Explaining and Justifying Expert Consulting Programs

William R. Swartout

Laboratory for Computer Science
Massachusetts Institute of Technology[1]

Abstract

Traditional methods for explaining programs provide explanations by converting to English the code of the program or traces of the execution of that code While such methods can provide adequate explanations of what the program does or did, they typically cannot provide justifications of the code without resorting to canned-text explanations. That is, such systems cannot tell why what the system is doing is a reasonable thing to be doing. The problem is that the knowledge required to provide these justifications is needed only when the program is being written and does not appear in the code itself.

The XPLAIN system uses an automatic programmer to generate the consulting program by refinement from abstract goals. The automatic programmer uses a domain model, consisting of facts about the application domain, and a set of domain principles which drive the refinement process forward. By examining the refinement structure created by the automatic programmer it is possible to provide justifications of the code. This paper discusses the system described above and outlines additional advantages this approach has for explanation.

1. Introduction

To be acceptable, expert programs must be able to explain what they do and justify their actions in terms understandable to the user. Expert programs usually have some heuristic basis While these heuristics may provide good performance for most cases, there may be unusual cases where they produce erroneous results, or where the rationale for using them is faulty. If a user is suspicious of the advice he receives, he should be able to ask-for a description of the methods employed and the reasons for employing them. In addition, the scope of expert systems, like that of human experts, is often quite narrow. An explanation facility can help a user discover when a system is being pushed beyond the bounds of its expertise.

In the area of medical consultant programs[2] the need for explanation is particularly acute. In designing a consultant program, we must consider what sorts of capabilities we are trying to provide tor the physician user. If we consider the interaction between a physician and a human consultant, we realize that it is not just a simple oneway exchange where the physician provides data and the consultant provides an answer in the form of a prescription or diagnosis. Rather, there is typically a lively dialog between the two. The physician may question whether some factor was considered or what effect a particular finding had on the final outcome. Viewed in this light, we realize that a computer program which only collects data and provides a final answer will not be found acceptable by most physicians. In addition to providing diagnoses or prescriptions, a consultant program must be able to explain what it's doing and justify why it's doing it.

Researchers have recognized this, and many proposals for new expert systems have at least mentioned the need for explanation. Some systems have actually provided an explanatory facility. Yet existing approaches to explanation fail in some important ways. This paper will document these failings and describe an approach toward their solution.

While we have concentrated on the problem of providing explanations to medical personnel, we do not feel that the need for explanation is limited to medicine nor that the techniques we have developed for explanation and justification are limited to medical applications. Medical programs provide a good testbed for the general problem of explaining a consulting program to the audience it is intended to serve.

The next section will describe the Digitalis Therapy Advisor, the program we have chosen as a testbed for our ideas about explanation, and some of the medical aspects of digitalis therapy. After that, we will describe some of the problems with previous explanation systems and the approach we have taken to overcome those problems.

2. Digitalis Therapy and the Digitalis Advisor

The digitalis glycosides are a group of drugs that were originally derived from the foxglove, a common flowering plant. Their principal effect is to strengthen and stabilize the heartbeat. In current practice, digitalis is prescribed chiefly to patients who show signs of congestive heart failure (CHF) and/or conduction disturbances of the heart. Congestive heart failure refers to the inability of the heart to provide the body with an adequate blood

[1] Author's current address USC/Information Sciences Institute. This research was supported (in part) by the National Institutes of Health Grant No 1 P01 LM 03374-01 from the National Library of Medicine The author wishes to express his thanks to Peter Szolovits for his insightful comments and suggestions during the course of this research

[2] Some medical consultant programs include MYCIN—a program that aids physicians with antimicrobial therapy [Shortliffe76], INTERNIST—a program that makes diagnoses in internal medicine [Pople77] and PIP—a program that makes diagnoses primarily in the area of renal disease [Pauker76]

flow This condition causes fluid to accumulate in the lungs and outer extremities and it is this aspect that gives rise to the term "congestive". Digitalis is useful in treating this condition, because it increases the contractility of the heart, making it a more effective pump A conduction disturbance appears as an arrhythmia, which is an unsteady or abnormally paced heartbeat. Digitalis tends to slow the conduction of electrical impulses through the conduction system of the heart, and thus steady certain types of arrhythmias. Due to the positive effect that digitalis has on the heart, it is one of the most commonly used drugs in the United States.

Like many other drugs, digitalis can also be a poison if too much is administered For a variety of reasons, including a small therapeutic window, subtle signs of toxicity, and high interpatient variability, digitalis is difficult to administer One complication the physician must deal with is the possibility that his patient may be more sensitive to the drug (for whatever reason) than the average patient If a physician knows those factors that make a patient more sensitive he can reduce the likelihood of overdosing (or underdosing) the patient by adjusting the dose depending on whether he observes the sensitizing factors or not.

