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CHAPTER 1

INTRODUCTION

Teaching most sciences is relatively straightforward. A concept is introduced and then an example or experiment is presented to demonstrate the concept in action. As a simple example, a physics instructor explains the concept of interference and then does an experiment in front of the class to demonstrate interference. Similar pedagogical techniques are employed in mathematics, engineering, chemistry, and other sciences. Techniques for teaching computer science, on the other hand, are still relatively new and often not effective, particularly in demonstrating new concepts in action.

The most common method of teaching programming concepts utilizes a blackboard or overhead projector where:

1) An algorithm is written down by hand;
2) The names of the variables, constants, and parameters used by the algorithm are written down separately by hand;
3) The instructor steps through the algorithm by hand showing how the variables and parameters change during program execution.

The purpose of this exercise is to teach students the dynamics, or semantics, of a program in action and to teach students how to do walkthroughs to verify their own program designs. There are, however, some serious flaws to this method of teaching program dynamics:

1) This method requires the instructor to simulate a computer by hand, a very error-prone process;
2) If the students take notes, they will generally find deciphering the dynamic flow of the algorithm later from their static notes impossible.

Another technique sometimes used for teaching program dynamics is to give a student a correct program that implements an algorithm. The student then must locate a computer or computer terminal, type in the program, compile the program, and then run the program. This method allows the student to enter and execute a correct program. Unfortunately, in order to benefit from this type of assignment, the student must be a somewhat sophisticated computer user to start with, which is certainly not the case with many beginning students. In particular, the student must have access to a computer, know how to use a text editor, and know how to compile and run a program. Even then, the compiled program will generally not give a dynamic display of the program in action, and no one is around to explain to the student what is happening.

What kind of system could be developed to solve the twin problems of teaching and learning program dynamics? Such a system should be usable by the instructor to demonstrate a new programming concept to an entire class in a clear, flexible, error-free, and repeatable manner. The same system should be available for student review at the student's leisure and be easy enough for a true novice to use without detailed knowledge. Some of the more important features of this system would be:

1) A comprehensive library of expertly constructed examples;
2) Forward and backward execution of program statements under user control;
3) Highlighting of statements being executed;
4) A clear display of variable and parameter values;
5) A clear delineation of the variables and parameters local to various procedures and functions.

A software system called DYNAMOD [Ross 88] was developed over a number of years to incorporate some of these features as an aid to teaching and learning programming. While it is still quite useful in this regard, both in the classroom and for individual student use, extensive experience with DYNAMOD has uncovered a number of deficiencies. It was therefore decided that a completely new approach to this problem was in order; this thesis represents a start on the solution. The primary contribution of this work is the design and definition of an "Education Machine", or E−machine. The E−machine is an abstract computer whose emulation on real computers will allow for the implementation of all of the desired features of the proposed new software system to replace DYNAMOD.

Chapter 2 contains a description of DYNAMOD, its advantages and limitations. Chapter 3 provides a description of the system proposed to succeed DYNAMOD. Chapter 4 is a review of relevant literature and a discussion of some existing systems that employ techniques similar to those to be incorporated into the new system. Chapter 5 contains the development and final design of the E−machine. Chapter 6 provides a number of examples of Pascal programs and demonstrates their translation into E−machine code. Finally, Chapter 7 describes new directions for the project. Chapters 1-4 contain background material essential to understanding the original work contained in Chapters 5-7.

CHAPTER 2

DYNAMOD

DYNAMOD stands for DYNamic Algorithm MODerator. DYNAMOD is a software system, the result of a pilot project that studied solutions to the problem of teaching and learning program execution dynamics. The first, primitive version was written by a deaf student to illustrate some concepts which were being presented in class (the student could not follow the discussions of the program walkthroughs, because the person signing to the student could not convey program dynamics along with the words of the lecture). This version inspired a formal test system called LOPLE (Library Of Programming Language Examples)[Rezvani 81],[Ross 81]. A grant from the Apple Education Foundation [Ross 80] led to the development of a more sophisticated version called LING [Ng 82-1,82-2]. A subsequent grant from the National Science Foundation [Ross 83] allowed LING to be completed and ported from Apple II+ microcomputers to other computers, including an Amdahl mainframe computer, a VAX minicomputer, and IBM PC and compatible microcomputers. The current version, which runs only on VAX and IBM PC and compatible microcomputers, is DYNAMOD Version 2.0 Release 2 [Ross 88].

DYNAMOD is simple for an instructor or student to use. It consists of a library of ready-to-run programs installed by an expert from which programs can be selected and executed under user control as many facets of program dynamics are displayed on the screen. Instructors can use DYNAMOD in the classroom with relatively little equipment. By utilizing a personal computer connected to a liquid crystal computer output display device and an overhead projector, the instructor can use DYNAMOD to illustrate programming concepts clearly and easily. Students can have their own disk containing DYNAMOD, which they can then use at their leisure to study concepts that are particularly difficult for them.

When DYNAMOD is started, the first thing displayed is a welcome screen, as shown in Figure 1. Option 1 enters the example library, option 2 displays an acknowledgement screen, option 3 displays an instructional manual, and option 4 explains the distribution system for obtaining copies of DYNAMOD. Normally the instructor or student types a 1 to enter the program library.

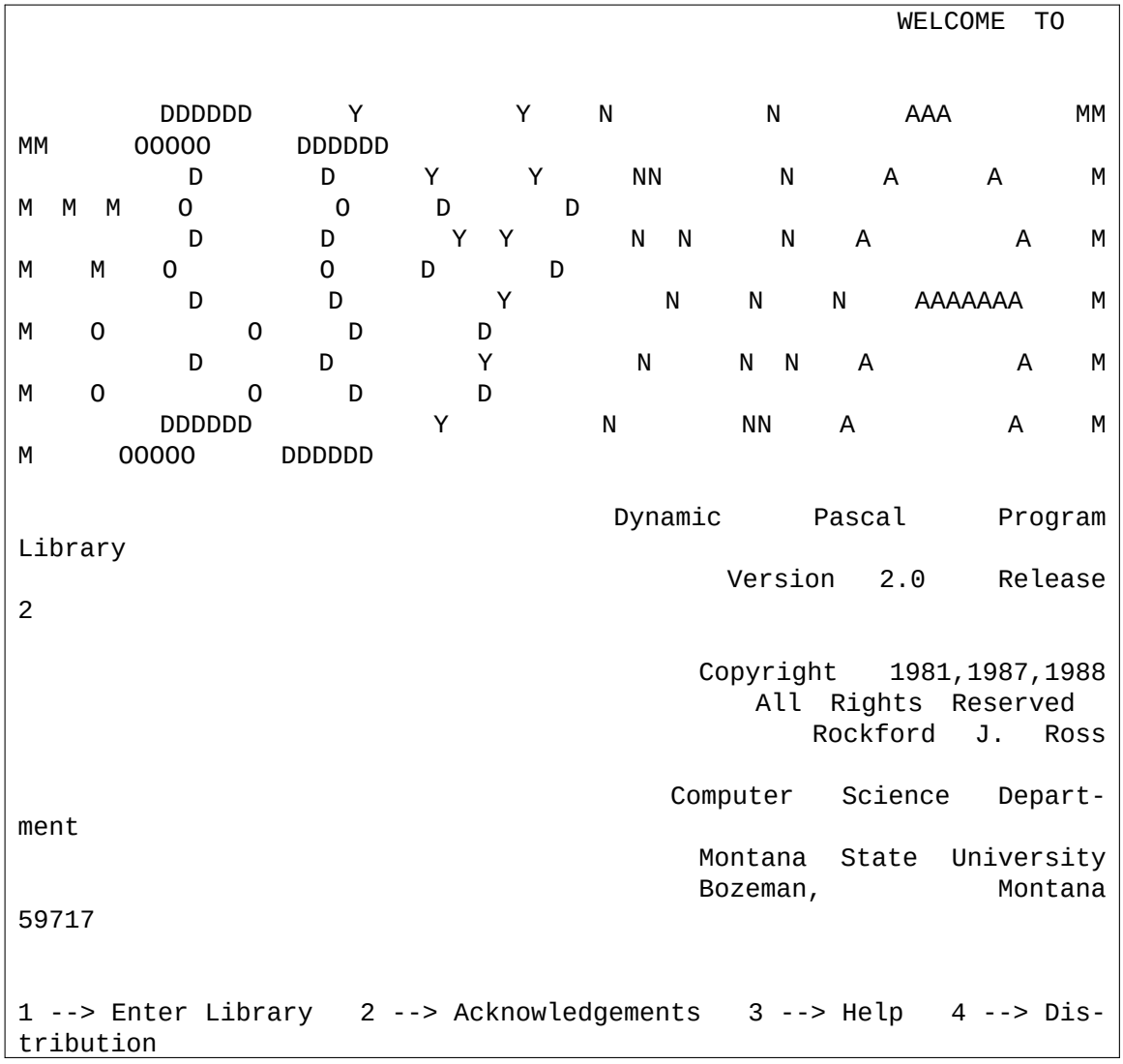


Figure 1
DYNAMOD Welcome Screen

After a 1 is typed to enter the program library, the screen of Figure 2 is displayed. In this new screen, option 1 exits DYNAMOD and returns control to the operating system. Option 2 refreshes the list of categories shown at the top of the screen. Option 3 lists the names of program examples indexed by a category; there are usually several examples which illustrate the same concept in slightly different ways. Option 4 also lists the names of program examples indexed by a category, but in addition, it includes a brief explanation of what each example program does. Finally, option 5 allows the user to execute an example.

```
array1d              array2d              assert                 boolean
bounds           case
char                   constant           div                    downto
else               elseif
for                    function           global                 header
if                   integer
loop               nesting          operator        parameter      pro-
cedure     readln
real                   record               recursion          repeat
search           sort
sqrt                   stats                summing              then
trailer          type
until              var                while             writeln




Select  1  of  the  following:

1)  QUIT
2)  Display  categories
3)  List  examples  in  a  category
4)  Extended  listing  of  examples  in  a  category
5)  Execute  an  example
```

Figure 2
DYNAMOD Library Screen

For example, suppose that after reviewing the program names indexed under category *recursion* the instructor or student wishes to review program *fact*. Typing a 5 causes DYNAMOD to prompt for the program name, at which point *fact* is typed by the user, resulting in the screen of Figure 3. On this screen, the symbol => indicates the line currently being executed. The Statement Count is the number of lines that have been executed so far. The area on the right of the screen bordered by dashed lines will contain the display of the program memory (at this point, no memory is in use since the *var* statement has not yet been executed). Finally, the 5 at the bottom left part of the screen is the input that the program will use.

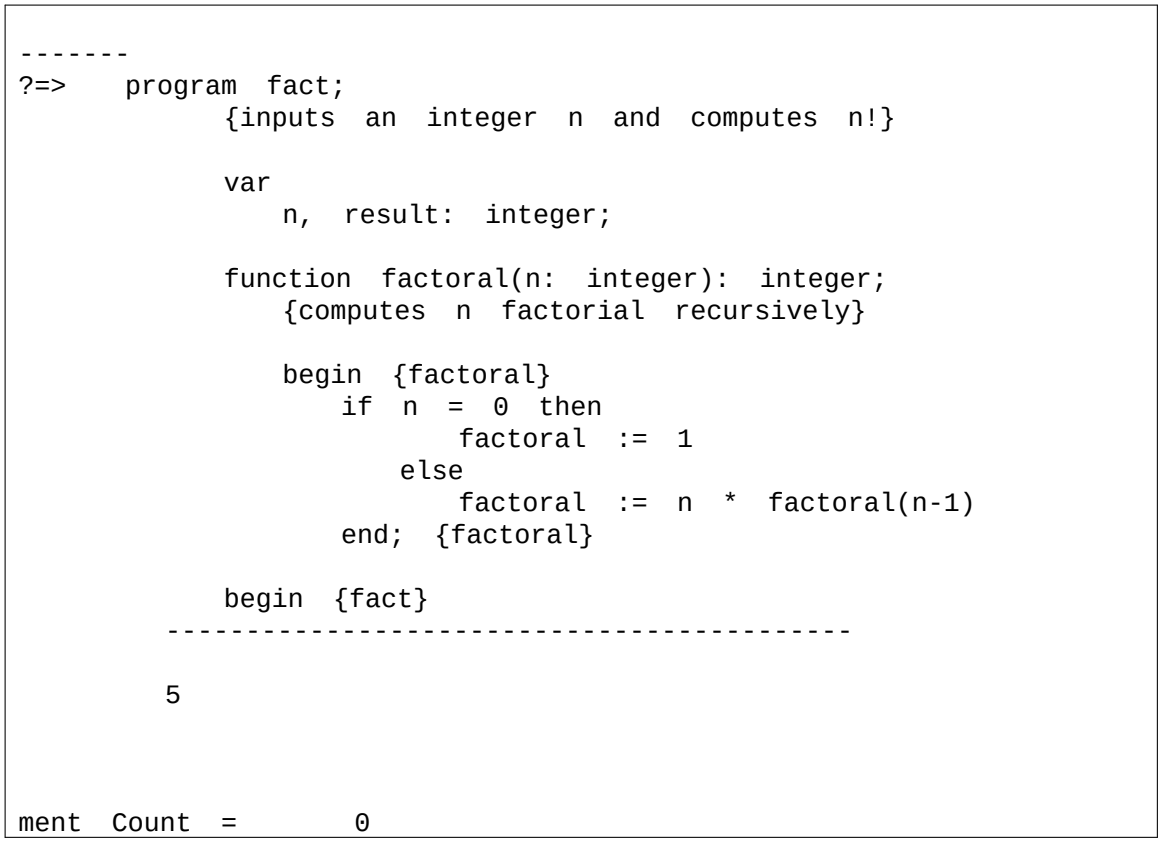


Figure 3
DYNAMOD Program *fact* Screen

At this point, the user can step through the program by hitting the return key. At each step, DYNAMOD moves the arrow to the next statement to be executed and waits for another return before executing the new statement. As can be seen in Figure 3, the entire program rarely fits onto the screen all at once. However, DYNAMOD keeps as much of the program on the screen as possible. Also, when an instructor is initially installing a program into the DYNAMOD library, he or she can specify blocks of lines that should be displayed together.

