A FRAMEWORK FOR MONITORING PROGRAM EXECUTION

Clinton Lewis Jeffery

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Department of Computer Science
The University of Arizona
Tucson, Arizona 85721

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TABLE OF CONTENTS

ABSTRACT

Program execution monitors are used to improve human beings' understanding of program run-time behavior in a variety of important applications such as debugging, performance tuning, and the study of algorithms. Unfortunately, many program execution monitors fail to provide adequate understanding of program behavior, and progress in this area of systems software has been slow due to the difficulty of the task of writing execution monitors.

In high-level programming languages the task of writing execution monitors is made more complex by features such as non-traditional control flow and complex semantics. Additionally, in many languages, such as the Icon programming language, a significant part of the execution behavior that various monitors need to observe occurs in the language run-time system code rather than the source code of the monitored program.

This dissertation presents a framework for monitoring Icon programs that allows rapid development of execution monitors in the Icon language itself. Monitors have full source-level access to the target program with which to gather and process execution information, without intrusive modification to the target executable. In addition, the framework supports the monitoring of implicit run-time system behavior crucial to program understanding.

In order to demonstrate its practicality, the framework has been used to implement a collection of program visualization tools. Program visualization provides graphical feedback about program execution that allows human beings to deal with volumes of data more effectively than textual techniques. Ideally, the user specifies program execution controls in such tools directly in the graphics used to visualize execution, employing the same visual language that is used to render the output. Some monitors that exhibit this characteristic are presented.

CHAPTER 1
Introduction

This dissertation presents a framework for monitoring the execution of programs written in the Icon programming language [Gris90c]. The motivation for this research is a need for better tools to aid in the understanding of dynamic aspects of program behavior during various phases of the software life cycle, including debugging, performance tuning, and maintenance.

This chapter describes these tasks and defines a class of programs called execution monitors that aid human beings' understanding of program behavior. The chapter concludes with an overview of the rest of the dissertation and its contribution to the field of execution monitoring.

1.1 Understanding program behavior

Program understanding is a very general topic. Some program understanding systems convey very specific information about a small portion of a program, such as the workings of a single algorithm. Others are concerned with explaining the role that a program or a collection of programs play within a larger computational system. This dissertation addresses a common problem in between these two extremes: understanding the workings of a single (possibly large) program.

Persons who are confronted by a need to understand a program usually have only two alternatives: studying the source code, or running the program to see what it does. Ideally, a program would be understandable using one or the other of these methods; in practice, reading source code is impractically cumbersome for many programs, and construction of test cases to explain program behavior is often a tedious and speculative undertaking. These difficulties motivate the development of special programs that are used to help explain the behavior of other programs.

Program understanding systems are used in a variety of applications. The most common motive for program understanding is *debugging*. Programs that produce incorrect output or fail to complete their execution due to bugs are prime candidates for tools that assist program developers and maintainers in program understanding tasks. A *debugger* is a program designed specifically to help with the debugging process. General-purpose program understanding tools are also used to assist in debugging.

A second major application of program understanding systems is *performance tuning* or *performance debugging*. A correct, working program may be of limited usefulness if its performance is poor. Frequently a program's authors or maintainers can improve execution speed by using different programming techniques or modifying the program's algorithms and data structures. By providing an accounting of what resources the program is using and which sections of code are primarily responsible, performance tuning systems can direct programmers' efforts to where they are most needed.

A third application of program understanding is *software instruction* and *orientation*. The internal workings of a program may be of special interest to students learning important algorithms, data structures, or programming techniques; this situation frequently arises when learning a new language. Persons assigned to maintain or improve a program written by someone else similarly need to *orient* themselves as to its general operation. In both of these cases the persons involved may be entirely unfamiliar with the program source code, and can benefit from information provided by program understanding tools before consulting source code, or without referring to it at all.

In addition to these established uses for program understanding systems, program understanding tools can provide language implementors with valuable assistance in the task of *language implementation tuning*. Program understanding tools that provide information about the execution of programs also directly or indirectly provide information about the language's implementation. This information can be used to improve performance or address problems in the implementation.

1.2 Types of program understanding tools

Programs that provide information about other programs can be separated into two main categories based on the kind of information they provide. *Static analysis tools* examine the program text and, in conjunction with knowledge of the language, provide information about a program that is true for all executions of that program independent of its input [Dunn84]. Compiler code optimizers, pretty printers, and syntax-directed editors frequently employ static analysis techniques.

In general, static information cannot explain program behavior because behavior depends on input data in addition to the program text. For example, the number of times through a loop may depend on the size of an input file, or the execution path through a conditional statement may depend on interactive user-input from a keyboard or mouse.

Dynamic analysis tools provide information about a specific program execution on a specific set of input data [Dunn84]. Since dynamic analysis involves extracting information from a running program rather than its source code, these tools pose implementation problems that are very different from those found in static analysis tools. Another name for a dynamic analysis tool is a *program execution monitor*; a program execution monitor is a program that monitors the execution of another program [Plat81]. Program execution monitors complement static analysis tools and provide execution information that static tools cannot, such as details about the program's control flow, intermediate results that are computed, or depictions of internal data structures as the program runs. On the other hand, static aspects of a program such as variable names often provide context crucial to the understanding of execution behavior. Good dynamic analysis tools incorporate static information in support of dynamic information. Execution monitors include the source-level debuggers and profilers commonly bundled with compilers and available on many operating systems.

An execution monitor may either present information to the user as the program executes (immediate or *run-time* analysis), or it may present information at some later time such as after execution completes (*post-mortem* analysis). Run-time analyzers provide immediate feedback and allow user direction of the kind and level of detail of the information monitored. In contrast, post-mortem analyzers may perform extensive computations to condense the execution information and present it in a useful way. The two methods are not mutually exclusive.

Run-time analysis tools can further be categorized as *passive* or *interactive*. In a passive system, the tool presents information to the user, but the user has little control over the activity. In an interactive system, the user may have external control over what information is displayed, or even may be able to modify the computation being observed or the data being processed.

1.3 Scope of this research

This research presents a framework that facilitates the development of superior execution monitors, particularly interactive run-time analysis tools for very high-level sequential languages. It is not concerned with monitoring techniques for parallel, distributed, or real-time computing systems, although the monitoring of such systems does require effective sequential monitoring techniques.

This dissertation discusses execution monitors within a well-defined context: the Icon programming language. Icon is a high-level procedural language that descends primarily from SNOBOL4 and SL5. A large array of language features, documented extensively elsewhere [Gris90c], make Icon very attractive for a variety of general-purpose application areas, notably text processing and rapid prototyping. Some of these features are

- a familiar syntax reminiscent of Pascal and C,
- generators, goal-directed evaluation, and backtracking,
- a rich set of built-in data structures and operations,
- advanced string scanning and text processing facilities,
- run-time type checking and coercion,
- automatic storage management, and
- invocation mechanisms that include variable number of arguments, and argument defaults for built-in functions.

Icon does not contain the concept of a statement found in most procedural languages. Instead, constructs such as assignments and if-then-else's that are statements in other languages are expressions that can produce values for a surrounding expression in Icon; for this reason conventional statement-level program monitoring is not well-defined in Icon, and statement-oriented linguistic mechanisms are inadequate in common monitoring situations.

Similarly, the manner in which a program uses Icon's built-in structured data types, scanning facilities, and run-time type coercion has a fundamental effect on program execution behavior [Gris92a]. These language features motivate an orientation in execution monitoring that is more directed towards observing the language's built-in "primitive" operations and run-time system behavior than would be appropriate for a lower-level conventional procedural language; some of the techniques used for Icon are general, while others are not. For example, while the technique of monitoring program behavior by instrumenting standard library calls is applicable to any language, in C or Pascal there is no incentive to monitor activity during an addition operator to see what it does. In Icon, integer overflow during addition results in the creation of an arbitrary precision value that is allocated from the heap and might go undetected by a programmer reading the source code.

Within the context of the Icon language, this research addresses several problems that are common to any execution monitoring system. The primary tasks of an execution monitor are to collect information about a program's execution and present that information to the user in an understandable way. In addition to the inherent complexity of these tasks, the main problems posed by execution monitoring in very high level languages are:

Volume — the large amount of data to be processed by the monitor code entails performance problems both in the gathering of information and in the presentation of that information. Efficient gathering of information involves selecting the relevant information from the huge pool of available program behavior data. Efficient presentation of information includes making effective use of the visual medium to communicate with the user, as well as understanding the user's powers of perception. Even if it is gathered and presented efficiently, the large amount of information inherent in monitoring tends to obscure items of interest.