Over the years, a number of factors have been identified that increase the automaticity of the heart.[3] These include, a low level of serum potassium (hypokalemia), a high level of serum calcium (hypercalcemia), damage to the heart muscle (cardiomyopathy), and a recent myocardial infarction (among others). When these exist in conjunction with digitalis administration, the automaticity can be increased substantially. We will concentrate on just the first three in this paper.[4]

2.1 The Digitalis Therapy Advisor Testbed

A few years ago, a Digitalis Therapy Advisor was developed at MIT by Pauker, Silverman, and Gorry [Silverman75, Gorry78). This program was later revised and given a preliminary explanatory capability [Swartout77]. The limitations of these explanations (and of those produced by similar techniques) will be discussed below. This program differed from earlier digitalis advisors [Peck73. Jelliffe70, Jelliffe72, Sheiner72] in two important respects. First, when formulating dosage schedules, it anticipated possible toxicity by taking into account the factors that increased digitalis sensitivity and reduced the dose when those factors were present. Second, the program made assessments of the toxic and therapeutic effects which actually occurred in the patient after receiving digitalis to formulate subsequent dosage recommendations. This program worked in an interactive fashion The program would ask the physician for data about the patient and produce recommendations after that data was entered. When the dose of digitalis was being adjusted, the physician was asked to consult with the program again to assess the patients response This is the program we used as a testbed for our work in explanation and justification In the remainder of the paper, we will refer to this program as the "old Digitalis Advisor"

3. Kinds of Questions

In the spring of 1979, we conducted a series of informal trials in an attempt to discover what kinds of questions occurred to medical personnel as they ran the Digitalis Advisor In this trial, medical students and fellows were asked to run the program and ask questions (verbally) as they occurred to them. The author attempted to answer these questions. The interactions were tape recorded and later transcribed.

No formal analysis of the data was attempted, but examination of the transcripts did provide an indication of types of questions that might arise while running a consulting program

These included:

1 Questions about the methods the program employed:

> *User: "How do you calculate your body store goaP That's a little lower than I anticipated."*

This sort of question could be answered by the explanation routines of the old Digitalis Advisor. It can also be answered by the system presented in this paper.

2. Justifications of the program's actions:

> *User: (peruses recommendations) "Why do we want to make a temporary reduction?*
>
> *Author: "We're anticipating surgery coming up and surgery, even non-cardiac surgery, can cause increased sensitivity to digitalis, so it wants to temporarily reduce the level of digitalis "*

This is exactly the sort of question we are concentrating on in this paper

3. Questions involving confusion about the meaning of terms:

```
IS THE RENAL FUNCTION STABLE''
THE POSSIBILITIES ARE:
    1. STABLE
    2  UNSTABLE
ENTER SINGLE VALUE = = = =>
```

> *User: "now this question...I'm not really sure...'renal function stable' does it mean stable abnormally or...because I mean, the patient's renal function is not normal but it's stable at the present time. "*
>
> *Author "That's what it means"*

This paper will not address this last type of question.

[3] In the normal heart, there is a place in the left atrium called the sinoatrial (SA) node, which sets the pace for the heart Under the right circumstances, other pans of the heart can take over the pace setting function Sometimes this can be life-saving if. tor example, the SA node is damaged But at other times it can be life-threatening, since several pace-makers operating simultaneously tend to increase the likelihood of setting up s dangerous arrhythmia When we say that digitalis increases the automaticity of the heart, we mean that digitalis increases the tendency of other parts of the heart to take over the pace-setting function from the SA node

[4] The XPLAIN system currently only knows about the first three factors, although it would not be particularly difficult to expand it to cover the others

4. Previous Approaches to Explanation

A number of different approaches have been taken to attempt to provide programs with an explanatory capability. The major approaches include using 1) previously prepared text to provide explanations and 2) producing explanations directly from the computer code and traces of its execution

The simplest way to get a computer to answer questions about what it is doing is to anticipate the questions and store the answers as English text. Only the text that has been stored can be displayed. This is called *canned text,* and explanations produced by displaying canned text are called canned explanations. The simplest sorts of canned explanations are error messages. For example, a medical program designed to treat adults might print the following message if someone tried to use it to treat an infant:

```
THE PATIENT IS TOO YOUNG TO BE TREATED BY THIS
PROGRAM.
```

It is relatively easy to get a small program to provide English explanations of its activity using this canned text approach. After the program is written, canned text is associated with each part of the program explaining what that part of the program is doing. When the user wants to know what's going on, the computer merely displays the text associated with what it's doing at the moment.