After the user has stepped through the variable declarations, the screen will appear as shown in Figure 4. Notice that the variables *n* and *result* now are displayed in the variable section on the right of the screen; the question mark indicates that their values are currently undefined. From this the user learns what the action of the *var* statement is.

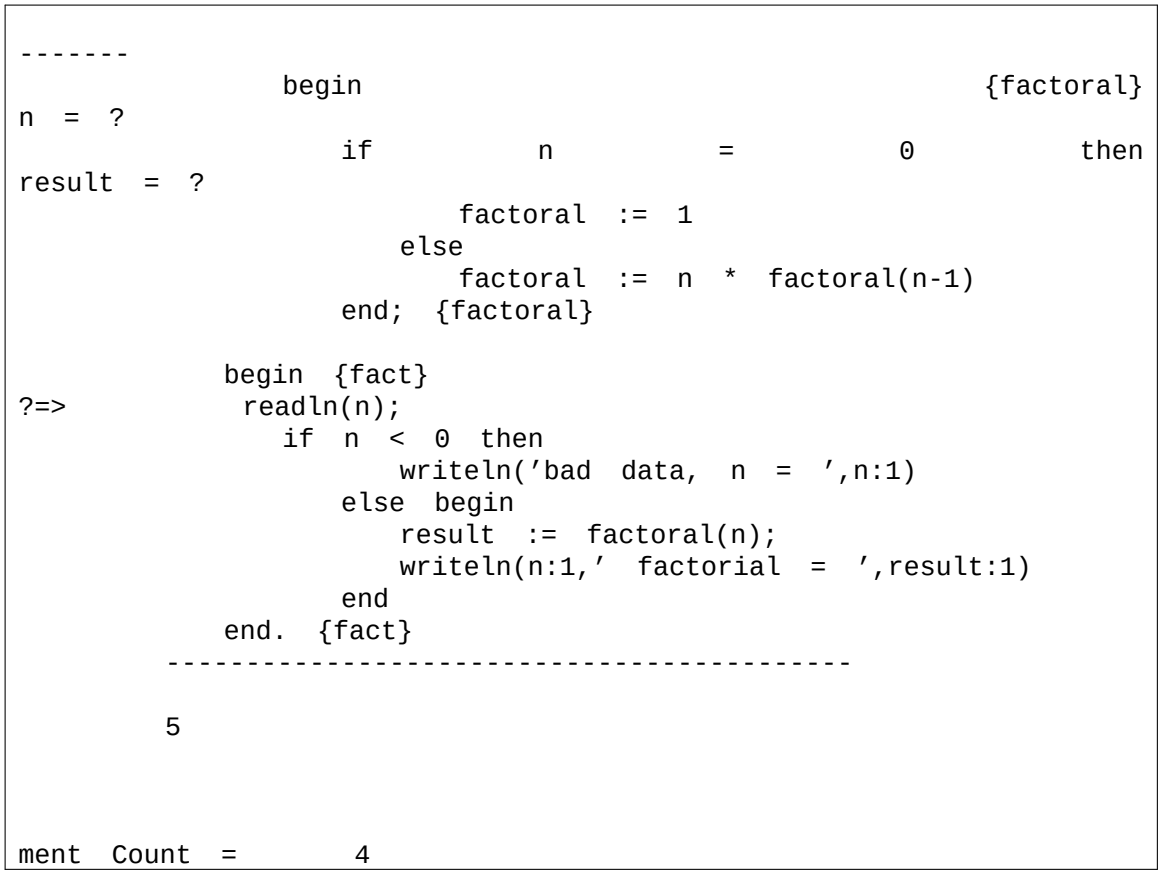


Figure 4
DYNAMOD Program *fact* Screen After Partial Execution

Stepping further through the program will eventually give a screen that looks like the screen of Figure 5. The user by this time has stepped through four calls of the recursive function *factoral* (this odd spelling of factorial is the result of a program restriction that limits the names of examples to eight characters). The memory section on the right of the screen contains new memory locations and their corresponding values associated with each call of *factoral*. By this time the student should have a clearer understanding of how recursion works in this case. Certainly, program dynamics are demonstrated very well.

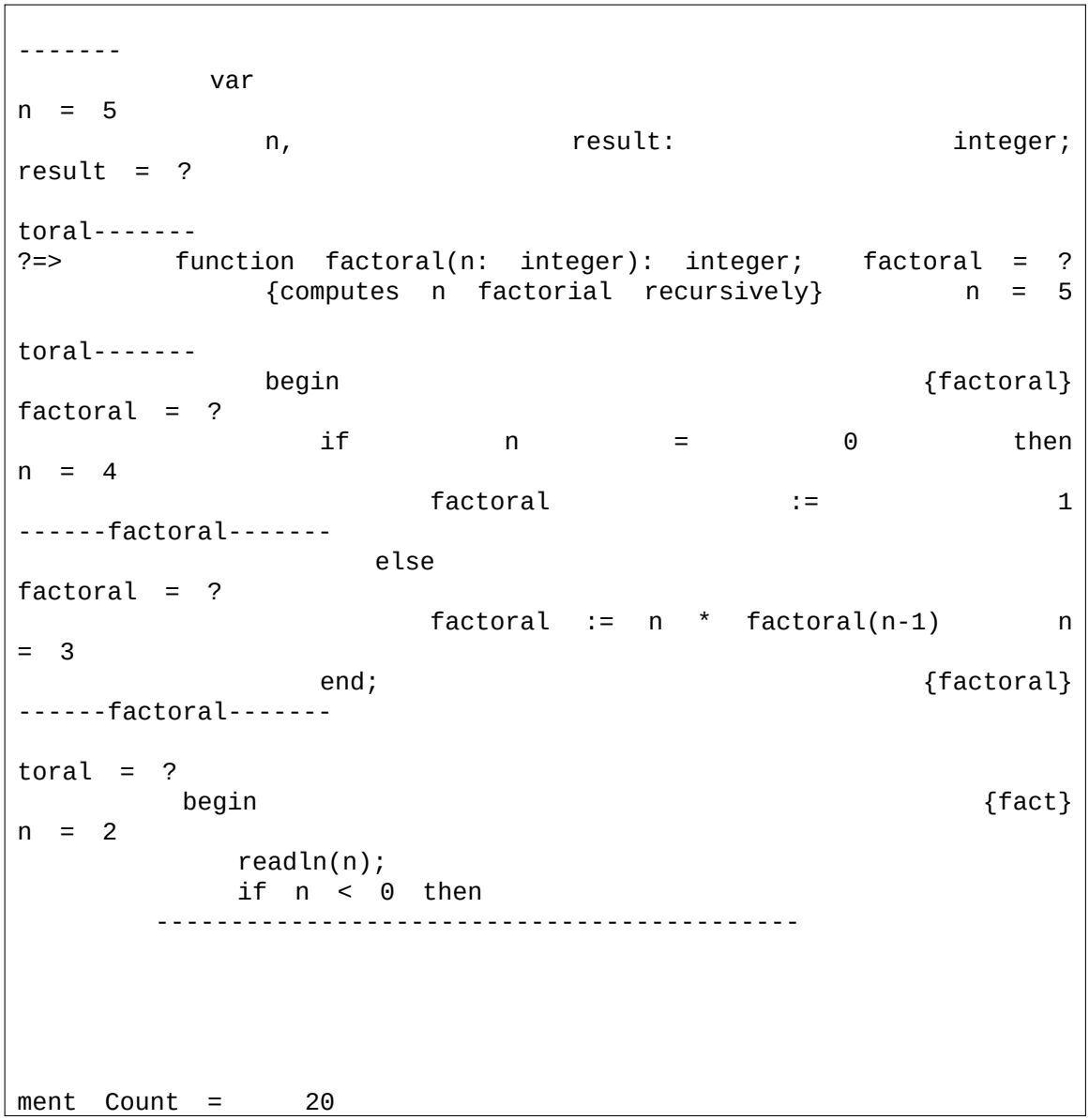


Figure 5
Program *fact* Screen After Four Calls to Function *factoral*

For the instructor, DYNAMOD removes nearly all of the work and frustration from doing a program walkthrough by hand in class. By using an overhead projector equipped with a liquid crystal computer output display, the instructor can run a desired program from the library and explain to his or her students key features of program dynamics. Furthermore, students can review the same program later or perform assignments related to programs in the DYNAMOD library. Thus DYNAMOD addresses many of the needs of teaching and learning programming by

providing:

1) Error-free, repeatable walkthroughs of algorithms;

2) Ease of use in a classroom setting;

3) A large library of expertly constructed programs for review by uninitiated students;

4) Effective display of the dynamics of a program in execution.

DYNAMOD also allows an instructor or student to alter program input and watch the effects of such changes on program execution and statement counts. Among other things, this feature can be used to demonstrate the notions of time and space complexity.

As a "proof of concept" pilot project, DYNAMOD is quite successful. However, DYNAMOD contains many limitations which must be addressed in order to create a truly robust, powerful system for supporting the goals of teaching and learning programming in a hypertext [CACM 88] environment. Some of the more crucial limitations are these:

1) Pascal is the only programming language supported;

2) A user can only step forward in the program;

3) It is not easily extensible to include complex constructs such as records and user-defined types;

4) It does not allow general program entry or modification by users.

Consideration of these drawbacks coupled with extensive use of DYNAMOD led to a vision of a completely new and flexible system that would better address the needs of both teachers and students of programming and introductory computer science. The proposed system, of which this thesis is an important part, is described in the next chapter.

CHAPTER 3

PROPOSED SYSTEM

The eventual goal of the system, of which this thesis is a small but critical part, is to construct a comprehensive introductory computer science teaching and learning software package. The system will run in a windowing environment (likely X Windows [Pountain 89]) and include such features as an interactive textbook, a large library of expertly constructed example programs, an editor for entering and modifying text and programs, and a DYNAMOD-like driver for interpreting programs and displaying their execution dynamics.

The interactive textbook will be a hypertext [CACM 88] system that will allow the user to interact with and modify the textual information of the book. Some of the planned features are listed below.

1) The user will be able to highlight text on the screen (the highlighting will remain for future readings).
2) The user will be able to place the cursor on a footnote and hit an "expand" key and the entire reference will "pop" onto the screen.
3) The user will be able to execute program fragments and examples from the text in a dynamic, DYNAMOD-like fashion.
4) The user will be able to interact with the index by highlighting a word and hitting the "index" key which will automatically display passages dealing with the word.
5) The user will be able to add or modify entries in the index in order to create a personalized index.