Intrusion — all monitoring systems alter the execution environment of the program under study; when the act of monitoring a program changes the behavior under observation, it is called *intrusion* [Aral88, Henr90]. Henry defines *control intrusive* and *data intrusive* methods of adding instrumentation to a program in order to monitor its execution [Henr90]. Control intrusive instrumentation takes the form of code (such as a procedure call to a monitor routine) embedded within the program. Data intrusion arises in object-oriented systems in which instrumentation is added by subclassing a class to be instrumented and overriding its access methods with additional code calls monitor code in addition to calling the superclass method(s) to perform the normal computation. The term intrusion has also been used to refer to the execution slowdown imposed by monitoring [Aral88]; in real-time and concurrent systems this can render monitoring useless. Since Icon's application domain does not include real-time or concurrent programs, this form of intrusion is not considered in this work. The effect of monitoring on execution speed is considered only so far as to establish framework viability on "real" Icon programs.

Access — execution monitors often require extensive access to the variables and structures in the program being monitored. If the monitor and program being monitored are distinct programs, operating system constraints may restrict this access, or create performance problems in this area, or both. From the point of view of the execution monitor author, the access problem may also be reflected by low-level or cumbersome notations used to read or write target program data. A good example of access is the traversal of pointers in data structures: if it requires operating system intervention or a notation other than that used in the target program source code, the monitor has poor access to the target program and the task of writing monitors is made difficult. Solutions to the access problem, such as adding monitor code directly to the program being monitored, often aggravate the intrusion problem.

These problems are universal in execution monitoring and appear repeatedly in the literature. While no general solution for these problems exists, improved monitoring techniques may lessen their severity or solve them for practical purposes on real programs. Traditionally the implementation of execution monitors has been very difficult because the programmers implementing a new monitor necessarily spent a considerable effort addressing these three problems. The difficulty of implementing monitors in turn limits or effectively prevents efforts to improve monitor technology by experimental means.

1.4 Dissertation contributions

The goal of this research is to reduce the difficulty of constructing execution monitors by developing a practical framework in which monitor construction is relatively easy. The problems of volume, intrusion, and access motivate the chosen solutions. The central thesis advocated in this research is the following.

> Source-language support for obtaining and presenting execution information is instrumental in the development of exploratory monitoring capabilities in very high-level languages.

The framework developed in this research consists of source-language support for the central act of gathering execution information. It addresses the problems of volume, intrusion, and access in the following ways.

Volume — Built-in language features for the central act of gathering execution information provide the performance that is necessary for effective monitors written in the source language, despite the generally slower speed of very high-level languages. Dynamic control over the information flow from the program to the monitor is essential for performance.

Intrusion — Language support that gathers execution from the run-time system eliminates the need for code intrusion. Provision of separate memory allocation areas for the monitor and target program avoids data intrusion.

Access — Source language support allows the execution of the monitor and target program in a shared interpeter and provides full source-level access of the monitor to the target program. The framework uses a synchronous coroutine execution model within a shared address space, offering significant advantages without restricting the kinds of monitors that the system supports.

In addition to these features that address core execution monitoring tasks, the framework provides full separation of the program and the various monitors that observe it. Taking the form of dynamic loading and a virtual monitoring interface, this separation provides the ease of use that is necessary in order to provide exploratory programming capabilities. The separation allows multiple monitors to observe a program at the same time, and allows new monitors to augment or enhance the capabilities provided by existing monitors.

The intent of the framework is to provide exploratory programming capabilities not just for expert monitor developers, but also for applications programmers who are trying to understand their programs. Given this framework and appropriate library support procedures, writing an execution monitor is no more difficult than writing other applications that involve communication between programs, and often is simpler than writing such applications.

This research is applicable to other high-level languages: It is relevant to most functional, logic, and object-oriented languages. A good first test of the applicability of the techniques presented in this dissertation to another language is whether the language provides automatic storage management; if it does, the run-time system probably supports other high-level features and makes up a large portion of both the language implementation and the behavior to be monitored. The results presented suggest that designers of such languages should consider integral support for monitoring, rather than adding it on as an afterthought.

1.5 Overview of this dissertation

The next chapter describes prior work in the areas of execution monitoring and program visualization. Following that, the primary objectives of the framework are presented in Chapter 3. Chapter 4 and Chapter 5 present the underlying mechanism developed to support Icon execution monitoring, and the monitoring instrumentation.

Chapter 6 through Chapter 10 give examples of fundamental monitoring techniques used by many execution monitors, including data collection, presentation and user interaction techniques. These examples, while simple, demonstrate that the framework makes it possible to develop useful monitors in an exploratory fashion. Chapter 11 discusses monitor communication and gives an example of a coordinator program that allows independently-written monitors to be run simultaneously. Chapter 12 includes timing measures that establish the practicality of the framework's performance. Chapter 13 summarizes the work and discusses future research areas. Appendices include larger source-code examples.

CHAPTER 2
Related Work

This dissertation is related to existing research in two major domains: program execution monitoring, and program visualization. The research being presented contributes to the first category, but it is designed to enable new research in the latter category. Consequently, this chapter presents related work in both areas, with a primary emphasis and organization revolving around the execution monitoring aspects of the respective systems. Like this work, a number of earlier systems contribute to both fields; such systems have been called *graphical debuggers* [Dewa86]. Existing systems are characterized in terms of three aspects that contribute to usability:

information sources and access methods by which monitors observe program behavior,

execution models that describe the relationship between the monitor and the program being monitored, and

user-interaction features such as the information the monitor provides to the user, how information is presented, and the extent to which the user controls and directs monitor activity.

Several aspects of these issues are presented first, followed by discussions of existing systems.

2.1 Information sources and access methods

Several methods are used to obtain information about program behavior during execution. Information sources and access methods determine the quality and quantity of the monitoring that can be performed, and are thus a primary design factor in monitoring systems. The method used to obtain information is limited by and often motivates the execution model adopted by a monitoring system. The most common methods are *run-time instrumentation* [Lint90], *manual instrumentation* [Brow84, Stas90], *interpreter instrumentation* [Bock86, Dewa86, Masn90], and *instrumenting compilers* [Henr90]. In addition to various methods of instrumentation, some systems provide additional access to program variables and other execution information. This access, if it is present, often makes it possible to monitor behavior not explicitly addressed by the instrumentation.

Run-time instrumentation refers to the modification of the monitored program code immediately prior to or during execution. Modifications often consist of overwriting an instruction of interest with a jump instruction or operating system trap. In either case, control temporarily transfers to code that sends information to the monitor and/or allows the monitor to query the program for information. The code is typically modified in selective areas of interest, and execution proceeds at full speed in other areas.

Manual instrumentation is the insertion of arbitrary monitoring code by hand into the program being monitored. This method is labor intensive, and requires an instrumentation effort for each program that must be monitored, and additional effort when an instrumented program is modified.

Interpreter instrumentation is the insertion of monitoring code into the language interpreter instead of the program being monitored. The instrumentation can then provide information about the behavior of any program executed by the interpeter.

Instrumenting compilers include preprocessors and code generators that add instrumentation to the code as they produce output. These systems have the potential of automatically instrumenting any program in the language that the compiler recognizes. The code they produce is usually much larger than the non-instrumented code and is usually intended solely for use within the monitoring system.

2.2 Execution Models

Of the many models of the relationship between the monitor and the program being monitored used in existing systems, three are primary: the *one-process model* [Brow84, Lond85], the *two-process model* [Lint90, Sosi92], and the *thread model* [Aral88]. In the one-process model, the monitor consists of a library of procedures linked to the program being monitored or integrated into the run-time system. This is the simplest, highest-performance arrangement, and it has the advantage that the monitor has convenient access to the program being monitored. The one-process model is code intrusive, and errors in the target program or monitor code can affect each other in critical ways. In addition, the control flow logic within the monitor is somewhat inside-out, since the monitor is activated strictly through callbacks.

In the two-process model, the monitor is a separate process from the program being monitored. This reduces or eliminates the problems of code and data intrusion, at the expense of greatly complicating monitor access to the state of the program being monitored. This access problem makes monitor construction more difficult, and frequently entails serious performance problems.