There are several problems with the canned text approach to explanation The fact that the program code and the text strings that explain that code can be changed independently makes it difficult to guarantee consistency between what the program does and what it claims to do. Another problem with the canned text approach is that all questions and answers must be anticipated in advance and the programmer must provide answers for all the questions that the user might ask. For large systems, that is a nearly impossible task Finally, the system has no conceptual model of what it is saying That is, to the computer, one text string looks much like any other, regardless of the content of that string. Thus, it is difficult to use this approach if we want our system to provide more advanced sorts of explanations such as suggesting analogies or giving explanations at different levels of abstraction.

```
TO CHECK SENSITIVITY DUE TO CALCIUM I DO THE
FOLLOWING STEPS:

1. I DO ONE OF THE FOLLOWING:

   1.1 IF EITHER THE LEVEL OF SERUM CALCIUM IS
   GREATER THAN 10 OR INTRAVENOUS CALCIUM IS GIVEN
   THEN I DO THE FOLLOWING SUBSTEPS.

      1.1.1 I SET THE FACTOR OF REDUCTION DUE TO
      HYPERCALCEMIA TO 0.75.

      1.1.21 ADD HYPERCALCEMIA TO THE REASONS OF
      REDUCTION.

   1.2 OTHERWISE, I REMOVE HYPERCALCEMIA FROM THE
   REASONS OF REDUCTION AND SET THE FACTOR OF
   REDUCTION DUE TO HYPERCALCEMIA TO 1.00.
```

Fig. 1. Explanation of How the System Checks Hypercalcemia

Another approach to explanation is to produce explanations directly from the program [Davis76, Shortliffe76, Swartout77, Wmograd71). That is, the explanation routines examine the program that is executed. Then by performing relatively simple transformations on the code these explanation routines can produce explanations of how the system does things. For example, the old Digitalis Advisor could examine the code it used to check for increased digitalis sensitivity caused by increased serum calcium and produce an explanation of what that code did (as shown in Figure 1).

The Digitalis Advisor, like most similar systems, also maintains an execution trace The trace can be examined by the explanation routines to tell what the system did for a particular patient Figure 2 describes how the system checked for myxedema. The system also has a limited ability to explain why it is asking the user a question Figure 3 shows the system's response when the user wants to know why he is being asked about serum calcium.

Since the explanation routines only perform simple transformations on the program code, the quality of the explanations produced in this manner depends to a great degree on how the system code is written. In particular, the basic structure of the program is not altered significantly, and the names of variables in the explanation are basically the same as those in the program. If the explanations are to be understandable, the expert system must be written so that its structure is easily understood by anyone familiar with its domain of expertise, and the variable and procedure names used in the program must represent concepts which are meaningful to the user.

```
I CHECKED SENSITIVITY DUE TO THYROID FUNCTION BY
EXECUTING THE FOLLOWING STEPS:

1. I ASKED THE USER THE STATUS OF MYXEDEMA. THE USER
RESPONDED THAT THE STATUS OF MYXEDEMA WAS
PRESENT.

2. SINCE THE STATUS OF MYXEDEMA WAS PRESENT I DID THE
FOLLOWING:

   2.1 I ADDED MYXEDEMA TO THE PRESENT AND
   CORRECTABLE CONDITIONS. THE PRESENT AND
   CORRECTABLE CONDITIONS THEN BECAME MYXEDEMA.

   2.2 I REMOVED MYXEDEMA FROM THE DEGRADABLE
   CONDITIONS  THE DEGRADABLE CONDITIONS THEN
   BECAME HYPOKALEMIA, HYPOXEMIA,
   CARDIOMYOPATHIES-MI, AND POTENTIAL POTASSIUM
   LOSS DUE TO DIURETICS

   2 3 I SET THE FACTOR OF REDUCTION DUE TO MYXEDEMA
   TO 0.67. THE FACTOR OF REDUCTION DUE TO MYXEDEMA
   WAS PREVIOUSLY UNDETERMINED.

   2.4 I ADDED MYXEDEMA TO THE REASONS OF
   REDUCTION. THE REASONS OF REDUCTION THEN
   BECAME MYXEDEMA
```

Fig. 2. Explaining How Thyroid Function Was Checked

```
WHAT IS THE LEVEL OF SERUM CALCIUM?

ENTER NUMERICAL VALUE = = = => why? (The user types
"why?" indicating that he questions why he is being asked to
supply the value of serum potassium.)

MY TOP GOAL IS TO BEGIN THERAPY. ONE STEP IN DOING
THAT IS TO CHECK SENSITIVITIES. I AM NOW TRYING TO
CHECK SENSITIVITY DUE TO CALCIUM.
```

Fig. 3. Telling Why a Question is Asked

This method of producing explanations has some advantages It is relatively simple. If the right way of structuring the problem can be found, it does not impose too great a burden on the programmer; since the explanations reflect the code directly, consistency between explanation and code is assured.

Despite these advantages, there are some serious problems with this technique It may be difficult or impossible to structure the program so that the user can easily understand it. The fact that every operation performed by the computer must be explicitly spelled out sometimes forces the programmer to program operations which a physician would perform without thinking about them. That problem is illustrated in Figure 2. Steps 2.1, 2.2, and 2.4 are somewhat mystifying. In fact, these steps are needed by the system so that it can record what sensitivities the patient had that made him more likely to develop digitalis toxicity. These steps are involved more with record keeping than with medical reasoning, but they must appear in the code so that the computer will remember why it made a reduction. Since they appear in the code, they are described by the explanation routines, although they are more likely to confuse a physician user than enlighten him. An additional problem is that it is difficult to get an overview of what is really going on here. While the system is explicit about record keeping, it is not very explicit about the fact that it is going to reduce the dose, though it hints at a reduction by saying that the "factor of reduction" is being set to 0.67.