The example library will be a comprehensive set of expertly constructed example programs that have been designed to illustrate specific programming constructs. This library represents the major philosophical difference between the proposed system and other extant systems. The library will exist to illustrate programming concepts to the beginning programmer. Each example program will be quite small compared to an actual, useful program. However, the examples will have been carefully constructed by an instructor to convey particular programming concepts, and by observing and experimenting with the examples, the user will gain insight into aspects of program execution dynamics that are not readily apparent in other systems. By accentuating certain programming concepts, this library, in conjunction with the dynamic execution module, will provide a programming laboratory in which specific, simple experiments can be carried out by the user to illustrate and verify the programming concepts under study.

At present it is proposed that the text editor of the proposed new system be a syntax-directed editor. The editor will allow instructors

to enter carefully designed programs into the library and also allow users to enter and experiment with programs of their own. Syntax directed editors have been shown to be effective in a learning environment [Scheftic 86]. A syntax directed editor presents the user with a blank template that the user fills in with the appropriate constructs or phrases. Additionally, the user can request an explanation of the structure that is currently being used. For example, the user may be using the Pascal *for* statement; in this case a display similar to Figure 6 may be shown. The user would then "fill in the blanks" for the entries in {}'s and would then have a valid *for* structure without having to recall from memory the exact syntax of a *for* statement. This type of editor eliminates many of the syntax errors commonly made by users and allows them to focus on the meaning of their program rather than the many syntactic details of the language.

```
FOR {variable} := {expression} {TO | DOWNTO} {expression} DO
    BEGIN

    END;
```

Figure 6
for Statement Display Window in a Syntax Directed Editor

Another useful feature of syntax editors is their capacity to provide explanations of various programming language structures. For example, a user may be able to place the cursor on the FOR keyword in the screen of Figure 6 and press a "help" key. This would then invoke another window that would contain an explanation of the *for* statement similar to that shown in Figure 7.

The combination of the "fill in the blank" format and the help windows to tell the users the meanings of the various language constructs enables users to implement programs more efficiently. In Chapter 4 some systems are described that incorporate these features.

```
HELP WINDOW


FOR {variable} := {expression} {TO | DOWNTO} {expression} DO
    BEGIN

    END;

The FOR statement is a statement for repeating a group of
statement a given number of times.  The variable identifier put in
place of the {variable} location is given the value of the first
{expression}.  If the variable is greater than the second
{expression} (in the case of TO) the loop is ended and the
statements following the END are executed.  If the variable is
less then the second {expression} (in the case of DOWNTO) the
loop is also ended.  Otherwise, the statements between the BEGIN
and END are executed.  Then the variable is incremented if the TO
was chosen, or decremented if DOWNTO was chosen and the loop goes
back to the comparison above.

The variable used in the FOR statement is treated as a normal
variable in all ways except one.  It can not be used on the left
side of an assignment statement.  Also, after the loop is ended,
the value of the variable becomes undefined.  It does not retain
the value it had inside the loop.
```

Figure 7
Help Window for a Syntax Directed Editor

In summary, the new system proposed to succeed DYNAMOD will have all of the features of DYNAMOD with some notable improvements. The most notable enhancement to the display of program execution dynamics will be the capacity for both forward and backward execution of program statements under user control. As stated before, the virtual E-machine will allow easy implementation of the necessary dynamic display features, especially the forward and backward execution of programs.

As a prelude to discussing the E-machine, the next chapter is devoted to an examination of the literature and a number of existing software systems that appear to incorporate many of the features proposed for the new system described in this thesis.

CHAPTER 4

REVIEW OF LITERATURE AND EXISTING SYSTEMS

The idea of a computer-based teaching aid for displaying program execution dynamics is not new. Some such aids were surely developed for local use only and never polished and published. Others had limited appeal because of being restricted to expensive, specialized hardware. Early references to such systems include [Ross 81,82] and [Hille 83]. The papers by [Ross 81,82] describe the early work that led to the DYNAMOD system [Ross 88].

In [Hille 83] a system for the visible execution of Pascal programs is described. The system accepts a Pascal program as input and processes it as follows. Each of the original statements in the Pascal program is passed through unchanged. Immediately after each statement, a new statement is inserted that consists of a *writeln* statement along with the line number of the statement. The new augmented program is then translated into a PL/1 program that is in turn executed step by step by a PL/1 interpreter. This system represents a direct solution to the problem of displaying program execution dynamics, but it does not include, or apparently allow easy inclusion of, many desired features, such as backward execution.

Other related systems for displaying program dynamics focus on the representation of data structures and the manipulation of data by an algorithm rather than the overall view of program dynamics. A recent, good paper on this aspect of programming pedagogy is [Brown 88]. This paper describes the Balsa-II system. Balsa-II is a system for displaying the variables and data structures used in a program in an intuitive fashion, rather than by their literal meanings. For example, the data in an array that is being sorted could be displayed in a meaningful manner by interpreting the value in a location of the array as a vertical line with height based on the value in the location. Then a sorting routine could run, and gradually the lines would be sorted into ascending order by height. The user could see the sorting happening by watching the random collection of lines of various heights form into a triangular shape (the lines being arranged from smallest to largest in height). When the triangle becomes smooth, the values will all have been sorted. This system shows strong promise of becoming an effective pedagogical tool in the teaching and learning of algorithms. Its features could become part of a new system similar to the one described in this thesis. Alone, however, it does not encompass the needs addressed by this thesis.

Interactive program debuggers also contain elements of the dynamic display system proposed here. Many, if not most, good program

development environments incorporate a debugger. A good debugger has such features as:

1) Line at a time program execution;
2) A display of variable values during execution;
3) The capability for specifying "break points" that temporarily halt program execution;
4) A provision for changing the values of variables during execution.

An example of an excellent interactive program debugger is the Turbo Debugger that comes with Turbo Assembler, produced by Borland [Turbo 88]. It incorporates all of the above features along with other special features, including the ability to examine the state of the microprocessor and machine registers. It allows the user to easily specify which variables to display and when to display them. It also allows the user to specify break points either by line number or by a condition, such as when a variable changes value. These features make this a valuable tool for the production programmer. Similar features are planned for the new system described in this thesis.

However, it should be clearly noted at this point that in spite of apparent similarities between the dynamic display system proposed here and high-quality debuggers available on the market, there are some crucial differences that arise from the entirely different philosophies behind the proposed dynamic display and existing debuggers. The purpose of a debugger, as the name implies, is to allow the user to debug a program. The purpose of the dynamic display is to show the user the dynamic changes in a program during execution. A debugger helps a person who already knows how to write a program uncover and fix errors. In fact, a user must be quite a sophisticated programmer to obtain the true benefit of a debugger. The proposed dynamic display system, on the other hand, is meant to let a beginner see how various program constructs function. Because of this, the proposed dynamic display must show much more and different information than a debugger and do this in a clearer fashion. It must also accomplish this in a manner that is useful to the utter novice. This naturally will make the dynamic display slower and larger than a debugger, which is not a disadvantage in the setting in which the dynamic display is meant to be used. A debugger is meant to be used in a production environment where speed and the production of sophisticated, useful programs is all-important. The dynamic display is meant to be used in a learning environment where understanding is the key, and small programs for presenting educational concepts is the overriding concern.

There are other systems on the market that incorporate many of the features of debuggers and the proposed dynamic display, but which are aimed more specifically towards education. One such system is ALICE [ALICE 89]. ALICE is a syntax directed editor and interpreter for Pascal that was specifically designed for student use. Some of ALICE’s features are:

1) Templates for "fill in the blank" style program entry;
2) A comprehensive help system (over 600 help screens);

3) An interactive interpreter that allows the user to step through the execution of his or her program one statement at a time;

4) Breakpoint setting capability, in the manner of a debugger.

Another system designed with the student in mind is Dr. Pascal by Visible Software [Visible 89]. This system has many educational features. Dr. Pascal consists of an editor and a display system for showing program execution. The editor is a standard text editor (not a syntax directed editor) that allows users to enter and modify programs. The display system of Dr. Pascal is quite good.

In Dr. Pascal each procedure is placed on the screen as it is executing. If the procedure is too large to fit on the screen, the display is adjusted so that the currently executing line is always on the screen.

As new procedures or instances of procedures are invoked, the old procedure calls are scrolled off the top of the screen. This gives the user a good intuitive feel for how recursive calls to a function or procedure execute.

One of the main disadvantages to standard debuggers for student use is that they give little indication of depth of recursion or even the fact that a recursive call has happened at all. Dr. Pascal still falls short of what is required in this regard in several ways. When a reference parameter is passed to a procedure, there is no indication of where the parameter's reference actually is. Also, the variable display does not show the values of variables which are not in the current scope, even though their values are being changed as a result of being passed as reference parameters.

To summarize, while the debuggers included in production programming systems similar to Turbo Pascal by Borland are of immense help to experienced programmers attempting to ferret out errors in programs, they are too limited and complex for the beginning programmer and cannot be adapted easily to the teaching and learning environment envisioned here. ALICE and Dr. Pascal are more suited to the teaching and learning environment, but they still are oriented towards the production side of programming. That is, their primary intent is to aid a student in walking through a program of his or her creation in search of errors. Neither of these systems incorporates a library of expertly constructed programs for perusal by students who do not yet have enough knowledge to write a program on their own. Also missing are facilities for stepping backwards through execution, explaining new programming concepts, and program fragment execution, which are all features of the system proposed in this thesis.

There have been many articles written about using virtual machines in computer science applications (see, for example, [Elsworth 78]). The earliest is probably [Share 58]. In all cases cited in the literature the purpose of the virtual machine is to reduce the effort needed in constructing compilers. See, for example [Kornerup 80]. Just one compiler is needed to translate a programming language, say FORTRAN, into the language of a virtual machine. Then the problem remains of either emulating the virtual machine on each real computer or further translating the virtual machine code into the machine language of each real computer. The emulation approach has proven unsatisfactory in real life, because an emulation program is invariably slow. However, this approach was used successfully with the P-machine and P-code of Pascal during the time when Pascal was viewed as an academic language ([Ellsworth 78] attributes the design of the P-machine to Nori *et al* and cites [Nori 74]). As Pascal has become production oriented, this emulation approach has been dropped for efficiency reasons.

In spite of the efficiency problems encountered by others, the abstract machine (the E-machine) approach incorporating an emulator is the most attractive for the new system proposed here. The entire purpose of this new system is academic, involving the teaching and learning of programming rather than the development of production programs. Speed of program execution will never be a primary concern. The E-

machine and its emulator will require just one E-machine emulator program and then one compiler for each targeted programming language. As long as the compilers and the emulator are written in a standard, portable, high level language they will run with only minor modifications on virtually any computer.

In the next chapter, the E-machine's design and implementation will be covered. A complete specification is not given, because the E-machine is intended to have an open-ended design that allows later incorporation of new features that are deemed important and interesting. The specification is, however, sufficient for the design of an emulator and compilers for the E-machine.

CHAPTER 5

THE E-MACHINE

The proposed dynamic display system will consist of various major parts. The *Education Machine*, or *E–machine*, will be one of the primary components. It will be a virtual machine (i.e., computer) with its own machine language, called *E–code*, and it will be responsible for executing the E–code translations of high level language (e.g., Pascal) programs. In addition to the E–machine there will be a user interface for user interaction with the system. There will also be a display interface that updates the screen displays. These two interfaces together can be thought of as an "operating system" with the E–machine as the "hardware". This chapter focuses on the design of the E–machine.

Design Considerations

The part played by the E–machine in the proposed system is central to its design. The E–machine will operate as follows. It will first be loaded with a compiled E–code translation of a particular high level language source program. The E–machine will then wait for the user interface to signal it to execute a step, either forward or backward. Once this signal has been received, the E–machine will execute the segment of E–code that corresponds to the current statement in the high level language source program and then return control to the user interface. Following this, the display interface will note the changes that have occurred in the E–machine's state and update the displays accordingly. Note that the E–machine does not interact directly with the user. All input to and output from the E–machine is handled through the user and display interfaces. The E–machine acts as if it were a dedicated microprocessor whose only purpose is to wait for a signal from "outside" and then execute its program based upon that signal. This definition of how the E–machine is to be used allows constraints to be placed upon its design that make the design process somewhat simpler.

As already noted, the E–machine is a virtual machine. The concept of a virtual machine, discussed in the last chapter, is central to many computer science applications. Compilers and interpreters are the most common examples of systems designed around a virtual machine. The design of a virtual machine must take into account the purpose of the application. This helps to define and give structure and logic to the virtual machine. In the case of the E–machine, the purpose of the machine is to enable program execution dynamics of high level programming languages to be displayed easily by the dynamic display interface.