In the thread model, the monitor is a separate thread in a shared address space occupied by the program and possibly other monitors. This provides many of the benefits as well as some of the drawbacks of both the one-process model and the two-process model, including the one-process model's risk that program errors in the target program or monitor may affect each other and compromise the monitoring results. The thread model's potential concurrency provides dramatically improved performance for monitoring on shared memory multiprocessors for those forms of monitoring that do not preclude it, such as profilers.

2.3 User-interaction facilities

A primary distinguishing characteristic in existing systems is whether they present material as text, or employ graphics to present information. A second distinguishing characteristic is whether a system updates information continuously during execution, or provides information during pauses in execution.

User-input facilities also vary in existing systems, from controls that can only start and stop execution to entire languages that can be used to query about execution information during execution or while the monitored program is stopped.

In addition to its uses in controlling the rate of execution and in query facilities, user input in some systems allows the user to modify the program being monitored. This capability is useful in debugging sessions in which an error may be repaired or an alternative value may be substituted.

An important class of execution monitors are those that employ *program visualization* techniques to provide information to the user. Program visualization refers to the use of graphics to depict program control and/or data at a particular instant, or to continuously update (*animate*) a graphic display to show dynamic behavior as program execution commences. Examples of such tools are the MemMon system for dynamic storage visualization [Gris89] and the Incense data structure visualization tool [Myer83].

The best-known area of program visualization is the field of algorithm animation. Some of the most famous examples are Ronald Baecker's motion picture, "Sorting Out Sorting" [Baec81], Marc Brown's research systems BALSA [Brow84] and ZEUS [Brow91], and John Stasko's Tango [Stas90]. The original motivation for algorithm animation was to explain an algorithm to an audience for educational purposes. Since then it has been applied to a number of tasks including algorithm research. Within these contexts, existing systems have been successful in producing high-quality animations of specific algorithms.

2.4 Run-time instrumentation systems

Representative run-time instrumentation systems include standard source-level debuggers as well as more general profiling and monitoring systems that modify the code at run-time.

2.4.1 Dbx

Dbx is representative of conventional source level debuggers, the most common form of execution monitor [Lint90]. Source-level debuggers vary widely in their capabilities, but the features of dbx are illustrative of this class of monitors:

- The basic interface is textual in nature. The user specifies both queries and execution controls in a textual command language.
- Execution proceeds, in the default case, just as if the target program were not under the control of the debugger. Ideally, the debugger does not *perturb* the execution at all. Compiling with "debugging support" or turning off compiler optimizations in order to debug often perturbs the execution.
- Source code can be displayed as it is executed, in a single-step mode.
- Execution can be directed to proceed until a particular point in the source code is reached. Such a point is called a *breakpoint*.
- Breakpoints can be made conditional, testing a predicate (usually expressed in a subset of the source language) in order to determine whether the debugger should be invoked. Unfortunately, conditional breakpoints are "so slow that using this capability is often not practical" [Lint90].
- Program variables can be displayed along with their values; in the case of structures, elements can be displayed and traversed.
- The procedure call chain can be displayed, including parameters passed at each level.

Dbx provides interactive control over program execution at a desirable level—the source language. However, because of language features such as loops and recursion, execution behavior is not proportional to the size of the program source code. The program execution space defined by so-called "hand-simulation" of a running program is orders of magnitude larger than the program source code space. For this reason source-level techniques do not scale well as program size increases. There is simply too much data to monitor, even for common programs of modest size and execution time.

2.4.2 Dalek

Of the many source-level debugging systems, one that deserves further mention in comparison with this dissertation is the Dalek system [Olss90, Olss91], an extension of the GDB debugger [Stal92]. Dalek is significant in offering both a special-purpose programming language with which to specify debugging operations and a coarse-grained dataflow approach for recognizing higher abstractions of execution behavior. This combination of features provides a very powerful mechanism for characterizing program behavior of interest. This flexibility is limited primarily by the low performance of the underlying UNIX operating system feature that supports debugging; the ptrace interface requires two context switch operations for every word of data obtained by the monitor from the program being debugged [ptr83].

2.4.3 Parasight

The Parasight system [Aral88, Aral89] uses a shared-memory thread model for execution profiling of parallel programs written in conventional languages such as C. In Parasight the profiler runs on a separate processor and thus has a minimal impact on the execution speed of the program being observed. The thread model provides monitors with complete access to program state. Parasight's user interface includes a C interpreter. The system provides for insertion of additional monitoring instrumentation at run-time by allowing code patching to be applied at any source line number.

2.4.4 FIELD

The FIELD programming environment developed at Brown University includes an in-process monitoring facility in which instrumentation is added by code patching [Reis90a, Reis90b]. FIELD provides monitoring in the context of a general message-based programming environment in which a central message server forwards messages to multiple tools using a *selective broadcast* model. Monitoring instrumentation is bound to application code at link time. During execution, instrumentation code sends messages to the message server; the message server in turn forwards the messages to those tools that have specified an interest in that type of message. Tools specify which kinds of messages they are interested in when they start executing; this configuration allows the message server to implement the selective broadcast mechanism.

Reiss notes that this general model has significant advantages in easing the integration of new tools into the environment. In addition to the benefits this provides during tool development, the generality of the model offers the advantage that execution monitoring tools coexist with other programming tools geared towards different parts of the program development cycle, such as compilers and cross-referencing tools. Since the message model is based solely on strings, communication of data structures is problematic and creates serious performance problems.

The Forest system employs a generalization of FIELD's selective broadcast paradigm [Garl90]. In Forest, the central message server maintains dynamic lists of *policies* regarding which tools should receive various events. Dispatching an event requires evaluation of the policies associated with that event. This adds flexibility but places greater computational requirements on the message server.

2.5 Manual instrumentation systems

Manual instrumentation is frequently employed in systems for algorithm animation. Although tedious, manual instrumentation also is employed during debugging when other debugging tools are ineffective or unavailable.

2.5.1 BALSA

In the BALSA system an animator (often the program's author) augments a well-understood program by inserting calls to the animation library at significant points in the algorithm to convey key aspects to some audience [Brow88]. This code-intrusive approach is suitable for many applications, but Brown notes that if the desired granularity is very detailed it may involve line-by-line annotations. In addition, the applicability of an algorithm animation system also is limited if the system does not provide access to program state such as the values of variables, as in the case of BALSA.

2.5.2 Smalltalk

London and Duisberg developed a kit for algorithm animation of Smalltalk programs [Lond85]. They emphasize detailed views of smaller program examples, for use in industrial prototyping and simulation.

Although instrumentation is manual, in Smalltalk instrumentation can be added by subclassing existing classes and adding monitoring code to various operations in a location that is textually distinct from the original program code. Monitoring instrumentation can also be added by modifying the implementation of various operations along the inheritance hierarchy used by the objects being monitored.

London and Duisberg's animation kit is quite suitable for the algorithm animations it was designed to support, and more generally for understanding tasks that are concerned solely with correctness and not performance. Although instrumentation need not obfuscate the program source text, the technique is data-intrusive, since it significantly modifies program behavior in the memory heap. This reduces the system's usability in performance tuning applications, since understanding memory heap behavior is often crucial to understanding performance.

2.5.3 Tango

The Tango algorithm animation system, developed at Brown University, emphasizes support for smooth transitions between states in the visualization in order to improve the quality of the animations and reduce the difficulty with which animations are programmed [Stas90]. Tango introduces a path-transition paradigm based on locations, images, paths, and transitions. In addition to smooth transition support, Tango also employs dynamic loading to simplify animation design and shorten the time required to modify an animation.

Tango's goal of supporting exploratory development of algorithm animations is noteworthy. Like BALSA, it employs manual instrumentation of the algorithms being animated; while it is easy to create many animated views of an algorithm in order to choose one that is useful, visualizing new algorithms and larger programs is a major undertaking requiring an understanding of the algorithm to be animated.

2.6 Interpreter instrumentation

Interpreter instrumentation is common for high-level languages, and it is used occasionally in debuggers for lower-level languages. Instrumented interpreters vary widely in the range of features that are instrumented and the nature of the monitoring facilities they provide.

2.6.1 SNOBOL4

The SITBOL implementation of SNOBOL4 was extended to include an *event association* facility [Hans78] by which built-in or user-defined functions were associated with significant program events. The program events available for association consisted of variable references, statement executions, program interruptions, function calls and returns, and run-time errors. The SNOBOL4 event association facility is an early example in which monitoring capabilities were implemented in the source-language, yet debugging code could be written separately and compiled in with programs when debugging was needed.