An additional problem, and the primary one we will address in this paper is that while this way of giving explanations can state *what* the system does or did, it can't state *why* the system did what it did. That is, the system can't give justifications for its actions In the explanations given above the system can't state that it reduces the dose because increased calcium causes increased automaticity The information needed to justify the program is the information that was used by the programmer to write the program, but it does not have to be incorporated into the program for the program to perform successfully—just as one can successfully bake a cake without knowing why baking powder appears in the recipe. Since it is desirable for expert programs to be able to justify what they do as well as do it successfully, we need to find a way of capturing the knowledge and decisions that went into writing the program in the first place The remainder of this report will describe recent efforts we have made toward achieving that goal in the context of the Digitalis Therapy Advisor.[6]

5. Providing Justifications

We need a way of capturing the knowledge and decisions that went into writing the program. One way to do this is to give the computer enough knowledge so that it can write the program itself and remember what it did. This notion of automatic programming has been researched considerably [Balzer77, Barstow77, Green79, Long77, Manna77] and is not a new idea. Using an automatic programmer to help in producing explanations is a new idea. Since we are primarily interested in explanation, we have chosen not to deal with a number of problems that arise in automatic programming, including: choosing between different implementations, backup and recovery from dead end refinements, and optimization.

5.1 System Overview

An overview of the XPLAIN system is given in Figure 4. The system has five parts a Writer, a Domain Model, a set of Domain Principles, an English Generator, and a Refinement Structure. The Writer is an automatic programmer It wrote new code which captured the functionality of major portions of the old Digitalis Advisor[6] The Domain Model and the Domain Principles contain knowledge about the domain of expertise. Thus, in this case, they contain information about digitalis and digitalis therapy They provide the Writer with the knowledge it needs to write the code for the Digitalis Advisor The Refinement Structure can be thought of as a trace left behind by the Writer. It shows how the Writer develops the Digitalis Advisor When a physician user runs the Digitalis Advisor, he can ask the system to justify why the program is doing what it is doing. The Generator gives him an answer by examining the Refinement Structure and the step of the Advisor currently being executed. If we wanted to write a new program covering a new medical domain, we would have to change the Domain Model and the Domain Principles, but we should not have to change the Writer or the English Generator.[7]

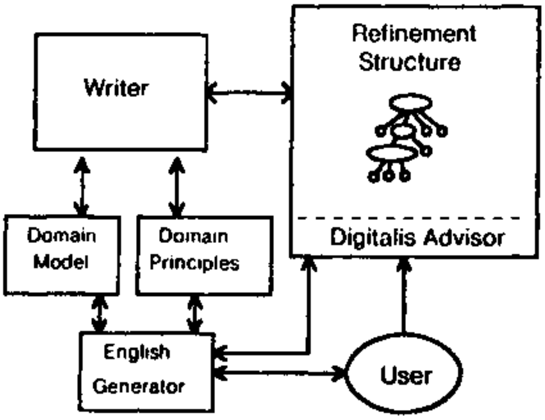


Fig. 4. System Overview

[5] [Clancey79] notes that even in rule-based systems, knowledge is often too "compiled" resulting in explanation problems very similar to the ones described here

[6] The code that has been written includes code to anticipate toxicities and to check for and assess various types of toxicities that may occur. As is discussed in [Swartout81], it should not be too difficult to complete the remainder of the implementation so that the functionality of the old Digitalis Therapy Advisor is completely captured

[7] Note that the Writer writes the program once, and once written, the program is static It is not written "on the fly" during interaction with the user/physician

The Refinement Structure is created by the Writer from the top level goal (in this case Administer Digitalis) as it writes the Digitalis Advisor. The Refinement Structure is a tree of goals, each being a refinement of the one above it in the tree (see Figure 5). By "refining a goal" we mean taking a goal and turning it into more specific subgoals Looking at Figure 5, we see that the top of the tree is a very abstract goal, in this case, Administer Digitalis. This goal is refined into less abstract steps by the Writer. These more specific steps are steps the system executes to administer digitalis. For example, one such step is to Anticipate Toxicity, that is, to anticipate whether the patient may become toxic due to increased digitalis sensitivity. The writer then refines this more specific goal to a still more specific goal. Eventually, the level of system primitives is reached. System primitives are operations which are built-in. Normally they are very basic, simple operations, so the fact that they cannot be explained is usually not a problem. Typical primitives include those that perform arithmetic operations like PLUS and TIMES and those that set variables to a particular value. The leaves of the refinement structure constitute the basic operations performed by the Digitalis Advisor, the program that we wanted the automatic programmer to produce