This goal places some considerations upon the E–machine's design. Most importantly, the E–machine must:

1) Have structures for easy implementation of high level programming language constructs;
2) Incorporate a simple method for implementing functions, procedures, and parameters;
3) Be able to execute either forward or backward.

The driving force in the design of the E−machine is the requirement for backward, or reverse, execution. What does it mean for a machine to run backwards? What does it mean for a high level language program to execute backwards? As will be seen, these two questions have very similar and related answers, but they are not the same.

In a machine (virtual or real), the program counter, registers, main memory and other status information can all be thought of as variables that change as the machine executes instructions. These variables can be collectively thought of as the "state" of the machine. If one knows the current state of a machine, one knows everything necessary for properly carrying out the next instruction to achieve the proper next state. In most machines, however, the current state does not contain enough information to reset the machine to a *prior* state. That is, most machines do not keep track of their history of execution. However, the machine's history is precisely what must be accessed in order to execute backwards. How can this information be retained? The previous states must be recoverable. That is, given the present state of the machine, there must be a mechanism for changing this state to an arbitrary past state.

The brute force approach to solving this problem is to store each current state of the machine just before each new instruction is executed (all instructions change the state of a machine). Then, when the machine is to be restored to some prior state, all that has to be done is to load the machine with that state and the operation is done. With this method, the machine can be restored to an arbitrary prior state in one step.

The brute force method is unnecessarily powerful and also very inefficient. For example, this approach would require that all of main memory be stored with each state, even though at most one memory location would have changed from state to state as single instructions were executed. A better approach would be to have the machine save the minimal amount of information necessary to recover just the previous state from the current state in a given reversal step. The machine could then be restored to an arbitrary prior state by doing the reversal one state at a time until the desired prior state were obtained. For the purpose of the E−machine, this approach is sufficient.

Backing up one state at a time is a much simpler proposition than backing up to an arbitrary state in one step. Rather than storing the entire state of the machine at each step, it is only necessary to store the difference between the previous state and the current state. For example, suppose the instruction

```
load  4,A
```

loads the value 4 into the register *A*. No other registers would have been changed by executing this instruction, so the only changes to the state of the machine (in most computer models) would be to the value in *A*, the program counter, and perhaps some status information. Saving these changes rather than the entire state of the machine takes much less memory, and in a real computer, memory is a valuable commodity. Therefore the E−machine was designed with this method of backing up in mind.

A natural question to ask at this point is whether it is possible to do even better: could the previous state be constructed directly from the current state without relying on some saved portion of the execution history? The answer is no, because of one class of instructions: assignment instructions. An assignment instruction destroys the value in the register or memory location receiving the assignment; the value being destroyed must therefore be saved in order for backup to be possible.

One other aspect of the proposed dynamic display interface influenced the design of the E−machine. The dynamic display is meant to work with high level language programs. This led to an important observation: the E−machine actually has to be able to reverse only high level language statements in one reversal step, not each individual low level E−code instruction involved in the translation of some high level language statement. In particular, the state of the E−machine has to be restored to the state it was in prior to the execution of the group of E−code instructions that are the translation of the corresponding high level language statement.

This observation led to further efficiencies in the design of the E−machine and to the incorporation of two classes of E−machine code instructions, critical and noncritical. As will be explained further later, an E−machine instruction is classified as critical if it destroys information essential to backing up through a high level language statement; it is classified as noncritical otherwise. In the translation of

a high level language statement into E−code, a number of E−machine instructions will be used only for dealing with intermediate values. For example, in a high level language arithmetic assignment statement, a number of intermediate values are likely to be needed in computing the arithmetic value on the right side of the assignment statement before this value can be assigned to the variable on the left. However, the only value that needs to be restored as far as the high level programming language is concerned upon backing up through this assignment statement is the original value of the variable on the left. The intermediate values computed by various E−code instructions are of no consequence. Hence, such instructions can be classified as noncritical and their effects ignored for backup purposes.

A particular E−code instruction can be classified as either critical or noncritical in different circumstances. Different high level languages will often have quite different statement sets, and what needs to be remembered for backup purposes may differ substantially from one language to another. It will be the responsibility of the compilers for each high level language to produce the correct E−code (involving critical and noncritical instructions) for allowing backup.

E-machine System Overview

With these considerations for backing up in mind it is now possible to describe the architecture of the E−machine in more detail. Figure 8 depicts the logical structure of the E−machine. After some deliberation, a stack-based architecture was chosen over other possibilities for its inherent simplicity. As can be seen, however, there are a number of components not found in real stack-based computers.

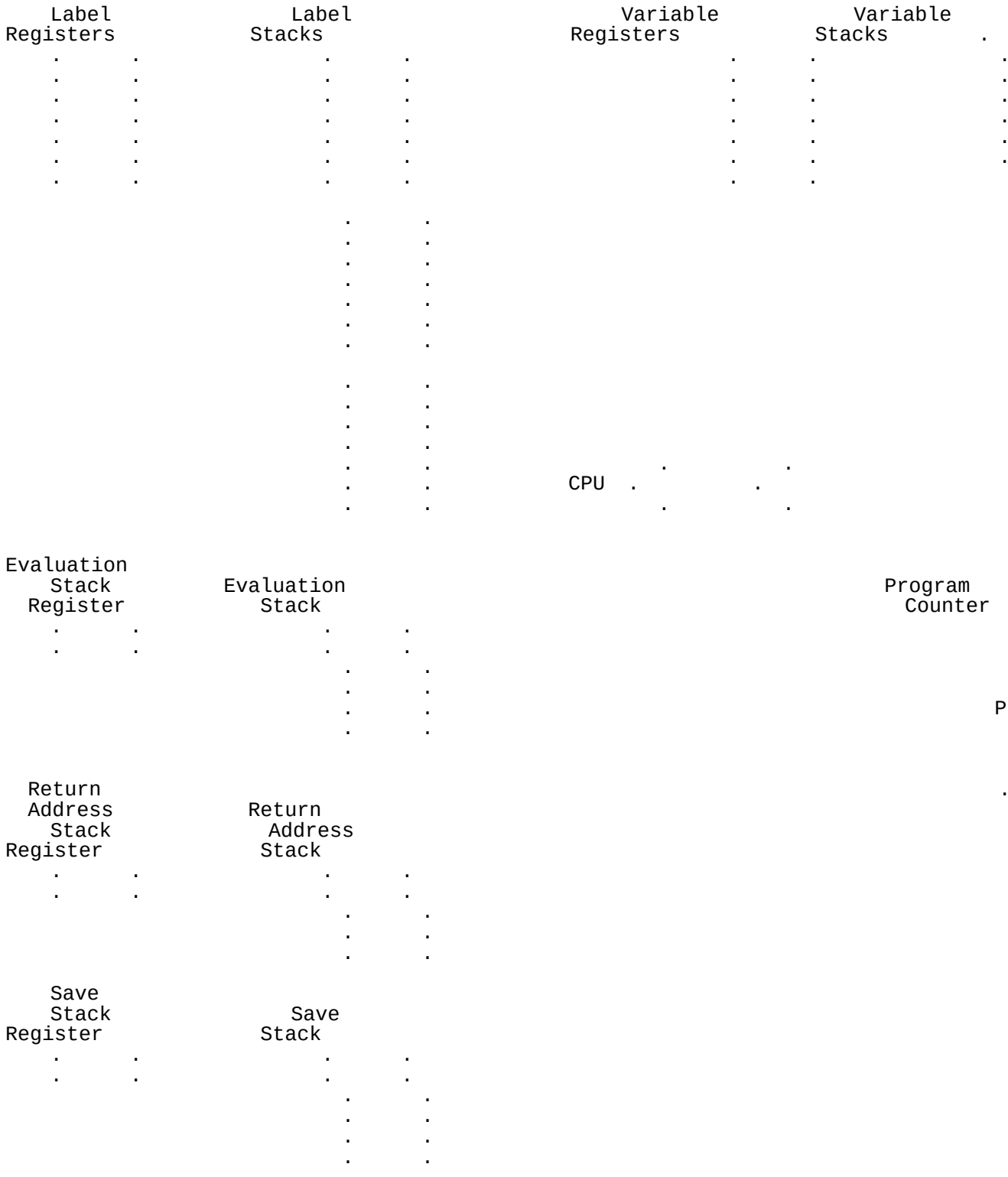


Figure 8
The E-machine

Program memory will contain the E−code program currently being executed by the E−machine. The *program counter* will contain the address in program memory of the current E−code instruction to be executed. The *previous program counter*, needed for backup purposes, will contain the address in program memory of the most recently executed E−code instruction. The *line number register* will contain the line number of the high level language program statement corresponding to the group of E−code instructions currently being executed. The line number will be needed by the dynamic display interface to highlight the current high level source program line being executed.

The *variable registers* are an unbounded number of registers that will be assigned to source program variables, constants, and parameters during compilation from the source program into E−code. Each identifier name representing memory in the source program will be assigned one variable register in the E−machine. As one can see in Figure 8, the variable registers only contain pointers to individual *variable stacks*, which in turn contain pointers into data memory, where the actual variable values are stored. The reason for this complex arrangement will become clearer as variables are discussed more thoroughly below.

The *label registers* are another unique component of the E−machine required for backup. There are also an unbounded number of these registers and, as described later, they are used to keep track of E−code label instructions in an E−code program for backup purposes. Each E−code label statement will be assigned a unique label register at compile time. A label register, in turn, points to a *label stack* that essentially maintains a history of previous instructions that caused a branch to this label.

The *index register* is found in real computers and serves the same purpose in the E−machine. Under normal circumstances, the data in a variable is accessed through the appropriate variable register. However, in the case of high level data structures, such as arrays and records, the address of an individual data value is not at the memory location directly accessible through a variable register. Rather, it is stored at a location offset from this memory location. When necessary, an offset value can be placed in the index register and the E−machine can then access the proper memory location as required (by an addressing mode called register-indexed).

The *evaluation stack pointer* is also found in real computers. The evaluation stack pointer keeps track of the top of the *evaluation stack*. The evaluation stack is where the results of all arithmetic and logical operations and assignments are maintained. For example, in an arithmetic operation, the operands are pushed onto the stack and the operation is then performed on them. The operands are consumed by the operation and the result is pushed onto the top of the stack. Assignments are performed by popping the top value of the evaluation stack and placing it into a variable. The advantages of a stack architecture are well known; several popular computers use this design.

The *return address stack pointer* is a mechanism for implementing procedure and function calls. When a call is made to an E−machine subroutine, the program counter plus one is pushed onto the *return address*

stack. Then, when the E–machine executes a return from subroutine instruction, all it has to do is load the program counter with the top of the return address stack.

The *save stack pointer* is used to store information required for backup, which would otherwise be lost. Whenever some critical information (as determined by the execution of a critical instruction) is about to be destroyed, the required information is pushed onto the *save stack*. This ensures that when backing up, the instruction that most recently destroyed some critical information can be reversed by retrieving that critical information from the top of the save stack.

Finally, *data memory* represents the usual random access memory found on real computers, but in the E–machine it is only used for holding data values. In real machines, a similar situation exists in some systems which provide for separate code and data segments in memory. On the E–machine, there is no bound to the available memory (or any of the stack memory). Implementations on real computers will naturally enforce some bounds, but for the academic (small program) environment envisioned for this system, no practical problems are expected to be encountered due to limited memory.

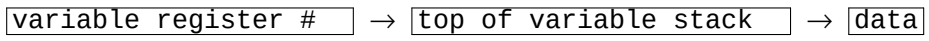
E-machine Instruction Set

The E–machine's instruction set is a quite small but complete set of instructions; these instructions allow an E–code program to access data easily and simply. All arithmetic, logical, and assignment operations occur on the evaluation stack. Data is stored and recalled using the variable registers. All operations for backing up occur with a minimum of information from the E–code program in question (in general, all the E–code program has to do is use the correct form of the instruction--critical or noncritical--to ensure that backing up can occur correctly).