2.6.2 PECAN

PECAN is an integrated programming environment for an extended dialect of Pascal [Reis84]. It employs multiple views of the static aspects of the program from a single underlying abstract syntax tree. PECAN also includes execution monitoring facilities and can display the current line being executed highlighted in a view of the program source code. PECAN's data visualization capabilities include graphical views of program data structures at break points. Reiss mentions plans to combine PECAN and BALSA to enable program animations.

2.6.3 KAESTLE and FooScape

KAESTLE and FooScape provide a visualization system for the Lisp environment that includes tools for both data and control visualization and provides both static and dynamic views [Bock86]. Their implementation is based upon the FranzLISP tracing system that provides for calls to a monitoring system upon function entry and exit. This system does not allow monitoring of behavior internal to a function, nor can it visualize implicit behavior such as garbage collection. The homogeneous nature of LISP with its simpler control structures and data types mitigates these limitations.

2.6.4 Dewlap

Dewar and Cleary developed a Prolog debugger called Dewlap (debugger with logical applications) that featured graphical displays of the Prolog execution tree [Dewa86]. They note that the simplicity of Prolog execution was obscured in earlier Prolog debuggers that employed textual traces of execution. The debugger is written in Prolog, and includes user-definable views of data. The authors observed that Dewlap is too slow to use as a production tool given the speed of their hardware and the interpretive Prolog implementation they used.

2.6.5 SeePS

In SeePS, Masnavi animated the internal workings of a NeWS PostScript interpreter by generating Display PostScript windows that reflect the state of various internal operations [Masn90]. The size and complexity of the program being animated (an entire language interpreter with hundreds of built-in primitives) take this project well beyond the realm of algorithm animation.

SeePS was not designed with construction of new visualizations in mind; it was designed to animate the workings of the language interpreter itself rather than the execution of the PostScript program being interpreted. This goal is ambitious as it stands, and since NeWS has sophisticated event handling and lightweight processes, it represents a challenge to visualization.

The initial approach in SeePS was similar to the one taken in this dissertation: NeWS source code was augmented to include interesting events; lightweight processes written in NeWS could then receive such events and generate visualizations for them. Masnavi cites the benefits of being able to write the visualizations in a higher-level language and not have to recompile the interpreter in order to modify a visualization.

In Masnavi's case, this approach was abandoned because it prevented the use of future, improved versions of the NeWS interpreter, and because SeePS could not be distributed in such a form. For these reasons, Masnavi rewrote SeePS entirely in NeWS. This prevents SeePS from visualizing implicit run-time system events; further, Masnavi notes SeePS suffers from efficiency problems.

2.6.6 Dynascope

Dynascope is a tool for directing the execution of C language programs using event streams [Sosi92]. Event streams are not at the source-level, but rather at the level of the machine instruction for an hypothetical processor [1]. Events are produced during the interpretation of code by a virtual machine. Dynascope supports execution of mixed virtual-machine and native-code programs and only the parts of a program under observation must be interpreted. In effect the monitoring instrumentation and virtual-machine interpreter are linked into the program as an extensive addition to the run-time library.

Dynascope directors are arbitrary programs written independently from the hypothetical processor interpreter; they run in a separate UNIX process connected using stream-based interprocess communication. This has the distinct advantage of allowing various directors to be attached to and detached from the system dynamically. On the other hand, it means that access to the full program state of the executing program is limited or non-existent.

2.7 Instrumenting compilers

Another alternative to instrumenting a program by hand or instrumenting an interpreter is to modify the translation process to automatically instrument the generated code to include execution monitor calls.

2.7.1 Voyeur

Voyeur is a system for visualizing the execution of parallel programs [Soch89]. It is noteworthy in that its authors designed it explicitly to simplify the task of learning how to build views in the system. Voyeur presumes that each new parallel program may require a new visualization, and therefore the system should be easy enough for programmers to construct new views without the aid of an animator-specialist as is generally required in BALSA and ZEUS. In their section on future work the authors note that Voyeur needs access to the program state, support for multiple views, and easier interface construction.

2.7.2 UW Illustrating compiler

The UW illustrating compiler (UWPI) visualizes the execution of programs for a subset of Pascal [Henr90]. It is intended for an educational audience. It is not intended as a framework for exploratory visualization development, but rather, it provides a few fixed views of execution. View selection is performed automatically by static analysis of the program, rather than being user-driven.

UWPI illustrations are driven by calls that are automatically inserted into the code during compilation. Since insertion is automatic, UWPI contrasts with manually code-intrusive systems such as PECAN and BALSA. On the other hand, since the code after analysis includes calls to the illustration system, UWPI can be said to be implicitly code intrusive. First of all, a program must be specially processed before it can be viewed. Second, after it has been so treated, the result does not run outside the illustration environment. Third, since illustration is driven by explicit calls in the code, the system cannot illustrate implicit run-time behavior, except that which is ascertained by the static analysis component that inserts the illustrator calls.

[1] This processor is not a high-level virtual machine such as those used by Smalltalk, Prolog, or Icon, but rather it is a low-level architecture typical of current RISC chips.

2.7.3 SMLD

The debugger for standard ML, SMLD, is based upon extensive, automatic instrumentation of the program code during compilation [Tolm92]. Compiler optimizations reduce the slowdown and code size blowup implied by the instrumenting compiler technique. The instrumentation supports relatively standard debugging features such as setting breakpoints and inspecting the values of variables, but not altering program execution by modifying variables. An extension of SMLD supports reverse execution by means of checkpointing.

2.8 Features in existing systems that facilitate monitor development

No existing system provides comprehensive support for exploratory execution monitor programming, but if several existing techniques are combined carefully a suitable framework emerges. The key is to select information sources and access methods, an execution model, and user interaction features that provide ease of programming with acceptable performance. Icon's execution monitoring framework can be viewed as one such configuration of monitoring characteristics.

An instrumented interpreter such as SeePS, or an instrumenting compiler such as Voyeur is potentially an ideal, fully-automated information source. An instrumented interpreter is easier to implement, but more importantly removes the requirement that a program be recompiled in order for it to be monitored. Instrumentation must be extensive or the monitoring capabilities provided will be limited, but extensive instrumentation poses its own performance and intrusion problems. Programming constructs to minimize the impact of extensive instrumentation are essential in dealing with the volume problem in a general-purpose framework.

A thread execution model such as that of Parasight provides crucial access and performance features. Since some monitors modify the program being monitored, ease of programming implies that synchronous execution should be the default or at least be easy to specify. Additionally, support for multiple monitors, such as the selective broadcast model developed in FIELD, allows monitors to specialize on specific aspects of program behavior and makes them easier to write. If multiple monitors are to be easily selected and used, the thread model must also include dynamic loading capabilities.

In the area of user-interaction facilities, an ideal environment would support advanced graphics and user-interface capabilities, including animation support such as that provided by Tango. This topic is almost unrelated to execution monitoring, but is very necessary in order to provide exploratory programming of state-of-the-art tools. One observation is that interactive user-input is expensive in a highly animated monitor, and specific support in the framework can mitigate this cost by integrating the user-input stream with the stream of information coming from the monitored program.

CHAPTER 3
Overview of the Framework

This chapter presents an overview of the execution monitoring framework that has been added to the Icon programming language. The framework allows the user to execute a given Icon program under the observation of one or more monitoring programs, also written in Icon. Since the models used and capabilities of execution monitoring systems vary widely, this chapter serves to position this research with respect to existing systems.

The overview begins with a brief inventory of the framework components, followed by an user's-eye-view of the system in the form of a standard execution monitoring scenario. The purpose of the scenario is to characterize the execution monitoring process that is supported and to motivate some of the features and limitations of the system.

Following the execution monitoring scenario, the functional characteristics of each of the primary components of the execution monitoring framework are described. Details of the use of these components and their implementation are presented in subsequent chapters.

3.1 Framework inventory

Icon's execution monitoring framework consists of the following components. These additions are characterized in terms of their relationship to pre-existing Icon features. Several of these components are general-purpose language features that are useful independent of execution monitoring; such features, when already present in other languages, may require modification if they were not designed to support execution monitoring.