The Domain Model is a model of the facts of the domain. In this case, it is a model of the causal relationships in digitalis therapy. A simplified portion of the model is shown in Figure 6 In this model, the boxes are states, and the arrows represent causality. This model shows some of the effects of increased digitalis. It also shows that increased serum Ca and decreased serum K can each cause increased automaticity These facts correspond to the sorts of facts that a medical student learns in class during the first two years of medical school. These facts are static. That is, they have no notion of process. The model says that increased digitalis can cause a change to ventricular fibrillation but it doesn't say what to do about it. Medical students go to medical school for an additional two years and acquire these procedures by observing more experienced personnel as they practice medicine on the wards. The set of Domain Principles provides the Writer with this sort of procedural knowledge.

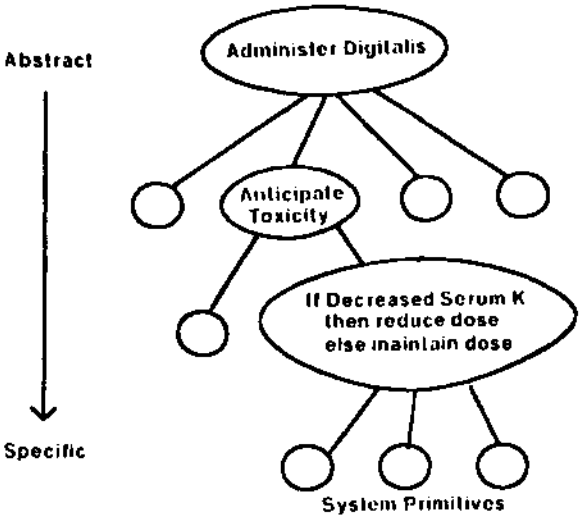


Fig. 5. Refinement Structure

Domain Principles tell the Writer how something (such as prescribing a drug or analyzing symptoms) should be done. They guide it as it refines abstract goals to more specific ones A (somewhat simplified) Domain Principle appears in Figure 7.[B] This particular Principle helps the writer in anticipating digitalis toxicity. It represents the common sense notion that if one is considering administering a drug, and there is some factor that enhances the deleterious effects of that drug, then if that factor is present in the patient, less drug should be given. This principle has three parts: a Goal, a Domain Rationale, and a Prototype Method.

The goal tells the Writer what it is that the Principle can help it do. In this case, the Principle can help the Writer in anticipating toxicity. The Domain Rationale is a pattern which is matched against the Domain Model to see where it is appropriate to achieve the goal. In the example, the system will look in the Domain Model to match a finding (e.g. increased Ca) which causes some sort of a dangerous deviation (e.g. change to ventricular fibrillation) which is also caused by an increased level of the drug. By looking at the Domain Model, we can see both increased Ca and decreased K will match as findings, since both can cause a change to ventricular fibrillation.

The Prototype Method is an abstract method which tells the system how to accomplish the goal. Once the Domain Rationale has been matched, the Prototype Method is instantiated for each match of the Domain Rationale. When we say that we instantiate the Prototype Method, that means that we create a new structure where the variables in the Prototype Method have been replaced by the things they matched. In this case, two structures would be created. In the first, finding would be replaced by increased serum Ca and drug would be replaced by digitalis. In the second, finding would be replaced by decreased serum K and drug would again be replaced by digitalis. Note that now, with these new structures, we have changed the single abstract problem of how to anticipate toxicity into several more specific ones, such as how to determine whether increased serum K exists, how to reduce the dose, and how to maintain it.

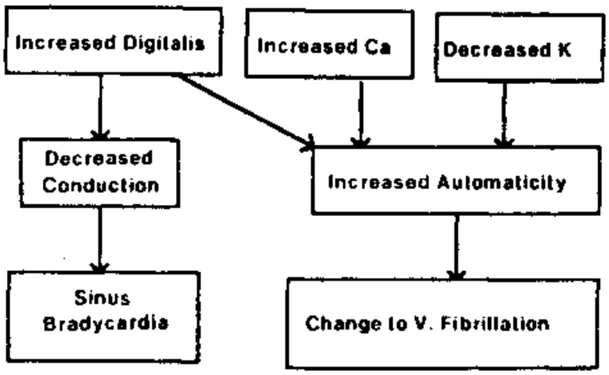


Fig. 6. Domain Model

[8] Domain Principles are composed of variables and constants Variables appear in boldface in Figure 7 When the writer is matching, a variable in a pattern will match anything which is of the same kind as itself Thus, the variable finding would match increased serum-Ca or decreased K, since increased serum-Ca and decreased K are both kinds of findings

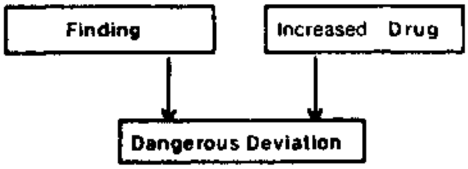
After instantiation, the more specific goals of the Prototype Method are placed in the Refinement Structure as sons of the goal being resolved. If we look at Figure 5, we can see that the instantiated Prototype Method that checks for decreased serum K has been placed below the Anticipate Toxicity goal Once they have been placed in the Refinement Structure, the newly instantiated goals become goals for the writer to resolve For example, after the Writer applied this Domain Principle, it would have to find ways of determining whether increased calcium existed in the patient, whether decreased potassium existed, and ways of reducing and maintaining the dose. The system continues in this fashion, refining goals at the bottom of the structure and growing the tree down and down until eventually the level of system primitives is reached.