Addressing Modes

In this section, the various addressing modes available to the E–machine instruction set are given.

variable mode - V# :



This mode accesses the data at the memory location given in the top element of the variable stack pointed to by variable register #.

constant mode - # :

```
 #
```

This mode is often called the *immediate mode* in other architectures; # is itself the integer, real, boolean, character, or address constant operand required in the instruction. Also, there are some defined constants. INTEGER, REAL, BOOLEAN, CHARACTER, and ADDRESS are the size in bytes of an integer, real, boolean, character, and address variable, respectively.

register mode - R# :

```
variable register #  → top of variable stack
```

This mode accesses the address at the top of the variable stack pointed to by variable register #. This address is the location in data memory of the current instance of variable #.

register indirect - R#+IR :

```
variable register #  → top of variable stack + IR  → data
```

This mode accesses the data at the memory location at the top of the variable stack pointed to by the variable register # plus the offset stored in the index register. This is the addressing method used to access array elements, record items, and elements of other high level data structures.

variable indirect - V#+IR :

```
variable register #  → top of variable stack  →
      memory location + IR  → data
```

This mode accesses the data at the memory location stored at the memory location at the top of the variable stack pointed to by variable register # plus the offset stored in the index register. This is the method used to implement high level language pointer variables.

Index Register - IR :

```
 IR
```

This mode accesses the value in the index register directly. This is the only register which acts like a standard, normal machines. It should only be used in conjunction with the indirect addressing modes above.

Instruction Set

This section lists all of the instructions in the instruction set of the E−machine. The argument ADDR refers to any addressing mode listed in the last section. The argument TYPE refers to any of the data types integer, real, boolean, char, and address; most instructions require that the type of data being operated upon be specified. The # refers to an integer constant. This differs from the constant mode described above in that this # is used only to specify the number of an E-code label or an E-machine variable register. The MODE argument determines whether the instruction is to be treated as critical or non-critical. The exact method for replacing the ADDR, TYPE, and MODE designators is unspecified and will be left up to the designer of the E−machine emulator. Backing up through a noncritical instruction often still requires that something be pushed onto the evaluation stack to keep the stack of the proper size; in such cases an arbitrary dummy value is used.

push ADDR, TYPE :

Forward :
Pushes the value in ADDR onto the evaluation stack.

Backward :
Pops the top value of the evaluation stack and stores it in ADDR.

pop MODE, ADDR, TYPE :

Forward-Critical :
Pushes the value in ADDR onto the save stack and then pops the top value of the evaluation and stores it in ADDR.

Forward-Noncritical :
Pops the top value of the evaluation stack and stores it in ADDR.

Backward-Critical :
Pushes the value in ADDR onto the evaluation stack and then pops the top value of the save stack and places it in ADDR.

Backward-Noncritical :
Pushes the value in ADDR onto the evaluation stack.

add MODE, TYPE :

Forward-Critical :
Pops the top two values of the evaluation stack, pushes them onto the save stack, and then pushes their sum onto the evaluation stack.

Forward-Noncritical :
Pops the top two values of the evaluation stack and pushes their sum onto the evaluation stack.

Backward-Critical :
Pops the top value of the evaluation stack and discards the value. Pops the top two elements of the save stack and pushes them onto the evaluation stack.

Backward-Noncritical :
Pushes a 0 onto the evaluation stack.

sub MODE, TYPE :

Forward-Critical :
Pops the top two values of the evaluation stack, pushes the two values onto the save stack, and then pushes the bottom value minus the top value onto the evaluation stack.

Forward-Noncritical :
Pops the top two values of the evaluation stack, and pushes the bottom value minus the top value onto the evaluation stack.

Backward-Critical :
Pops the top value of the evaluation stack and discards it. Pops the top two values of the save stack and pushes them onto the evaluation stack.

Backward-Noncritical :
Pushes a 0 onto the evaluation stack.

mult MODE, TYPE :

Forward-Critical :
Pops the top two values of the evaluation stack, pushes the two values onto the save stack, and then pushes their product onto the evaluation stack.

Forward-Noncritical :
Pops the top two values of the evaluation stack and pushes their product onto the evaluation stack.

Backward-Critical :
Pops the top value of the evaluation stack and discards it. Pops the top two values of the save stack and pushes them onto the evaluation stack.

Backward-Noncritical :
Pushes a 0 onto the evaluation stack.

div MODE, TYPE :

Forward-Critical :
Pops the top two values of the evaluation stack, pushes the two values onto the save stack, and pushes the bottom value divided by the top value onto the evaluation stack.

Forward-Noncritical :
Pops the top two values of the evaluation stack and pushes the bottom value divided by the top value onto the evaluation

stack.

Backward-Critical :
Pops the top value of the evaluation stack and discards it. Pops the top two values of the save stack and pushes them onto the evaluation stack.

Backward-Noncritical :
Pushes a 0 onto the evaluation stack.

neg TYPE :

Forward :
Pops the top of the evaluation stack and pushes the negation of that value onto the evaluation stack.

Backward :
Pops the top of the evaluation stack and pushes the negation of that value onto the evaluation stack.

mod MODE, TYPE :

Forward-Critical :
Pops the top two values of the evaluation stack, pushes the two values onto the save stack, and then pushes the bottom value modulo the top value onto the evaluation stack.

Forward-Noncritical :
Pops the top two values of the evaluation stack and pushes the bottom value modulo the top value onto the evaluation stack.

Backward-Critical :
Pops the top value of the evaluation stack and discards it. Pops the top two values of the save stack and pushes them onto the evaluation stack.

Backward-Noncritical :
Pushs a 0 onto the evaluation stack.

line # :

Forward :
Loads the line number register with #, then the machine returns control to the dynamic interface and enters a wait state.

Backward :
Loads the line number register with #, then the machine returns control to the dynamic interface and enters a wait state.

cast TYPE, TYPE :

Forward :
Pops the top value of the evaluation stack, transforms the value from the first TYPE to the second, then pushes the value

onto the evaluation stack.

Backward :
Pops the top value of the evaluation stack, transforms the value from the second TYPE to the first, then pushes the value onto the evaluation stack.

cmp MODE, TYPE :

Forward-Critical :
Pops the top two values of the evaluation stack, pushes the two values onto the save stack, compares the bottom value with the top value and then pushes the result of the comparison onto the evaluation stack (i.e., one of LESS, EQ, and GREATER is pushed).

Forward-Noncritical :
Pops the top two values of the evaluation stack, compares the bottom value with the top value and then pushes the result of the comparison onto the evaluation stack (i.e., one of LESS, EQ, and GREATER is pushed).

Backward-Critical :
Pops the top value of the evaluation stack and discards it. Pops the top two values of the save stack and pushes them onto the evaluation stack.

Backward-Noncritical :
Pops the top value of the evaluation stack and discards it. Pushes two 0's onto the evaluation stack.

label MODE, # :

Forward-Critical :
Pushes the previous program counter onto the stack pointed to by label register #.

Forward-Noncritical :
No operation.

Backward-Critical :
Pops the top value of the stack pointed to by label register # and places it in the program counter.

Backward-Noncritical :
No operation.

br #:

Forward :
Load the program counter with the address of the label # instruction.

Backward :
No operation.

beql, bneql, bless, bleql, bgtr, bgeql MODE, # :

Forward-Critical :
Pops the top value of the evaluation stack and pushes it onto the save stack. If the value satisfies the conditional on the branch, load the program counter with the address of the label # instruction.

Forward-Noncritical :
Pops the top value of the evaluation stack. If the value satisfies the conditional on the branch, loads the program counter with the address of the label # instruction.

Backward-Critical :
Pops the top value of the save stack and pushes it onto the evaluation stack.

Backward-Noncritical :
Pushes EQUAL onto the evaluation stack.

call # :

Forward :
Pushes the current program counter onto the return address stack, then loads the address of the label # instruction into the program counter.

Backward :
No operation.

return :

Forward :
Pops the top value of the return address stack and loads it into the program counter.

Backward :
No operation.

alloc # :

Forward-Critical :
Pops the top value of the evaluation stack, pushes the value onto the save stack, pushes the address of a chunk of free memory of that size onto the variable stack pointed to by variable register #.

Forward-Noncritical :
Pops the top value of the evaluation stack, pushes the address of a chunk of free memory of that size onto the variable stack pointed to by variable register #.

Backward-Critical :
Pops the top value of the variable stack pointed to by variable register # and frees the memory allocated, pops the top value of the save stack and pushes it onto the evaluation stack.

Backward-Noncritical :
Pops the top value of the variable stack pointed to by variable register # and frees the memory allocated. Pushes a 0 onto the evaluation stack.

link # :

Forward :
Pops the top value of the evaluation stack and pushes it onto the variable stack pointed to by variable register #.

Backward :
Pops the top value of the variable stack pointed to by variable register # and pushes it onto the evaluation stack.

unlink # :

Forward :
Pops the top value of the variable stack pointed to by variable register # and pushes it onto the save stack.

Backward :
Pops the top value of the save stack and pushes it onto the variable stack pointed to by variable register #.

Source Program Variable Representation in E-machine Code

Understanding how the E-machine provides for the implementation of high level source language variables is vital to understanding the operation of the E-machine, especially in backing up. (In this context, the term variable refers to any identifier in the source program that requires memory, such as variables, constants, and parameters.) First, a compiler that generates E-code translations of, say, Pascal programs assigns each variable in the Pascal program a unique E-machine variable register. This is done statically at compile time, so that every variable is associated with a unique variable register for the duration of program execution, regardless of whether that variable is currently active or not. The variable register for a variable does not contain the value of the variable. Rather, it contains a pointer to a unique variable stack for that variable (look at Figure 8 again). Since each variable register is really only a pointer, it will be the same size regardless of whether the variable is a simple variable or, for example, an array.

The variable stack pointed to by a variable register also does not contain the value of the variable. In this case, each element of the variable stack is itself a pointer to the actual variable value in data memory. The stack is necessary because a particular variable may have multiple associated instances. Consider the case of a variable *A* that is local to a recursive Pascal procedure. Each new recursive call to that procedure would require that a new data memory location be set aside for new instance of *A*. *A*'s variable register would point to *A*'s variable stack, and the top of *A*'s variable stack would point to the value of the current instance of *A* in data memory. The second stack element would point to the previous instance of *A* in data memory, and so on. Most variables are not in recursive procedures and thus will only have at most one instance during program execution. In such cases, the variable register would point to a variable stack that is just one element deep. The case for a variable *A* with just a single instance is illustrated in Figure 9. Figure 10 shows the situation of a variable *A* having three instance as the result of three recursive calls to a procedure.

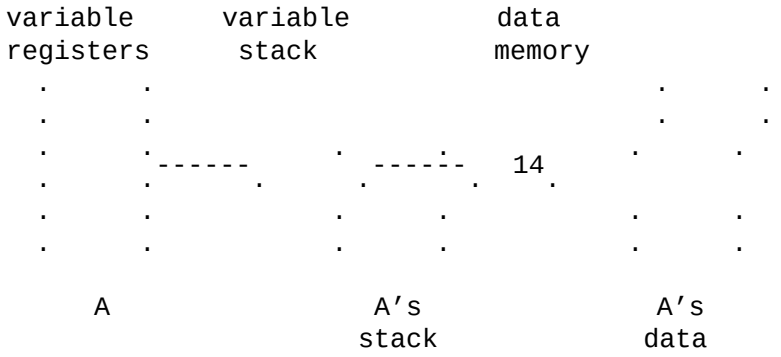


Figure 9
E-machine Global Variable Implementation

Whenever a procedure or function exits, the compiled E−code will ensure that local variable instances are properly removed from data memory by simply causing the top of the variable stacks to be popped for each affected variable. If a variable is totally deactivated as a result, its variable register will simply point to an empty variable stack.

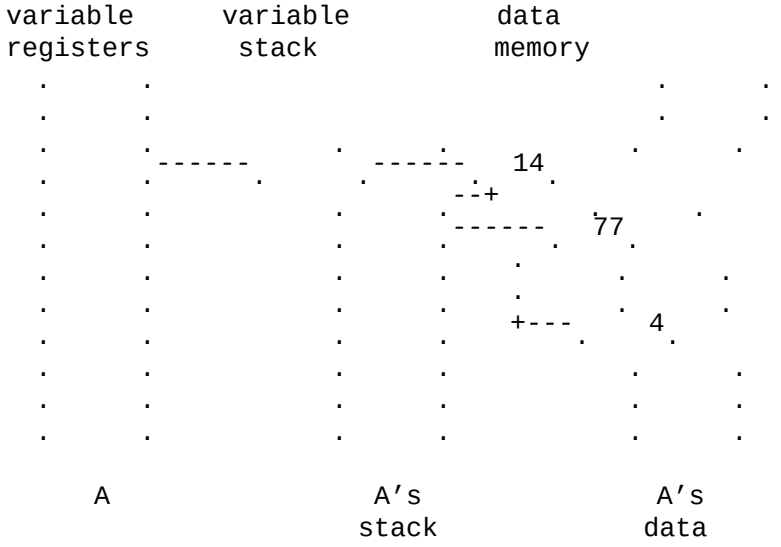


Figure 10
E-machine Recursive Variable Implementation

Notice that arrays and records can be handled in the usual fashion, using offsets (in the index register) from the first location for the variable in data memory to arrive at individual elements.