Dynamic loading — The ability to load multiple programs into a shared execution environment is provided in order to adequately support monitor access to target program data. Prior to this work, Icon had no concept of dynamic loading. *Dynamic linking* is *not* desirable in the context of execution monitoring, since the names in the monitor are distinct from those in the target program.

Synchronous execution — The monitor and target program execute independently, but not concurrently. This allows the monitor to control target program execution using a simple programming model. Icon already has a language mechanism and data type that support synchronous execution of independent threads of execution; the mechanism is slightly extended to support the relationship between monitor and target program.

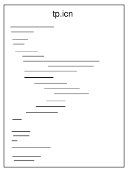
Run-time system instrumentation — Extensive information about execution is available to the monitor from locations in the language run-time system that are coded to report significant events. This obviates the need for control-intrusive techniques of obtaining information from the target program. It also offers higher performance than target program instrumentation. The run-time system instrumentation is an extension and generalization of an earlier special-purpose monitoring facility oriented around dynamic memory allocation and reclamation [Gris89]. It also supercedes the language's built-in procedure tracing mechanism [Gris90c].

Event masks — Monitor control over target program execution is coupled with the concept of *filtering* [Elsh89] in a language mechanism called an *event mask*. Event masks provide a simple, dynamic model of execution control that adequately meets performance requirements in processing the high volume of execution information. Events that are of no interest to the execution monitor are never reported and do not impose unreasonable execution cost. Event masking uses a set abstraction to describe the execution behavior that is of interest to the monitor; an existing Icon type that supports high-performance set operations is employed to provide event masking in a manner that is familiar to Icon programmers.

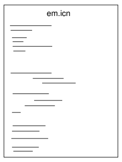
3.2 Standard execution monitoring scenario

Understanding the framework begins with a description of the monitoring activities that it supports. This scenario presents the relationship between the execution monitor and target program in its simplest form; more sophisticated relationships between the monitor and target program are discussed later in this chapter and in Chapter 11.

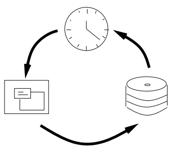
Preliminary definitions



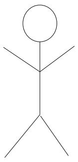
target program (TP) – the Icon program under study, a translated Icon executable file. Monitoring does not require that the TP be recompiled, nor that the TP's Icon source code be available, although some monitors make use of program text to present information.



execution monitor (EM) – an Icon program that collects and presents information from an execution of a TP.



program behavior – the results of executing the TP. Behavior is meant in a general sense that includes program output, execution time, and the precise sequence of actions that take place during execution.



user – a human user, capable of understanding the TP's execution behavior. The user must know Icon in order to make good use of many EMs or to write a new EM. In general, the user need not necessarily be familiar with the TP's source code.

Sources of relevant execution behavior

Execution monitoring begins with a user who has questions about the behavior of a TP (Figure 3.1).

Answers to important questions often may be found by following the execution as it proceeds through source-language constructs, but in high-level languages the behavior in question often depends upon the language semantics as implemented by the language run-time system (Figure 3.2; `iconx.c` denotes the

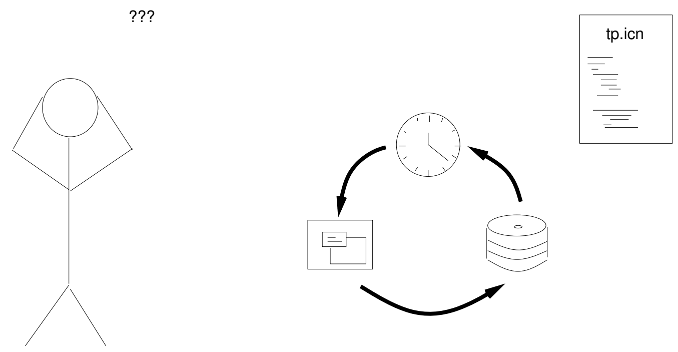


Figure 3.1: Monitoring starts with a user, a program, and questions

aggregate of files that comprise the Icon language run-time system). For this reason, many forms of execution monitoring provide useful information even if the TP's source code is not available. Figure 3.2 could be further elaborated to include behavioral dependencies on the platform on which Icon is implemented and run. Such dependencies are outside the scope of this dissertation.

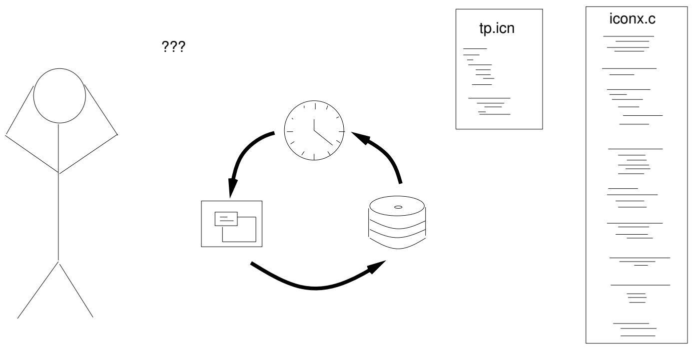


Figure 3.2: Behavior depends on the language, not just the program

Selecting or developing appropriate monitors

Rather than focusing on one monolithic EM that attempts to accomodate all monitoring tasks, the framework advocates development of a suite of specialized EMs that observe and present particular aspects of a TP's behavior. The user is responsible for selecting an appropriate EM or set of EMs that address the user's concerns.

If no available EM can provide the needed information, the user can modify an existing EM or write a new one. This end-user development of execution monitors also is useful when an existing EM provides the needed information but it is obscured by other information; existing EMs can be customized to a particular problem.

Running the target program

The user runs the TP one or more times, monitored by a selection of EMs (Figure 3.3). General-purpose EM's provide an overall impression of program behavior.

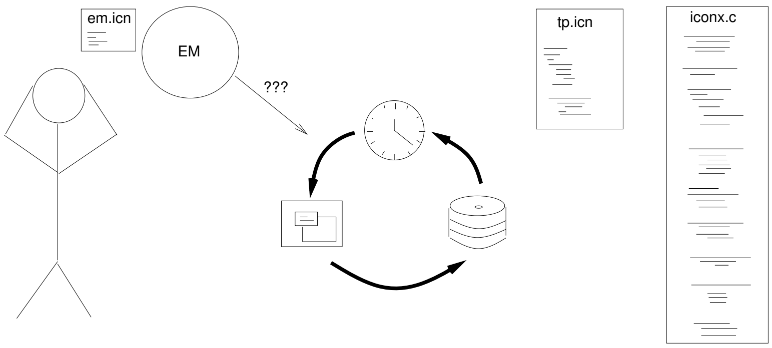


Figure 3.3: EMs can answer questions about TP behavior

Obtaining more specific information frequently requires that the user interact with the EMs to control the TP's execution, either to increase the amount of information presented during specific portions of execution or to stop execution in order to examine details. In order to provide this interactive control, EMs must present execution information as it happens during the TP's execution, rather than during a post-mortem analysis phase.

3.3 Framework characteristics

The preceding scenario depends on support for exploratory programming in several areas: controlling a program's execution, obtaining execution information, and interacting with the user. In order to support these tasks, the framework provides synchronous shared-address multi-tasking and an event-driven execution control model. These features are provided by extensions to the Icon language.

Multi-tasking

The first and most basic characteristic of the framework is an execution model in which an EM is a separate program from the TP — a multi-tasking model. In this model the EM views the TP as a separately loaded coroutine [Marl80]. The coroutine relationship is the primary means by which EMs control TP execution and coroutine transfers of control are the primary source of execution information from a TP (Figure 3.4). The precise nature of the interaction between the EM and TP (the arrows in Figure 3.4) is a major contribution of this dissertation and is discussed further in Section 3.3.2 in this chapter and in Chapter 5.

Multi-tasking is provided by a set of facilities collectively named MT Icon. MT Icon has the following benefits in an exploratory programming environment: the EM and TP are independent programs, the EM has full access to the TP, and the mechanism accomodates multiple EMs. These benefits are described in more detail below.

