )
   (ASSERT 0.85 ) ))
(NORMAL_RENAL_FUNCTION (
   (MKEXEC MKRULE u002 MKNULL 0.1e1 0.1e1 )
   (MKTVARS MKLHSV NRF )
   (UPWARD SIADH EVIDENCE )
   (UPWARD NEONATE_PATTERNS EVIDENCE )
   (MKVALTUPLE BARULE 0.8 0.0 0.8 0.1e1 )
   (ASSERT 0.95 ) ))
(NORMAL_ADRENAL_FUNCTION (
   (MKEXEC MKRULE u004 MKNULL 0.1e1 0.1e1 )
   (MKTVARS MKLHSV NAF )
   (UPWARD SIADH EVIDENCE )
   (UPWARD NEONATE_PATTERNS EVIDENCE )
   (MKVALTUPLE BARULE 0.8 0.0 0.8 0.1e1 )
   (ASSERT 0.99 ) ))
(GLYCOSURIA (
   (MKEXEC MKRULE u006 MKNULL 0.1e1 0.1e1 )
   (MKTVARS MKLHSV GLY )
   (UPWARD ba1 EVIDENCE )
   (UPWARD NEONATE_PATTERNS EVIDENCE )
   (MKVALTUPLE BARULE 0.8 0.0 0.8 0.1e1 )
   (ASSERT 0.1 ) ))
(HYPONATREMIC (
   (MKEXEC MKRULE u008 MKNULL 0.1e1 0.1e1 )
   (MKTVARS MKLHSV HYP )
   (UPWARD SIADH CONTEXT 0.75 )
   (UPWARD NEONATE_PATTERNS EVIDENCE )
   (MKVALTUPLE BARULE 0.8 0.0 0.8 0.1e1 )
```

```
    (ASSERT 0.5e-1 ) ))
(SIADH (
    (UPWARD NEONATE_PATTERNS EVIDENCE )
    (MKVALTUPLE BAYESIAN 0.8 0.79680e-8 0.16318 0.09995e1 )
    (DOWNWARD ba0 EVIDENCE 0.1e1 0.0999e-2 0.1e1 0.4875e-1 0.1e1 )
    (DOWNWARD NORMAL_ADRENAL_FUNCTION EVIDENCE 0.1e1 0.0999e-2
     0.0999e-2 0.1e1 0.1e1 )
    (DOWNWARD NORMAL_RENAL_FUNCTION EVIDENCE 0.1e1 0.0999e-2
     0.0999e-2 0.1e1 0.1e1 )
    (DOWNWARD HYPONATREMIC CONTEXT 0.501e3 0.19960e-2 0.19960e-2
     0.1e1 0.500999999e3 )
    (ASSERT 0.5e-1 ) ))
(ba0 (
    (UPWARD SIADH EVIDENCE )
    (MKVALTUPLE BAOR 0.1e1 0.1e1 0.199999999 0.1e1 )
    (DOWNWARD ba4 EVIDENCE 0.0 0.1 0.1e1 )
    (DOWNWARD ba3 EVIDENCE 0.0 0.1 0.1e1 )
    (DOWNWARD ba2 EVIDENCE 0.0 0.1 0.1e1 )
    (DOWNWARD ba1 CONTEXT 0.1e1 0.199999999 0.0 ) ))
(ba1 (
    (UPWARD ba0 CONTEXT 0.75 )
    (MKVALTUPLE BANOT 0.1e1 0.1e1 0.199999999 0.0 )
    (DOWNWARD GLYCOSURIA EVIDENCE 0.1e1 0.1e1 0.1e1 ) ))
(ba2 (
    (MKEXEC MKRULE u010 MKNULL 0.1e1 0.1e1 )
    (MKTVARS MKLHSV URINE_OSM )
    (UPWARD ba0 EVIDENCE )
    (MKVALTUPLE BARULE 0.1 0.0 0.1 0.1e1 0.8 ) ))
(ba3 (
    (MKEXEC MKRULE u012 MKNULL 0.1e1 0.1e1 )
    (MKTVARS MKLHSV URINE_OSM )
    (UPWARD ba0 EVIDENCE )
    (MKVALTUPLE BARULE 0.1 0.0 0.1 0.1e1 0.8 ) ))
(ba4 (
    (MKEXEC MKRULE u014 MKNULL 0.1e1 0.1e1 )
    (MKTVARS MKLHSV URINE_SG )
    (UPWARD ba0 EVIDENCE )
    (MKVALTUPLE BARULE 0.1 0.0 0.1 0.1e1 0.8 ) ))
(GLOBALS (
    (MKVARS NRF NAF HYP GLY SERUM_OSM URINE_OSM URINE_SG ) ))
(SERUM_OSM (
    (MKDOMAIN MKINTERVAL 1 1000 ) ))
(URINE_OSM (
    (MKDOMAIN MKINTERVAL 1 1000 ) ))
(URINE_SG (
    (MKDOMAIN MKINTERVAL 0.1e1 0.2e1 ) ))
(RULESET (
    (MKLHSV URINE_SG ba4 )
    (MKLHSV URINE_OSM ba2 ba3 )
    (MKEXEC MKRULES NORMAL_RENAL_FUNCTION NORMAL_ADRENAL_FUNCTION
     GLYCOSURIA HYPONATREMIC ba2 ba3 ba4 )
    (MKVARDCL GLOBALS ) ))
(u010  (
    (MKEXEC MKVAR URINE_OSM MKGT MKREF2
     SERUM_OSM SERUM_OSM 0.1 ) ))
(u012  (
    (MKEXEC MKVAR URINE_OSM MKGT MKREF2 300 300 0.9 ) ))
(u014  (
    (MKEXEC MKVAR URINE_SG MKGT MKREF2 0.101e1 0.101e1 0.8 ) ))
```