The Save Stack

To see how backing up is accomplished with this method of representing variables, the role of the save stack must be explained. The first thing to consider is the kinds of information associated with a variable. There are two kinds: the location of the variable's memory and the data in the variable's memory location. Both are subject to destruction or loss during normal program execution. It is easier to see how the second type of information, the data, can be destroyed. Whenever an assignment is made into a variable, the old data in the variable's memory location is destroyed. Therefore, in order to restore the E–machine's state to the state prior to the assignment, it is necessary to save the old data. This is done on the save stack. Upon backing up, the old variable value can then be restored by retrieving it from the save stack.

Now consider the case of a memory *location*. Recall that the data memory location of a variable is kept in the stack corresponding to that variable. In the case, say, of a Pascal global variable, the single stack element for that variable continues to point to the proper data memory location for that variable throughout the execution of the program. In the case of a variable (again, this refers to both local variables and parameters) in a procedure or function, however, the data memory location, and hence the pointer to this location on the variable stack, may change with each call. That is, each time a call to the procedure or function is made, a different data memory location may be allocated for the value of the variable and pushed onto the top of that variable's stack; upon return from the procedure or function, that address will be popped off the variable's stack as the variable is deallocated. At this point, information critical to backup would be lost if the address popped off were not saved in some way.

This is where the save stack comes in. Whenever any information is about to be lost in one of the above fashions, the information instead is pushed onto the save stack. Figure 11 shows the initial variable register, variable stack, and data memory location for a variable *X*. Also included is the save stack.

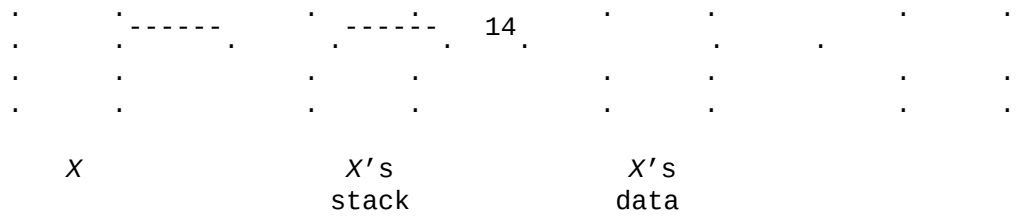


Figure 11
Variable and Save Stack for a Variable X

ce that the save stack is empty now. (Technically, this situation d not arise since *X* has a value at this point, and therefore at some t in the past must have had an assignment statement performed upon which would have required the old value to be pushed onto the save k. For purposes of this example, we will ignore this fact.) Now, s perform an assignment operation:

```
X = 27
```

effect this will have upon the E–machine's structures is shown in re 12. Notice that the top of the save stack now contains the old e of *X* and that the new value of *X* is stored in the old memory loca- . In this case, the information which would have been destroyed was data, not the memory location.

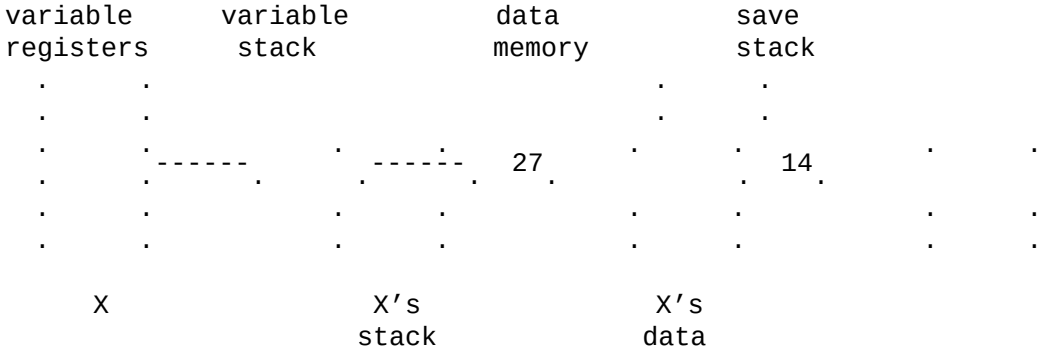


Figure 12
Variable and Save Stack After Assignment to X

In order to back up at this point, all that would be necessary would be to pop the top of the save stack and place the popped value into the memory location pointed to by the top of *X*'s variable stack. This procedure allows any assignment to be reversed.

Preparing for the reverse execution of statements that lose location information is somewhat more involved. To understand this task better, recall from the previous section how the E—machine architecture provides for the implementation of high level language variables (remember, too, that the term variable is used here to stand for any high level language identifier requiring memory, such as actual variables, parameters, and constants). Each variable has a permanently assigned variable register. Each variable register points to a unique, associated variable stack.

Each element of the variable stack is a pointer to an instance of the variable value in data memory; the top of the variable stack points to the current, active instance of the variable.

Thus, since the location of a variable's assigned variable register remains constant throughout program execution, and this variable register always points to the current top element of the associated variable stack, the only location information that can be lost during normal forward execution is the location of a variable's value in data memory as a procedure or function is exited (i.e., the value on top of the variable stack for the variable). Thus, upon exit of a procedure or function, when the values of local variables (including parameters and constants) and their locations in data memory are normally lost, the locations of these variables, must be saved on the save stack. When backing up through a procedure or function call, (i.e. executing the procedure or function in reverse), the original locations of the local variables in data memory can be restored to the top of their respective variable stacks from the save stack.

How can one be certain that the original variable values will be in the restored locations upon backing up? Consider how a value in data memory is changed. The only way this can happen is through an assignment operation. But earlier in this chapter, a mechanism was introduced that allowed an assignment instruction to be reversed. Therefore, even though a memory location may have been assigned numerous different values since the procedure exited, as backing up occurs, that memory location will have been reset to the required value by the time the procedure is encountered in reverse.

Consider the example Pascal program fragment in Figure 13. It consists of a header definition for procedure *something* with one value parameter; there are three calls to that procedure from another routine. The lines labeled 0,1,2, and 3 have corresponding sections in Figure 14. Figure 14 contains the variable structures and the save stack that correspond to each of the procedure calls in Figure 13. The section labeled 0 in Figure 14 refers to the state of the structures before any procedure call has been executed. Notice that the save stack is empty, and notice too that the variable stack for P is also empty.

```
        Procedure  something(P  :  integer);
                          .
                          .
                          .
0
1                  something(7);
2                  something(5);
3                  something(-16);
```

Figure 13
A Pascal Procedure Fragment *something*

Now let’s examine line 1 in Figure 13. This is the first call to procedure *something*. Notice that during the call, P’s stack in section 1 of Figure 14 now has a value, 1, which is a location in data memory. Notice also that the data memory location which this points to (data memory location 1) contains the value of the parameter which was passed to *something*. During this call, any references to P are referring to the data memory location that is pointed by the top of P’s variable stack.

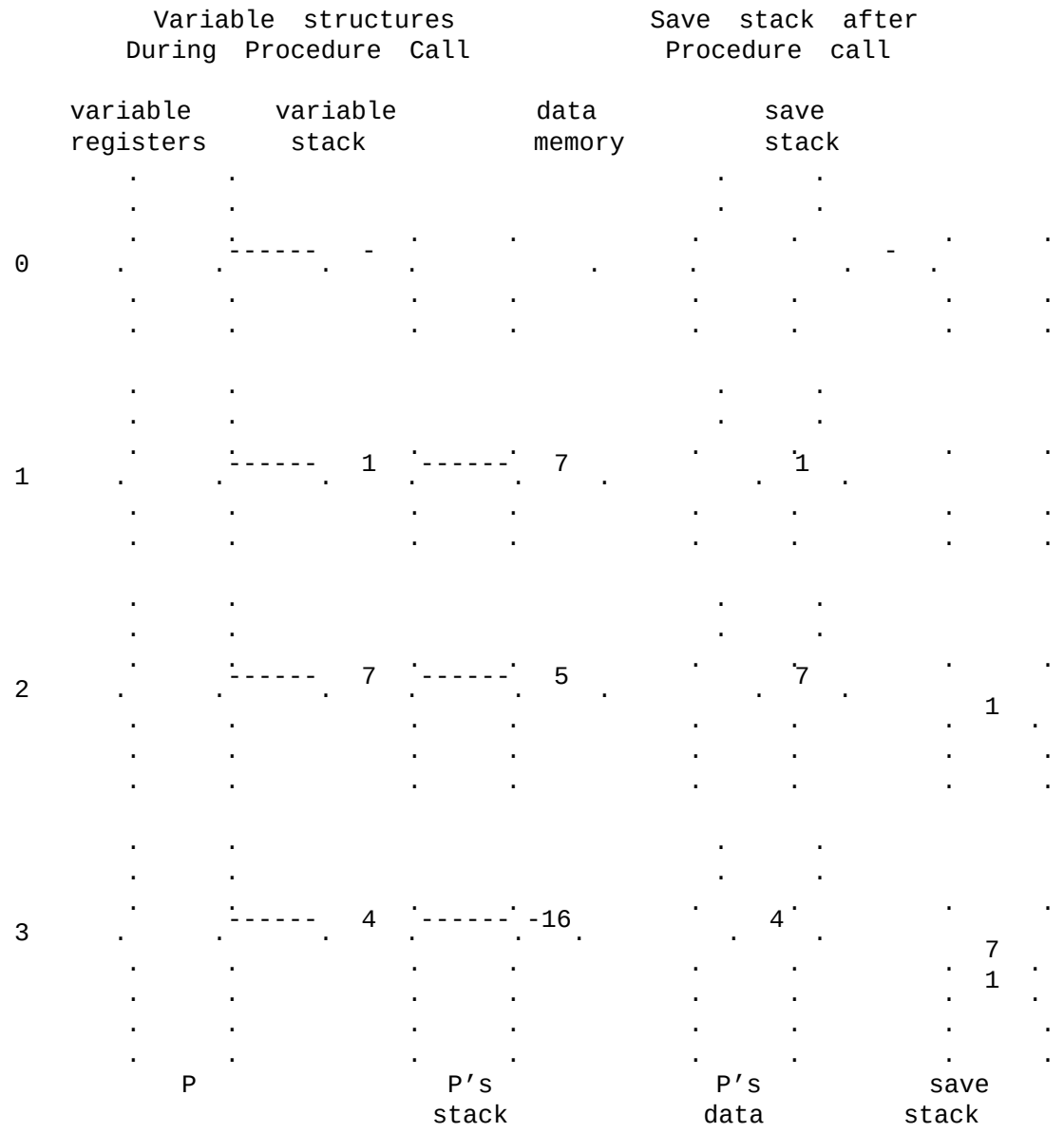


Figure 14
Variable and Save Stack During Successive Calls to Procedure *something*

The save stack in section 1 of Figure 14 shows the state of the stack after procedure *something* finishes executing for the first time. Notice that it now has the value 1 on top. This is because when the procedure exited, the data memory location to which P was pointing would have been lost, so it was saved by the E–machine on the top of the save stack. Consider now the second call to *something* in line 2 of Figure 13 and compare it with section 2 in Figure 14.

The top of P's variable stack now contains the value 7, which points to data memory location 7, which contains a 5. Now any references to P will refer to memory location 7 (i.e., to the value 5). When procedure *something* is exited this time, the top of the variable stack would again be lost if it were not saved. Thus, the 7 on top of the variable stack for P is pushed onto the save stack by the E–machine, resulting in the save stack configuration of section 2 in Figure 14.

The third call to procedure *something* follows in exactly the same manner. When the procedure is executing, the variable P refers to the data memory location contained on the top of P's variable stack, and when the procedure ends, that data memory address is pushed onto the save stack.

Reversing through these procedure calls simply consists of popping the addresses off the save stack and pushing them onto P's variable stack when reversing through the procedure's exit, and popping the top of P's variable stack when reversing through the procedure's entrance.

The Label Registers

Execution in a program is not a simple, linear affair. There are branches, calls to subroutines, returns from subroutines, and other nonsequential types of instructions that add complexity to the problem of backing up. We have seen how to reverse many E–machine instructions by utilizing the save stack. What we haven't yet determined is how to reset the current program counter so that it points to the proper previous instruction. If the current instruction was arrived at from some instruction other than the immediately preceding instruction (e.g., via a branch instruction) there must be some method available for recovering the line number of the instruction branched from.