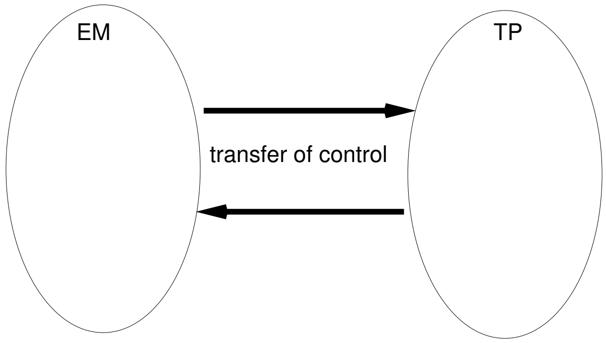


Figure 3.4: EM and TP are separately loaded coroutines

Independence

Because the EM and TP are separate programs, the TP need not be modified or even recompiled in order to be monitored by an EM; neither does an EM need modification or recompilation in order to be used on different target programs. The separation of EMs and TPs also simplifies the writing of EMs because an EM need not be implemented as a set of callback functions — it has its own control flow. By definition, execution of tasks such as EMs and TPs is synchronous in MT Icon. The TP is not running when an EM is running, and vice-versa. This synchronous execution allows EMs and TPs to be independent without introducing the complexity inherent in concurrent programming.

Another degree of EM and TP independence is afforded by separate memory regions; EMs and TPs allocate memory from separate heaps. For this reason memory allocation in the EM does not affect the allocation and garbage collection patterns in the TP. Because Icon is a type-safe language with run-time type checking and no pointer data types, EMs and TPs cannot corrupt each others' memory by accident; only code that contains explicit references to another program's variables and data can modify that program's behavior.

Access

An address space is a mapping from machine addresses to computer memory. Within an address space, access to program variables and data are direct, efficient operations such as single machine instructions. Accessing program variables and data from outside the address space is slower and requires operating system assistance.

In MT Icon, programs such as the EM and TP reside within the same address space. This allows EMs to treat TP data values in the same way as their own: EMs can access TP structures using regular Icon operations, compare TP strings with their own, and so forth.

Because of the shared address space, the task switching operation needed to transfer execution between EMs and TPs is a fast, "lightweight" operation. This is important because monitoring requires an extremely large number of task switches compared to typical multi-tasking applications.

Multiple monitors and monitor coordinators

MT Icon's dynamic loading capabilities allow simultaneous execution of not just a single EM and a single TP, but potentially many EMs, TPs, and other Icon programs in arbitrary configurations. Although uses for many such configurations can be found, one configuration merits special attention when many specialized EMs are available: the execution of multiple monitors on a single TP (Figure 3.5).

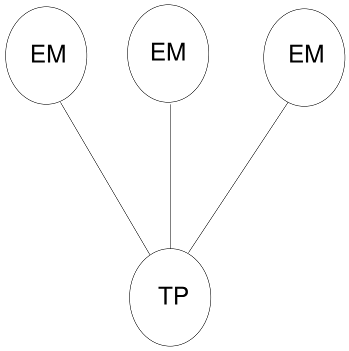


Figure 3.5: Multiple EMs

The difficulty posed by multiple monitors is not in loading the programs, but in coordinating and transferring control among several EMs and providing each EM with the TP execution information it requires. Since EMs are easier to write if they need not be aware of each other, this motivates construction of *monitor coordinators* (MCs), special EMs that monitor a TP and provide monitoring services to one or more additional EMs (Figure 3.6). EMs receiving an MC's services need not be aware of the presence of an MC any more than a TP need be aware of the presence of an EM.

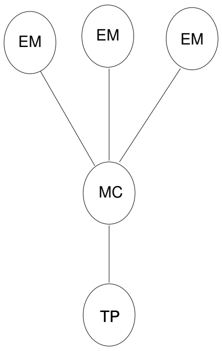


Figure 3.6: An Execution Monitor Coordinator

Execution control

The primary task of an EM is to collect data from a TP's execution. This task poses difficult coding problems and is frequently a performance bottleneck. The nature of the data collection facilities available in a monitoring system also define and limit the kinds of monitors that can be implemented.

Figure 3.7 depicts the system layers present in running an Icon program under the Icon interpreter. The TP code is executed by a virtual machine interpreter written in C, which in turn calls C language run-time support code to perform various language operations [Gris86].

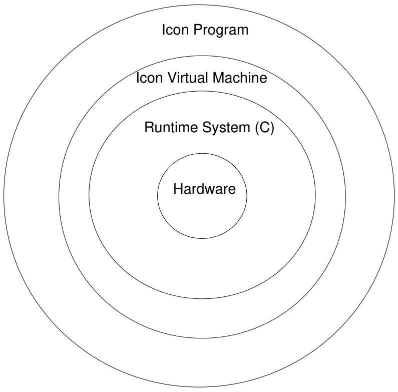


Figure 3.7: Layers in the Icon implementation

Of these layers, the TP code, the virtual machine (VM), and the run-time support code are responsible for aspects of program behavior within the scope of this research. The VM and the run-time system have been extensively instrumented to produce this information for EMs at the Icon level without requiring instrumentation of the TP code.

While the behavior observable from instrumentation of the VM is specific to the Icon interpreter and is of interest primarily to language implementors, run-time system behavior is more general and of interest to normal Icon programmers. This dissertation is primarily concerned with monitors of run-time system behavior. Most of this behavior takes place even in compiled versions of the TP, with the exception of behavioral aspects such as run-time type checks that an Icon compiler can avoid when static analysis determines that they are unnecessary.

This instrumentation consists of locations within the run-time system at which control can be transferred and information reported to the EM. When execution proceeds through one of these points in the run-time system, an *event* occurs. Many events take place during even the simplest of Icon operations. When an EM resumes execution of the TP, it explicitly specifies what kinds of events are to be reported; other kinds of events are not reported. The kinds of events to be reported can be changed dynamically each time the TP's execution is resumed (Figure 3.8). The processing of an event includes a test of whether the TP should transfer control to the EM and code to perform the transfer only if the test succeeds.

Those events at which control is transferred produce *event reports*. When an event is reported the TP's execution is suspended and execution commences in the program that loaded the TP — an EM. Event reporting supports data collection in two ways: An event report contains some information associated with the event itself, and in addition, when the EM gains control it can interrogate the TP's variables and keywords for further information. When an EM requests another event report, the EM suspends execution and the TP's execution resumes where it left off.

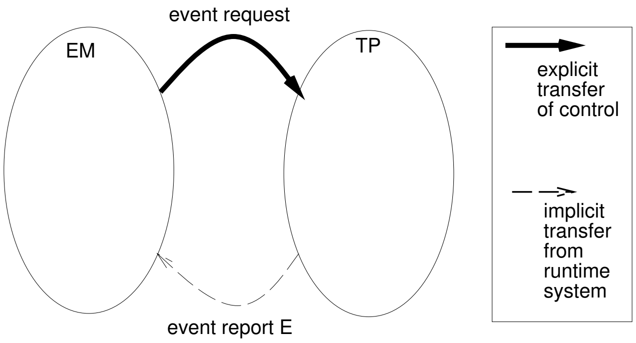


Figure 3.8: Event-driven control of TP

3.4 Comparison with earlier systems

Several specific comparisons between the Icon monitoring framework and existing systems are useful. Icon's monitoring framework integrates ideas found in several previous systems. In addition, it contributes dynamic event masking to control the volume of information generated and adds support for user input in animated tools. The end result is a simplicity in obtaining execution information that achieves the framework goal of supporting exploratory programming.

MT Icon's thread model is synchronous and differs from that of Parasight in that it is designed to simplify the programming task required of monitor writers, rather than to take advantage of shared-memory multiprocessor hardware. Parasight is best suited for passive profiling tasks where the target program and monitor code can run asynchronously.

Dalek [Olss90] provides a programming language with which to write customized monitors; Dalek's language is special-purpose and must be learned while the Icon monitoring framework provides the target program's entire source language, including sophisticated data presentation facilities. Dalek suffers from performance problems when accessing target program state due to its two-process model. If Dalek's implementation were modified to employ shared memory, and it were coupled with some automated instrumentation system, it could provide support similar to that provided by Icon's monitoring framework.

FIELD supports multiple, independent tools that can simultaneously observe program behavior [Reis90b]. Forest extends FIELD's selective broadcast model, adding flexibility comparable to that provided by this framework [Garl90]. The message server employed by FIELD and Forest is geared toward building programming environments that make use of existing tools such as compilers and editors. This mandates a separate process model and is ill-suited to accomodating the volume of events generated by extensive instrumentation. MT Icon does not attempt to integrate existing tools, but instead facilitates the development of new monitors that can take advantage of MT Icon's execution model to provide better information about target program behavior.