The system must also take into account interactions between the actions it takes. For example, while the individual instantiations above say that if increased serum calcium exists the dose should be reduced, and if decreased serum potassium exists the dose should be reduced, but they don't give any indication ot what should happen if *both* increased calcium *and* decreased serum potassium co-occur. Exactly what should happen depends on the characteristics of the domain. It could be that the occurance of either sensitivity "covers" for the other, so that only one reduction should be made and the predicate of the IF should be made into a disjunction. Or, (as is actually the case), it could be that when multiple sensitivities appear, multiple reductions should be made. The way to resolve that is to serialize these two program fragments, connecting the outputs of the first to the inputs of the second. The automatic programmer handles this situation by setting it up as something to be refined. The domain principle used in the refinement of this problem may further constrain the way in which other goals may be refined. The details of this operation will not be presented here. The interested reader should see [Swartout8i].

Once the refinement process is complete, we have a working expert system. A sample interaction with the system is given in Figure 8. The first sentence of the explanation was produced by stating the higher goal (that is, anticipate toxicity) Next, the explanation routines located the Domain Principle which caused the step *in* question to appear in the program. The domain rationale associated with that principle was then converted to English (with pattern variables replaced by the facts in the Domain Model they matched). That step produced the next two sentences of the explanation The last sentence is just the instantiated version of the Prototype Method of the Domain Principle These explanations should be compared with those presented in Figure 3 to appreciate the improvement that is possible with this approach (The generation routines are described in detail in [Swartout8l]).

Goal Anticipate Drug Toxicity

Domain Rationale:



Prototype Method:

If the Finding exists
then: reduce the drug dose
else: maintain the drug dose

Fig. 7. An Example of a Domain Principle

5.2 Explanations of Domain Principles

In the original version of the Digitalis Advisor, when we wanted to give a more abstract view of what was going on. we just described a higher level procedure [Swartout77] In this regard we were following the principles of structured programming While this approach often gave reasonable explanations, there were times when it was considerably less than illuminating The general method for anticipating digitalis toxicity was called "Check Sensitivities" in the old version of the Digitalis Advisor. An explanation of it appears in Figure 9. While this explanation does tell the user what sensitivities are being checked,[9] it does not say what will be done if sensitivities are discovered nor does it say why the system considers these particular factors to be sensitivities Finally, it is much too redundant and verbose The first objection can be dealt with by removing the calls to lower procedures and substituting the code of those procedures inline This results in the somewhat improved explanation produced by XPLAIN when it

```
Please enter the value of serum-k: why?

The system is anticipating digitalis toxicity. Decreased serum-k causes
increased automaticity. which may cause a change to ventricular
fibrillation. Increased digitalis also causes increased automating.
Thus, if the system observes decreased serum-k. it reduces the dose of
digitalis due to decreased serum-k.

Please enter the value of serum-k: 3.7

Please enter the value of serum-ca: why?
```

(The system produces a shortened explanation, reflecting the fact that it has already explained several ot the causal relationships in the previous explanation Also, since the system remembers that it has already told the user about serum K, it suggests the analogy between the two here)

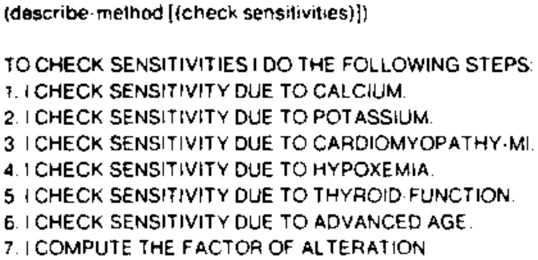
```
The system is anticipating digitalis toxicity. Increased serum-ca also
causes increased automating. Thus, (as with decreased serum-k) if the
system observes increased serum-ca, it reduces the dose of digitalis due
to increased seruni-ea.Please enter the value of serum-ca: 9
```

Fig. 8. A Sample Interaction Providing Justifications

[9] The reader may notice that there were more sensitivities checked in the original version of the program than in the current version We now feel that some of these. such as thyroid function and advanced age. should not be treated as sensitivities per se because they tend to have an effect on reducing renal function and hence slowing excretion. rather than on increasing sensitivity to digitalis The other sensitivities would be easy to add by including the appropriate causal links in the domain model

is asked to describe the method for anticipating digitalis toxicity (see Figure 10) However, while this explanation shows what the system does, it doesn't say why things like increased calcium, cardiomyopathy and decreased potassium are sensitivities, and if anything, it is even more verbose than the original explanation