For example, Figure 15 gives a simple E–code program (for clarity, variables are referred to by name rather than their variable registers, and addressing modes, data types, and critical and noncritical designators have been omitted). The program does the following: I's value is pushed onto the evaluation stack followed by J's value. The *cmp* instruction of line 3 then compares the top two stack values, consuming these values, and pushing the result of the comparison onto the stack. Notice line 4; if the top of stack value denotes "equal", a branch must be made to the *label 1* instruction, which is in line 7 (that is, the current program counter must be set to 7). Otherwise execution proceeds sequentially through lines 5 and 6 until line 7 is reached.

The *label* instruction of line 7 is the interesting instruction in this case. As seen, depending on the values of I and J, the instruction executed just previous to line 7 could have been either line 4 or 6. How can it be determined for backing up which one really did precede line 7?

The brute force method of solving this problem is simple but very inefficient. If, at each step, the current program counter is stored on a stack, all that is needed to restore the current program counter upon backing up is to replace its value with the top of stack value. This method

```
1     push   I
2     push   J
3     cmp
4     breq   1
5     push   I
6     pop     J
7     label  1
8     halt
```

Figure 15
Simple E-code Program With a Branch

will work, but it is inefficient for the following reason. Most instructions in a program have only one possible previous instruction, the one that directly precedes it in the program. In the example of Figure 15, only line 7 has more than one possible previous instruction. All of the other instructions have only one. A more elegant and efficient method to solving this problem, then, is to identify the instructions with more than one possible previous instruction (referred to hereinafter as "branch points") and only save the *previous* program counter when one of these instructions is executed in the forward direction. In order to do this, branch point instructions must be identifiable.

How can branch points be identified by the E−machine as it executes an E−code program? The characteristics of a branch point are easy to categorize. A branch point is any instruction that can be executed in some order other than sequentially from the instruction immediately preceding it. Most such instructions can be readily identified: since both branch and call instructions require a label as one of their arguments, any instruction that is a branch point because of a branch or call must be an E−code *label* instruction. This leaves one class of branch points still unidentified, those arrived at by a return from a procedure or function. The return instruction does not--and indeed cannot--have a label as an argument; instead, control must be returned to the instruction immediately following the call that invoked the procedure or function (the utility of a procedure or function lies in the fact that it can be called from anywhere and, after execution, will return to the instruction immediately after the call).

From the above discussion, it is clear that each E−code instruction that immediately follows a procedure or function call is a branch point. However, examining an arbitrary E−code instruction in isolation does not

allow one to determine whether the previous instruction was a call. Thus, some sort of mechanism must be employed to mark such an instruction as a branch point at compile time. Since all branch points except those arrived at by a return are E–code label instructions in any case, the same technique can be employed to branch points arrived at by a return. The compiler can simply be designed to generate an E–code *label* instruction immediately following each procedure or function call.

This technique ensures that all branch points are E–code *label* instructions. Thus, for successful backup, when the E–machine executes a *label* instruction in the forward direction, it must save the previous program counter value in some fashion. Recall that in the E–machine, the previous program counter is always maintained in the register by that name. Every time the current program counter is changed, its old value is first placed into the previous program counter. (Notice that this structure is not a stack. Only one value is stored at any one time in the previous program counter.)

In order to save the previous program counter for successful backup, then, whenever an E–code *label* instruction is executed, the E–machine employs its label stacks and label registers (see Figure 8). Each label instruction is to be assigned a label register at compile time, where each label register is a pointer to a unique label stack (the reason for the stack is given later). Thus whenever a *label* instruction is encountered by the E–machine, the value in the previous program counter is pushed onto the stack referenced by that label's register.

Now, look at the example program given in Figure 16. There are two branch points in this program: line 1 and line 11. This program contains a loop in which lines 1 through 10 are executed until I and J are equal. Obviously, this loop could iterate a large number of times, and each time the *label* instruction of line 1 is executed, it appears that the previous program counter should be pushed onto the label stack of label 1. However, except for the very first time line 1 is executed, the previous program counter will always contain 10. There should be a way to take advantage of this repetition and save some space.

The E–machine does this in the following way. Each element of the label stack associated with each branch point has two parts, one for holding the value of the previous program counter and one for holding a count, as shown in Figure 17. Rather than just pushing the previous program counter onto the label stack when a label instruction is executed by the E–machine, the E–machine first compares the previous program counter to the number stored in the top element of the label stack. If these two values are equal, the associated counter on the stack is simply incremented, thus recording the number of times this label instruction was reached from the same previous instruction. Thus, rather than storing *n* identical previous program counter values, where *n* is the number of times the loop is iterated, only one copy of the repeated previous program counter value is saved along with *n*, a tremendous savings.

```
0       ...
1      label  1
2      push    I
3      push    J
4      cmp
5      breq    2
6      push    I
7      push    1
8      add
9      pop      I
10    br        1
11    label  2
12    halt
```

Figure 16
Simple E-code Program with a Loop

Address	Counter
Address	Counter
Address	Counter
Address	Counter

. .
. .
. .

Figure 17
General Label Stack

Look again at Figure 16 and consider what will happen to the label stack for the branch point instruction at line 1 as the E–machine executes the instructions. Assume that I equals 3 and J equals 5. The E–machine will step sequentially through the instructions starting at 0. When the *label 1* instruction at line 1 is executed for the first time, the address of the the instruction executed just prior to it (at this point, instruction 0) is pushed onto label 1's label stack, resulting in the label stack of Figure 18.

0	1

. .
. .
. .

Figure 18
Label Stack After 0 Loop Iterations

As the E–machine continues executing, I and J will be compared, they will be found to be not equal and so the E–machine will continue executing sequentially, incrementing I in the process, until line 10 is reached. At that point, a branch to the *label 1* instruction is executed, which loads 1 into the program counter. When the *label 1* instruction is executed, the address of the instruction that was executed just prior to this is pushed onto label 1's stack. Since that instruction was the branch instruction at line 10, a 10 must be pushed as shown in Figure 19.

At this point in the execution, the loop has executed once, I equals 4, J equals 5, and the E–machine has just executed line 1. Proceeding sequentially with the execution of the program results in I and J being compared. Once again, I does not equal J and the E–machine executes sequentially, again incrementing I, until line 10 is reached. At this point, the branch to *label 1* is executed. The execution of *label* 1 causes the address of the instruction executed just prior to the *label 1*, 10, to be pushed onto label 1's stack. This results in the label stack of Figure 20. Notice that no new address was actually pushed onto the stack. Since the top of the stack had the same value as the value that was to be pushed, the counter of the top of the stack was simply incremented (from 1 to 2). If the address had been different than the value of the top of the stack, a new value and counter would have been pushed onto the top of the stack.

10	1
0	1

. .
. .
. .

Figure 19
Label Stack After 1 Loop Iteration

10	2
0	1

. .
. .
. .

Figure 20
Label Stack After 2 Loop Iterations

How to reverse through a *label* instruction should now be clear. The address on top of that label's stack is simply placed in the program counter. If the corresponding count is one, the label stack is also popped, otherwise the count is just decremented.

Critical vs. Noncritical Instructions

Early on in the chapter, it was mentioned that a machine running backwards and a high level language program executing backwards represented similar but not identical processes. The reason this is so is that one high level language statement will, in general, correspond to many machine language instructions. For example, the Pascal assignment statement

```
Y := X + Y - 17 * Z * Z;
```

will be translated into at least ten machine language instructions, as shown in Figure 21, only one of which has any effect on the values of the variables in this statement (the final pop instruction). Since the intent of the proposed system is to display the execution dynamics of high level language programs, it is unnecessary to be concerned about precisely backing up the E-code instructions that only calculate intermediate values. This observation led naturally to a classification system for E–machine instructions that reflects this situation. If an E–machine instruction destroys information necessary for backup in the high level language program, it is classified as *critical* by the compiler; if it does not, it is classified as noncritical.

This identification of E–code instructions as either critical or noncritical allows the E–machine to save for backup purposes only that information necessary to reverse statements in the high level language program. Since the vast majority of compiled E–code instructions will be noncritical, a large savings in storage space and time is realized. However, it should be noted that the flexibility is present to accurately back up E-machine code line by line by simply designating each instruction as critical.

```
push    X
push    Y
push    17
push    Z
```

```
        mult
        push    Z
        mult
        sub
        add
        pop     Y
```

Figure 21
Translation of X := X + Y - 17 * Z * Z;

CHAPTER 6

COMPILING TO E-CODE

The actual design of a compiler for translating some high level programming language (e.g., Pascal) into E-code; as well as other applications for the E-machine, is left for others. However, this chapter is included as a starting point to assist those who will be developing compilers for the E-machine. The following description is only a guide to the most important considerations facing a compiler writer and is not meant to be complete.

Recall that the purpose of the E-machine is to allow high level programming language execution dynamics to be displayed dynamically as an aid to teaching and learning programming. Therefore, when the dynamic display interface is to show a high level language program executing, both the high level language source program and the compiled E-code program must both be available. Only the E-code program will be executing. However, to the user it must appear as if the high level language program were executing. This can be accomplished using two E-machine components: the line number register and the variable registers.

Recall from Chapter 5 that the line number register contains the line number of the source program statement that was translated into the E-code instruction group that is currently executing. The dynamic display interface will use the information in this register to indicate to the user which source program statement in his or her program is executing. Generating E-code instructions that correctly update the line number register is one of the most important parts of an E-code compiler.

The variable registers are the second component of the E-machine that will be used by the dynamic display interface in showing source program execution. Recall that each variable (that is, each variable, parameter, and constant) of the source program will be assigned a unique variable register at compile time. Since it will be necessary for the dynamic display interface to update the values of any variables that have changed with each statement execution in the source program, it is essential that the dynamic display interface have access to a *symbol table* that associates each variable in the source program with its unique variable register. The symbol will allow the dynamic display interface to ascertain the value of each variable and update the display of variable values. The creation of this symbol table is another important task of an E-code compiler.

Recall from Chapter 5 that many E-code instructions have two modes: critical and noncritical. An E-code compiler must decide during translation whether a given E-code instruction should be used in critical or in noncritical mode. This decision will perhaps be the most compiles

part of designing an E-code compiler. Later in this chapter, an *ad hoc* method for doing this is presented.

First, let's look at one possible method of building the symbol table, a straightforward task. Consider the Pascal program in Figure 22. A simple way to generate a symbol table for this program is just to start at the beginning of the program and scan one line at a time. Each time a variable declaration is encountered (again, this is the extended definition of variable), assign the next available E-machine variable register to that variable. When the last line of the program is reached, each program variable will have been assigned a variable register. This would take only a single pass through the source program. The symbol table in Figure 23 was generated in this way from the Pascal program in Figure 22. Notice in Figure 23 the method used for tagging parameters with the procedure or function to which they belong. This same method could be used to tag local variables.

```
1         program  recurse  (input,output);
2
3         var
4              ct,n,sum  :  integer;
5
6         function  factorial(n  :  integer)  :  integer;
7
8         begin
9              if  n  =  0
10                  then
11                       factorial  :=  1
12                  else
13                       factorial  :=  n  *  factorial(n-1)
14        end;
15
16        procedure  increment(var  x  :  integer);
17
18        begin
19             x  :=  x  +  1
20        end;
21
22        begin
23             sum  :=  0;
24             n  :=  1;
25             while  n  <  4  do
26                  if  sum  <  10
27                       then  begin
28                            sum  :=  sum  +  factorial(n);
29                            increment(n)
30                            end
31        end.
```

Figure 22

Example Pascal Program

Generating E-code instructions to update the line number register and deciding whether an instruction is critical or not can both be handled with the same technique. This technique is called *packetizing*. Packetizing is a method for dividing the source program into a set of packets, where each packet represents the smallest unit of a source program to be highlighted by the dynamic display interface as execution progresses. Until now, it has been assumed that the dynamic display interface would simply highlight the current source program statement being executed. However, in typical high level languages, a statement can be quite complex (e.g., an if statement). A packet will represent smaller components of the source program that will need to be highlighted by the dynamic display interface. The compiler writer must use his or her knowledge of the high level programming language to decide how to packetize that language. Then it must be determined in the E-code where critical instructions are to occur in translation of packets and the types of critical instructions to employ. Figure 24 is a diagram showing how Pascal can be packetized. Following the example of Figure 24, a packet is defined as the smallest element a user of the dynamic display interface would find interesting. This is a very *ad hoc* definition, but it should help direct the efforts of a compiler writer, who obviously must work in close collaboration with the designer of the dynamic display interface.