Novel features within Icon, the language under study, provided extra motivation for a general approach to experimental monitor development that may not be present in other languages. On the other hand, all programming systems can benefit from improved execution monitor support and therefore stand to gain from new ideas that result from experimental monitor development undertaken in the context of Icon, the exploration made possible by this framework.

The execution monitoring framework introduced in this chapter simplifies development of execution monitors in several ways, while avoiding common pitfalls associated with monitoring. EMs developed in this system tend to be very short compared with those in other languages, because they are developed in the source language rather than the implementation language, because they have full access to TP's program variables, and because EMs can specialize on particular program behaviors of interest.

Shorter EMs are in turn easier to understand, to write correctly, and to enhance. Execution monitoring may not be a simple task, but using this system, execution monitors are no more difficult to develop than other programs with substantial inter-program communication requirements. The next two chapters present the Icon language extensions that comprise the execution monitoring framework.

CHAPTER 4
A Multi-Tasking Icon Interpreter

4.1 Introduction

As mentioned in the preceding chapter, MT (Multi-Tasking) Icon is an Icon interpreter that allows multiple Icon programs to be loaded and run simultaneously within a shared address space. MT Icon is *not* a concurrent programming language nor does it include special support for multiprocessor hardware. Instead, MT Icon provides a task model that supports both cooperative and preemptive multi-tasking without mandating a particular scheduling policy or algorithm. MT Icon's domain is that of high-level language support for programs that benefit from or require a tighter coupling than that provided by inter-process communication; that is, programs that require extensive access to each other's state.

MT Icon's task model is based on Icon's co-expression facility. This chapter starts with a summary of co-expressions, followed by sections that describe MT Icon language extensions and common applications. In addition to its general multi-tasking execution model, MT Icon has features specific to the control and monitoring of loaded programs by the program that loads them. The following chapter describes MT Icon's monitoring features in detail.

4.2 Co-expressions

A co-expression in Icon is a first-class value that encapsulates the execution state of an expression [Gris90c]. Co-expressions are the expression-level equivalent of the *coroutine* facility found in other languages [Marl80]. A coroutine is a process, specified in terms of a procedure call in which the values of local variables are retained even when control is not within that process, and in which execution upon entry continues from the point where control last left that process. Co-expressions generalize coroutines to allow independent threads of control to be created for arbitrary expressions, not just procedure calls.

In addition to their role of providing coroutine semantics at a fine granularity of control, co-expressions were developed as a control mechanism necessary to fully utilize the capabilities of Icon's generators [Wamp81]. In Icon, a generator is an expression whose evaluation may produce more than one result. This feature is extremely useful and permeates the language, but a generator's results are produced only at the generator's lexical location. Co-expressions liberate generators from their lexical site by placing the expression in a value from which results can be extracted one at a time.

Creating co-expressions

A co-expression value is created by the Icon control structure

```
create expr
```

When a `create` expression is executed, *expr* is not evaluated; instead its evaluation is encapsulated as a first-class data object that can be assigned to a variable, passed as a parameter, and so forth. In addition to explicitly created co-expressions, a single co-expression is created implicitly when program execution starts; it is equivalent to the expression `create main()`. Program execution begins in this implicit co-expression.

Co-expression transfers of control

Results are obtained from a co-expression by *activating* it using the operation

[*expr*] @ *coexpr*

Activation transfers control from the current co-expression to the referenced co-expression; control remains in that co-expression until it produces a result. If the referenced co-expression is subsequently activated, its execution continues from where it last produced a result.

If the *expr* is present in the activation expression, it is evaluated and its result is *transmitted* to the co-expression as control is transferred. If *expr* is omitted, a null value is transmitted.

When each co-expression transfers control only by activating co-expressions it has created or by implicitly producing results for its parent, the control graph formed by co-expressions and their transfers of control is a tree. Explicit transfers of control by co-expression activation may result in an arbitrary control graph, generalizing co-expressions to full coroutine semantics.

Co-expression keywords

In Icon, keywords are named global objects that may have special semantics associated with various control structures. Three built-in co-expression values are available to Icon programs in the form of keywords.

&main is the co-expression for the invocation of the main procedure that initiates program execution.

&current is the co-expression in which execution is currently taking place.

&source is the co-expression that activated the currently executing co-expression.

These keywords and their use are further documented in [Gris90c].

4.3 MT Icon preliminary terminology

Before describing the MT Icon task model, a few definitions are needed. These definitions pertain to regions of memory referenced by programs during execution.

Name spaces

A *name space* is a mapping from a set of program source-code identifiers to a set of associated memory locations [Abel85]. Icon programs have a global name space shared across the entire program and various name spaces associated with procedures. Procedures each have a static name space consisting of memory locations shared by all invocations of the procedure and local name spaces private to each individual invocation of the procedure.

When a co-expression is created, a new local name space is allocated for the currently executing procedure, and the current values of the local variables are copied into the new name space for subsequent use by the co-expression.

Program and co-expression state

An Icon program has an associated *program state* consisting of the memory associated with global and static name spaces, keywords, and dynamic memory regions. Similarly, a co-expression has an associated *co-expression state* consisting of an evaluation stack that contains the memory used to implement one or more local name spaces. Co-expressions in an Icon program share access to the program state and can use it to communicate.

4.4 Tasks: an extended co-expression model

The central concept in MT Icon is the *task*; a task is the execution state of a program within the Icon virtual machine [Gris86]. A single task called the *root* is created when the interpreter starts execution. Additional tasks can be created dynamically as needed.

A task consists of a main co-expression and zero or more child co-expressions that share a program state. At the source-language level, tasks are loaded, referenced, and activated solely in terms of one of their member co-expressions; the task itself is implicit.

This definition of tasks is related to the concept of the same name commonly used in operating systems and concurrent programming languages. It differs, however, in certain fundamental respects. Icon is a sequential language; co-expressions in Icon provide a synchronous coroutine execution model, not a concurrent execution model with implicit task switching and scheduling. Another way to view this is that unlike other languages such as Ada, MT Icon provides the task model as a mechanism for multi-tasking, but does not predefine the policy; matters such as the scheduling algorithm used and whether multi-tasking is co-operative or pre-emptive are programmable at the user level.

Another useful comparison can be made between Icon tasks and Smalltalk processes. Both provide pseudo-concurrency within the context of a sequential virtual machine. Since Icon tasks have their own dynamic memory regions, their presence affects each other less than Smalltalk processes affect each other. For example, if one task is exhibiting thrashing heap behavior in which garbage collections are frequent, the other tasks in the system can execute at full speed during the portion of time in which they are running, since they do not allocate memory out of the thrashing task's (full) heap. This minimal effect of tasks on each others' behavior is especially important in the domain of execution monitoring.

4.5 Task creation

In MT Icon, a task can create other tasks. The MT Icon function

```
load(s, L)
```

loads an *icode* file [Gris86] specified by the file name `s`, creates a task for it and returns a co-expression corresponding to the invocation of the procedure `main(L)` in the loaded icode file. `L` defaults to the empty list. Unlike conventional Icon command-line argument lists, the argument list passed to `load()` can contain values of any type, such as procedures, lists, and tables in the calling task.

The task being loaded is termed the *child* task, while the task calling `load()` is termed the *parent*. The collection of all tasks forms a tree of parent-child relationships.

4.6 Running other programs

A co-expression created by load() is activated like any other co-expression. When activated with the @ operator, the child task begins executing its main procedure. Unless it suspends or activates &source, the child task runs to completion, after which control is returned to the parent. Chapter 5 presents an alternative means of executing a child with which the parent retains control over the child as it executes.

An example

This default behavior is illustrated by the program seqload, which loads and executes each of its arguments (string names of executable Icon programs) in turn. In this program the variable arguments is a list of strings passed into the Icon program from the operating system. Each of these strings (extracted from the list using the element-generation operator, !) is passed in turn to load(). load() reads the code for each argument and creates a task in which to execute the loaded program; the tasks are then executed one-by-one by the co-expression activation operator, @. This is ordinary Icon code; there is nothing special about this example except the semantics of the load() function and the independent execution environment (separate global variables, heaps, and so forth), that load() provides to each task.

```
# seqload.icn
procedure main(arguments)
    every @load(!arguments)
end
```

For example, if three Icon programs whose executable files are named translate, assemble, and link are to be run in succession, the command

```
seqload translate assemble link
```

executes the three programs without reloading the interpreter for each program.