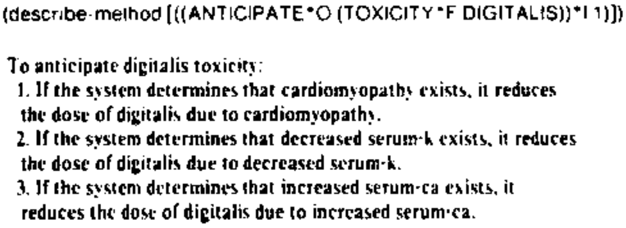
The reason we can't get the sorts of explanations we want by producing explanations directly form the code is that much of the sort of reasoning we want to explain has been "compiled out." Thus, we are forced into explaining at a level that is either too abstract or too specific The intermediate reasoning which we would like to explain was done by a human programmer in the case of the old Digitalis Advisor However, because this performance program was produced by an automatic programmer, that reasoning is available in the domain principle. For example, if we were to use the English generator to explain the domain principle that produced the code for anticipating digitalis toxicity rather than the code itself we would get the explanation that appears in Figure 11. Thus, the use of an automatic programmer not only allows us to justify the performance program, but it also allows us to give better descriptions of methods by making available intermediate levels of abstraction which were not previously available.



```
(describe-method [(check sensitivities)])

TO CHECK SENSITIVITIES I DO THE FOLLOWING STEPS:
1. I CHECK SENSITIVITY DUE TO CALCIUM.
2. I CHECK SENSITIVITY DUE TO POTASSIUM.
3  I CHECK SENSITIVITY DUE TO CARDIOMYOPATHY-MI.
4. I CHECK SENSITIVITY DUE TO HYPOXEMIA.
5  I CHECK SENSITIVITY DUE TO THYROID-FUNCTION.
6. I CHECK SENSITIVITY DUE TO ADVANCED AGE.
7. I COMPUTE THE FACTOR OF ALTERATION
```

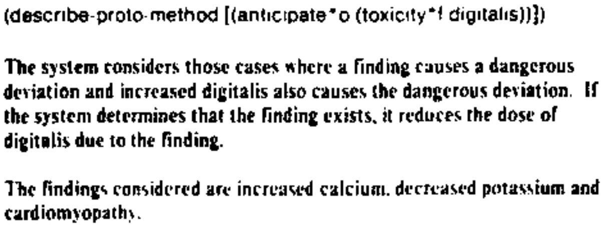
Fig. 9. An Explanation From the Old Digitalis Therapy Advisor



```
(describe-method [((ANTICIPATE*O (TOXICITY*F DIGITALIS))*I 1)])

To anticipate digitalis toxicity:
 1. If the system determines that cardiomyopathy exists, it reduces
  the dose of digitalis due to cardiomyopathy.
 2. If the system determines that decreased serum-k exists, it reduces
  the dose of digitalis due to decreased serum-k.
 3. If the system determines that increased serum-ca exists, it
  reduces the dose of digitalis due to increased serum-ca.
```

Fig. 10. An Explanation From the Code for Anticipating Toxicity



```
(describe-proto-method [(anticipate*o (toxicity*f digitalis))])

The system considers those cases where a finding causes a dangerous
deviation and increased digitalis also causes the dangerous deviation.  If
the system determines that the finding exists, it reduces the dose of
digitalis due to the finding.

The findings considered are increased calcium, decreased potassium and
cardiomyopathy.
```

Fig. 11. Explanation of a Domain Principle

6. Is Automatic Programming Too Hard?

One possible objection to the whole approach to explanation advocated in this paper is that it is just too hard to get an automatic programmer to write the performance program. When I first began this research, I thought that was the case. The original plan for producing better explanations was to create structures detailing the development of the performance program, but these structures would be created by hand rather than automatically It was feared that automatic programming was just too hard However, as the research progressed, it became clear that if we had sufficiently powerful representations available so that it could be said that explanations were being produced from an understanding of the program, then actually writing the program automatically wouldn't be all that much more difficult. I suspect this is true in general It seems that the primary difficulty in both explanation and automatic programming is a knowledge representation problem, and that the kinds of knowledge to be represented in both cases are similar so that a solution to one case makes the other much easier However, it must be pointed out that the field of automatic programming is still an active research area and a number of difficult problems remain to be solved in addition to the knowledge representation problem so this conjecture still awaits a final resolution.