Name	Register
ct	1
n	2
sum	3
factorial:n	4
increment:x	5

Figure 23
Symbol Table For Pascal Program

The packetizing method illustrated in Figure 24 can be used in compilation as follows. Take each packet in the diagram and write out if and where critical instructions may occur in the translation of the packet. Figure 25 shows the result of this process applied to the diagram in Figure 24. Notice that the only critical E-code instructions are *alloc*, *link*, *pop*, and *label*. Since this is the case, a usable heuristic for identifying critical instructions is to make every instance of those instructions critical. This will ensure that proper backup will occur, but not necessarily in the most efficient fashion. If some of these instructions were designated critical, when, in fact, they could have been designated noncritical, this would mean some information that is unnecessary for backing up is being stored. Finding an optimal way to generate code for backing up is beyond the scope of this thesis, however, and will be left for others.

```
[program  name(input,output,files);]

[const]
     [const  declaration]

[type]
     [type  declaration]

[var]
     [variable  declaration]

[assignment  statement]

[begin]

[end]

[procedure  call]

[if  (boolean  expression)]
     [then]
          then  clause
     [else]
          else  clause

[case  (expression)  of]
     [const  :  ]  case  body;
[end]

[repeat]
     loop  body
[until  (boolean  expression)]

[while  (boolean  expression)  do]
     loop  body

[for  VAR  :=  EXPR  to|downto  EXPR  do]
     loop  body

[procedure  name]
  [(parameter  declaration);]
     procedure  body

[function  name]
  [(parameter  declaration):type;]
     function  body
```

Figure 24
Ad Hoc Packetizing Method for Pascal

There is still one unusual area of code generation that should be mentioned: how to generate the E-code instructions necessary to update the (source program) line number register. This can be done easily once the source program has been packetized. Whenever the compiler encounters a left packet symbol, in this case, [, it can generate the command

line #

where # is the line number in the source program of the line that contains this packet. The line command generated by the left packet symbol can be considered to be an E-machine interrupt: it can have the effect of causing control to be returned to the dynamic display interface just following the execution of the E-machine code corresponding to the current source program packet being executed, and just prior to the execution of the next packet. When the dynamic display interface sends a signal to the E-machine to resume, the E-code corresponding to the next packet of instructions can be executed by the E-machine, and so.

A packetized version of the program of Figure 22 is given in Figure 26. Figure 27 presents a possible in-line translation of the program of Figure 26. The mode designator *c* is used for critical instructions and *n* for noncritical instructions. Comments are included to help explain the translation. In the comments, PC refers to program counter and PPC to previous program counter. Figure 27 should also be viewed in conjunction with Figure 23, the associated symbol table for the dynamic display interface.

Critical Instructions	Program Packet
[program name(input,output,files);]	none
[const]	none
[const declaration]	none
[type]	none
[type declaration]	none
[var]	none
[variable declaration]	alloc #
[assignment statement]	pop V#
[begin]	none
[end]	none
[procedure call]	none
[if (boolean expression)]	none
[then]	none
then clause	
[else]	label #
else clause	label
[case (expression) of]	none
[const :] case body;	label #
[end]	label #
[repeat]	label #
loop body	
[until (boolean expression)]	none
	label
[while (boolean expression) do]	label #
loop body	
	label
[for VAR := EXPR to downto EXPR do]	label #
loop body	
	label
[procedure name]	none
[(parameter declaration);]	alloc #/link #
procedure body	
[function name]	
[(parameter declaration):type;]	alloc #/link #
function body	

Figure 25
Packetizing and Determination of Critical Instructions

```
1       [program  recurse  (input,output);]
2
3       [var]
4            [ct],[n],[sum]  :  [integer;]
5
6       [function  factorial]([n  :  integer])  :  [integer;]
7
8       [begin]
9            [if  n  =  0]
10                [then]
11                     [factorial  :=  1]
12                [else]
13                     [factorial  :=  n  *  factorial(n-1)]
14     [end;]
15
16     [procedure  increment]([var  x  :  integer]);
17
18     [begin]
19          [x  :=  x  +  1]
20     [end;]
21
22     [begin]
23          [sum  :=  0;]
24          [n  :=  1;]
25          [while  n  <  4  do]
26               [if  sum  <  10]
27                    [then  begin]
28                         [sum  :=  sum  +  factorial(n);]
29                         [increment(n)]
30                         [end]
31     [end.]
```

Figure 26
Example Packetized Pascal Program

```
1       [program recurse (input,output);]
                line    1             {display should highlight line 1}
2                                        {no E-code generated}
3       [var]
                line 3                {display should highlight line 3}
4            [ct],[n],[sum] : integer;]
                line    4             {display should highlight line 4}
                push    INTEGER,integer {push INTEGER onto evaluation stack}
                alloc c,1           {allocate top-of-stack bytes to variable 1}
                line    4             {display should highlight line 4}
                push    INTEGER,integer {push INTEGER onto evaluation stack}
                alloc c,2           {allocate top-of-stack bytes to variable 2}
                line    4             {display should highlight line 4}
                push    INTEGER,integer {push INTEGER onto evaluation stack}
                alloc c,3           {allocate top-of-stack bytes to variable 3}
5
6       [function factorial([n : integer]) : integer;]
                label c,1           {push PPC onto label 1's stack}
                line    6             {display should highlight line 6}
                line    6             {display should highlight line 6}
                push    INTEGER,integer {push INTEGER onto evaluation stack}
                alloc c,4           {allocate top-of-stack bytes to variable 4}
                pop     c,V4        {pop the top of the stack into variable 4}
7
8       [begin]
                line    8             {display should highlight line 8}
9            [if n = 0]
                line    9             {display should highlight line 9}
                push    V4,integer    {push value in V4 onto the evaluation stack}
                push    0,integer     {push 0 onto the evaluation stack}
                cmp     n,integer     {compare top of stack to next lowest,}
                                                {push result}
                bneq    n,2         {branch to label 2 if the condition is met}
10                [then]
                line    10           {display should highlight line 10}
11                      [factorial := 1]
                line    11           {display should highlight line 11}
                push    1,integer     {push 1 onto the evaluation stack}
                br       3             {branch to label 3}
12                [else]
                label c,2           {push PPC onto label 2's stack}
                line    12           {display should highlight line 12}
```

Figure 27
Example In-Line E-code Translation of a Packetized Pascal Program

```
13                  [factorial := n * factorial(n-1)]
                line    13          {display should highlight line
                label   c,3         {push PPC onto label 3's stack}
                push    V4,integer   {push v4 onto the evaluation stack}
                push    V4,integer   {push v4 onto the evaluation stack}
                push    1,integer    {push 1 onto the evaluation stack}
                sub     n,integer    {subtract top of stack from next down,}
                                                    {push result}
                call    1            {call label associated with factorial}
                label   c,4         {push PPC onto label 4's stack}
                mult    n,integer    {multiply the top two values of the stack}
                                                    {push result}
14      [end;]
                line    14          {display should highlight line 14}
                unlink  4           {pop the top of 4's variable stack}
                                                    {deactivate 4}
                return              {pop top of the return address stack into th
                                                    {program counter}
15
16      [procedure increment([var x : integer]);]
                label   c,5         {push PPC onto label 5's stack}
                line    16          {display should highlight line 16}
                line    16          {display should highlight line 16}
                link    c,5         {pop address from top of stack}
                                                    {push onto label 5's stack}
17
18      [begin]
                line    18          {display should highlight line 18}
19          [x := x + 1]
                line    19          {display should highlight line 19}
                push    V5,integer   {push V5 onto the evaluation stack}
                push    1,integer    {push 1 onto the evaluation stack}
                add     n,integer    {add top two values of stack}
                                                    {push the result}
                pop     c,V5,integer{pop the top the the evaluation stack into \
20      [end;]
                line    20          {display should highlight line 20}
                unlink  5           {pop address off 5's label stack}
                return              {pop top of the return address into the PC}
21
22      [begin]
                line    22          {display should highlight line 22}
23          [sum := 0;]
                line    23          {display should highlight line 23}
                push    0,integer    {push 0 onto the evaluation stack}
                pop     c,V3,integer{pop the top of the stack into V3}
```

Figure 27 (continued)

```
24          [n := 1;]
               line  24            {display should highlight line 24}
               push  1,integer{push 1 onto the evaluation stack}
               pop   c,V2,integer  {pop the top of the stack into V2}

25          [while n < 4 do]
               label 6             {push PPC onto label 6's stack}
               line   25           {display should highlight line 25}
               push   V2,integer    {push V2 onto the evaluation stack}
               push   4,integer     {push 4 onto the evaluation stack}
               cmp     n,integer     {compare the top two values of the stack}
               bgeq   n,7         {if the top of the stack matches the}
                                                {condition, branch to label 7}
26               [if sum < 10]
               line   26           {display should highlight line
               push   V3,integer    {push V3 onto the evaluation stack}
               push   10,integer    {push 10 onto the evaluation stack}
               cmp     n,integer     {compare top of stack to next down}
               bgeq   n,8         {branch if the top of stack matches}
                                                {the condition}
27                    [then begin]
               line   27           {display should highlight line
28                         [sum := sum + factorial(n);]
               line   28           {display should highlight line 27}
               push   V3,integer  {push V3 onto the evaluation stack}
               push   V2,integer  {push V2 onto the evaluation stack}
               call   1             {call subroutine at label 1}
               label  c,9         {push PPC onto label 9's stack}
               add     n,integer   {add top two values of the evaluation stack}
29                         [increment(n);]
               line   29           {display should highlight line 29}
               push   R2,address  {push V2's address onto the stack}
               call   5             {call procedure increment}
30                         [end]
               label  c,8         {push PPC onto label 8's stack}
               line   30           {display should highlight line 30}
               br       6                    {branch to label 6}
               label  c,7         {push address of PPC onto label 7's stack}
31     [end.]
               line   31           {display should highlight line 31}
               halt                 {stop executing}
```

Figure 27 (continued)

The translation in Figure 27 provides the intuition for the way that compiling a Pascal program to E-code should proceed. A more rigorous definition is beyond the scope of this thesis. The next chapter contains a recap of some of the main points of this thesis and some new directions that this project could take.

CHAPTER 7

CONCLUSIONS AND NEW DIRECTIONS

The goal of this thesis was the design of a virtual machine architecture to support research and development in the realm of dynamic teaching aids for introductory computer science courses, primarily beginning programming courses. Thus this virtual machine architecture was to support the execution of high level language programs in a fashion that made the display of all facets of program execution dynamics feasible and flexible. The most important specification for the virtual machine architecture was the requirement for reverse execution. This specification arose from experience with DYNAMOD; a common request from students viewing DYNAMOD examples in the classroom was for the instructor to back up and repeat certain statements. Thus was born the E-machine, a virtual machine that appears to meet the goals of the thesis quite well.

Much remains to be done to realize the ultimate goal of a comprehensive teaching and learning tool for introductory computer science. An emulator for the E-machine must be written, a dynamic display interface must be designed and implemented, and a user interface must be developed. Furthermore, at least one compiler, for example, a Pascal to E-code compiler, must be written. It is proposed that the emulator, all compilers, and both interfaces be implemented in C in order to ensure the system’s portability to virtually all computer types likely to be

used by students. Once this has been accomplished, the entire package can be incorporated into a hypertext environment built around an online textbook.

If this looks like a never-ending project, it is! Unlike a commercial system that must support the production people who develop applications with that system, and therefore cannot later incorporate radical changes without disrupting the continued effective use of the system, the project envisioned here will suffer no such constraints. As a purely academic system, it can be changed at will to incorporate pedagogical innovations that support the mission.

Consider the E-machine itself. As it stands, it should support the execution of Pascal programs quite well, with one exception: no provision has been made for handling input and output. This was a conscious omission that leaves this portion of the design to those implementing the dynamic display interface. If it turns out that input and output is best handled by the display interface, that will be fine. However, if it becomes clear that new instructions need to be added to the E-machine instruction set to support input and output, that will be fine, too. Other high level programming languages, if incorporated into this system, may also require that new instructions be added to the instruction set of the E-machine. A good example of this would be the bit-level operations of C. The E-machine was intended to be an open-ended project from the start.

In conclusion, it is hoped that the E-machine will not just sit on a shelf and gather dust, but that it will soon be implemented and become a part of the envisioned dynamic teaching and learning system. There is every reason to believe that this will be the case.

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