7. A Summary of Major Points

First, we have argued that to be acceptable, consultant programs must be able to explain what they do and why. Second, we have described the various ways that traditional approaches fail to provide adequate explanations and justifications Major failings include: 1) the inability of such approaches to justify what the system is doing because the knowledge required to produce justifications is not represented within the system, and 2) a lack of distinction between steps required just to get the computer-based implementation to work, and those that are motivated by the application domain. Third, we have outlined an approach which captures the knowledge necessary to improve explanations This involves using an automatic programmer to generate the performance program As the program is generated, a refinement structure is created which gives the explanation routines access to decisions made during the creation of the program. The improvement in explanatory capabilities that is achieved is due more to the availability of this refinement structure than to the use of more sophisticated English generation functions, since the explanation routines used in this paper do not differ greatly from those used in the old Digitalis Advisor.

8. References

[Barstow77] Barstow, D., "A Knowledge-Based System for Automatic Program Construction," Proceedings of the Fifth International Conference on Artificial Intelligence, 1977

[Ba!zer77] Balzer, R., Goldman, N., Wile, D., "Informality in Program Specificatioos," Proceedings of the Fifth International Conference on Artificial Intelligence, 1977

[Clancey79] Clancey, W.J., "Transfer of Rule-based Expertise Through a Tutorial Dialogue", Stanford University, Department of Computer Science, STAN-CS-79-769.1979

[Davis76] Davis, R., "Applications of Meta Level Knowledge to the Construction, Maintenance and Use of Large Knowledge Bases," PhD thesis, Stanford Artificial Intelligence Laboratory Memo 283(1976).

[Gorry78] Gorry, G. A., Silverman, H.. and Pauker, S. G., Capturing Clinical Expertise: A Computer Program that Considers Clinical Responses to Digitalis, *American Journal of Medicine* 64:452-460. (March 1978).

[Green79] Green, C.C., Gabriel, R.P., Kant, E , Kedzierski, B.I.. McCune, B.P., Phillips, J.V., Tappel, ST., Westfold, S.J., "Results In Knowledge Based Program Synthesis," Proceedings of the Sixth International Joint Conference on Artificial Intelligence, 1979

[Jelliffe70] Jelliffe R.W., Buell J., Kaiaba R. et al, "A Computer Program for Digitalis Dosage Regimens," Math. Biosci. 9:179-193, 1970

[Je!liffe72] Jelliffe R.W., Buell J, Kaiaba R, "Reduction of digitalis toxicity by computer-assisted glycoside dosage regimens," Ann Intern. Med. 77:891-906,1972

[Long77] Long, W.J., "A Program Writer," MIT Laboratory for Computer Science, TR-187,1977

[Manna77] Manna, 2., Waldinger, R., "The Automatic Synthesis of Systems of Recursive Programs," Proceedings of the Fifth International Conference on Artificial Intelligence, 1977

[Peck73] Peck C.C., Shemer L.B. et al: "Computer-assisted Digoxin Therapy," *New England Journal of Medicine* 289:441-446. 1973.

[Pauker76] Pauker, S G . Gorry, G.A.. Kassirer, J P., and Schwartz. W.B., "Toward the Simulation of Clinical Cognition: Taking a Present Illness by Computer," The American Journal of Medicine 60:981 995 (June 1976)

[Pople77] Pople, HE Jr., "The Formation of Composite Hypotheses in Diagnostic Problem Solving, an Exercise in Synthetic Reasoning," Proceedings of the Fifth International Joint Conference on Artificial Intelligence (1977).

[Sheiner72) Sheiner LB., Rosenberg B.. Melmon K., "Modelling of Individual Pharmacokinetics for Computer-aided Drug Dosage," *Compufers and Biomedical Research* 5:441 -459,1972

[Shortliffe76] Shortliffe, E.H., Computer Based Medical Consultations: MYCIN, Elsevier North Holland Inc. (1976)

[Silverman75] Silverman, H , "A Digitalis Therapy Advisor," MIT Project MAC TR 143, 1975

[Swartout77] Swartout, W.R., "A Digitalis Therapy Advisor with Explanations," *Proceedings of the Fifth International Joint Conference on Artificial Intelligence,* August 1977

[Swartout8l] Swartout, W.R., "Producing Explanations and Justifications of Expert Consulting Systems," MIT Laboratory for Computer Science Technical Report (in press)

[Winograd71] Winograd, T., "A Computer Program for Understanding Natural Language," MIT Artificial Intelligence Laboratory TR 17, 1971

REFERENCES

(1) "Periodical Title Abbreviations." ACM Computing Reviews. 19:8 (1978) 342-345.

[2) Chamiak, E. "A Framed PAINTING: The Representation of a Common Sense Knowledge Fragment." Cognitive Science 1:4 (1977) 355-394.

(3] American Psychological Association. Publications Manual. Washington, DC: American Psychological Association, 1974.

[4] Soloway, E. and Riseman, E. "Levels of Pattern Description in Learning." In Prpc. IJCAI-77. Cambridge, MA, August, 1977, 801-811.

[5] Schank, R., Kolodner, J., and DeJong, G. "Conceptual Information Retrieval", Technical Report 190, Computer Science Department, Yale University, New Haven, CT, 1978.