4.7 Data access

Although tasks have separate sets of global variables and keywords, they reside in the same address space and can share data. This data access applies to all first-class data objects in Icon, such as procedures and co-expressions. Values can be transmitted from task to task through main()'s argument list, by means of explicit inter-task access functions, or by use of event monitoring facilities described in the next chapter.

Access through task argument lists

The following program takes its first argument to be an Icon program to load and execute as a child, sorts its remaining arguments, and supplies them to the child program as its command line arguments (pop() and sort() are Icon built-in functions that extract the first list element and sort elements, respectively):

```
procedure main(arguments)
    @load(pop(arguments), sort(arguments))
end
```

Argument lists allow more sophisticated data transfers; the seqload example presented earlier can be extended to transmit arbitrary structures between programs using argument lists in the following manner. As in seqload, each string naming an executable Icon program is passed into load() and the resulting task is activated to execute the program. In this case, however, any result that is returned by one of the programs is assigned to local variable L and passed to the next program in the list via the second argument to load().

```
# seqload2.icn
procedure main(arguments)
   every program := !arguments do
      L := @load(program, L)
end
```

The net effect of seqload2.icn is similar to a UNIX pipe, with an important difference: Arbitrary Icon values can be passed from program to program through the argument lists. This capability is more interesting in substantial multi-pass tools such as compilers, where full data structures can be passed along from tool to tool instead of writing out text encodings of the structures to a file.

Inter-task access functions

Several of Icon's built-in functions are enhanced under MT Icon to provide inter-task access to program data. For example, the variable() function in MT Icon takes a co-expression value as an optional second argument denoting the task from which to fetch the named variable. When called with this second argument, variable() is useful for assigning to or simply reading values from another task's variables. In this modified version of the seqload example, the parent task initializes each child task's Parent global variable (if there is one) to refer to the parent's &main co-expression. A child task can then use this variable to determine whether it is being run stand-alone or under a parent task. Inter-program access through the variable() function also is useful in inspecting values, especially at intermediate points during the monitored execution of a TP as described in the next chapter.

```
# seqload3.icn
procedure main(arguments)
   every arg := !arguments do {
      Task := load(arg)
      variable("Parent", Task) := &main
      @Task
      }
end
```

In addition to MT's extensions of existing functions, several new functions have been added. These facilities are useful in execution monitoring and are used in examples in Chapters 6 through 11. Some of the inter-task access functions used in examples are listed in Figure 4.1. In these functions parameter C refers to a co-expression that may be from a task other than the one being executed. Functions that generate can produce more than one result from a given call.
There are other inter-task access functions; [Jeff90] serves as a reference for MT Icon programming.

globalnames(C)	generates the names of C's global variables.
keyword(s, C)	produces keyword s in C.
localnames(C)	generates the names of C's local variables.
paramnames(C)	generates the names of C's parameters.
staticnames(C)	generates the names of C's static variables.
structure(C)	generates the Icon values in C's block region (heap). These values are of various types such as lists and tables.

Figure 4.1: MT Icon inter-program access functions

CHAPTER 5
Execution Monitoring in MT Icon

MT Icon allows the execution of multiple Icon programs in almost any configuration, including execution monitoring. As motivated in Chapter 3, MT Icon characterizes monitoring as a special case of multi-tasking execution in which the nature and extent of inter-program communication warrants additional language support. This chapter describes additional MT Icon facilities specifically added to support monitoring. After some relevant definitions, a description of the programming interface and underlying interpreter instrumentation are given. Additional programmer's reference material is available for these facilities [Gris92c].

5.1 Terminology

The terminology used in discussing execution monitoring relates to events and the linguistic features associated with them. These terms are used throughout the rest of the dissertation.

Events

The primary linguistic concept added in order to support execution monitoring is an *event*. An event is the smallest unit of execution behavior that is observable by a monitor. In practice, an event is the execution of a section of instrumentation code that is capable of transfering control to the monitor.

This definition limits events to those aspects of program behavior that are instrumented in the language run-time system or the program itself. The event model is only as useful or general as is the instrumentation that extracts program information. If instrumentation does not exist for an aspect of program behavior of interest, it often is possible to monitor the desired behavior by means of other events. In the present implementation, for example, no instrumentation exists for file input and output. If an EM wishes to monitor I/O behavior, it can monitor function and operator events and act on those functions and operators that relate to input and output. A similar example involving the monitoring of Icon's built-in string scanning functions is presented in Chapter 9.

The MT Icon definition of event also differs from that of many monitoring systems, in which the term event refers to the basic unit of information *received* by the monitor [Bate89]. The distinction is that in the MT Icon definition, events occur whether they are monitored or not, and each event may or may not be observed by any particular monitor. This definition is useful in the MT Icon environment, in which EMs are not coupled with the instrumentation and multiple EMs can observe a TP's execution.

Event codes and values

From the monitor's perspective an event has two components: an *event code* and an *event value*. The code is generally a one-character string describing what type of event has taken place. For example, the event code C denotes a procedure call event. Event codes all have associated symbolic constants used in program source code. For example the mnemonic for a procedure call event is E_Pcall. These constants are available to programmers as part of a standard event monitoring library described below.

The event value is an Icon value associated with the event. The nature of an event value depends on the corresponding event code. For example, the event value for a procedure call event is an Icon value designating the procedure being called, the event value for a list creation event is the list that was created, the event value for a source location change event is the new source location, and so forth. Event values can be arbitrary Icon structures with pointer semantics; the EM accesses them just like any other source-language value.

Event reporting and masking

The number of events that occurs during a program execution is extremely large — large enough to create serious performance problems in an interactive system. Most EMs function effectively on a small fraction of the available events; the events that an EM uses are said to be *reported* to the EM. An *event report* results in a transfer of control from the TP to the EM. Efficient support for the selection of appropriate events to report and the minimization of the number of event reports are primary concerns.

MT Icon supports *dynamic event masking* based on event codes, a dynamic variation of the filter concept found in most event-based monitoring systems [Bate89, Elsh89]. Event masking allows the monitor to specify what events are to be reported and to change the specification at run-time. When the program being monitored starts execution, the monitor selects a subset of possible event codes from which to receive its first report. The program executes until an event occurs with a selected code, at which time the event is reported. After the monitor has finished processing the report, it transfers control back to the program, again specifying an event mask. Dynamic event masking enables the monitor to change the event mask in between event reports.

The use of one-character strings as event codes has a more practical value than its mnemonic merit: It allows sets of codes to be efficiently and easily manipulated at the Icon level by the *cset* (character set) data type. Csets are represented internally by bit vectors, so a cset membership test is very efficient compared to Icon's more generic set data type, whose membership test is a hash table lookup.

When an event report transfers control from TP to EM, the two components of the event are supplied in the Icon keywords `&eventcode` and `&eventvalue` respectively [1]. The monitor then can act upon the event based on its code, display or manipulate its value, etc.

5.2 Obtaining events

A standard library is available for use by EMs in order to provide a means of obtaining events. The library is described more completely in [Gris92c]. Programs wishing to use the standard library include a link declaration such as `link evinit`.

Setting up an event stream

An EM first sets up a source of events; the act of monitoring then consists of a loop that requests and processes events from the TP. Execution monitoring is initialized by the procedure `EvInit(x)`. If `x` is a string, it is used as an icode file name in a call to the MT Icon function `load()`. If `x` is a list, its first argument is

[1] Those not familiar with Icon may view these keywords as special global variables that are given their values by the Icon interpreter rather than by explicit user assignment. Keywords may be associated with a particular control structure (as in this case), and they may also be subject to constraints not imposed on regular global variables, such as the constraint that `&subject`, the string scanning subject, must always be a string.

taken as the icode file name and the rest of the list is passed into the loaded function as the arguments to its main procedure.

The typical EM, and all of the EMs presented as examples in this dissertation, follow the general outline:

```
link evinit
procedure main(arguments)
    EvInit(arguments) | stop("can't initialize monitor")
    # ... initialization code, open the EM window
    # ... event processing loop (described below)
    EvTerm()
end
```

This template is generally omitted from program examples for the sake of brevity.

EvGet()

Events are requested by an EM using the function EvGet(mask). EvGet() activates the co-expression value of the keyword &eventsource to obtain an event. The TP executes until an event report takes place; the resulting code and value are assigned to the keywords &eventcode and &eventvalue. EvGet() fails when execution terminates in TP. The mask parameter is a cset used for event selection.

Selection of virtual machine instruction subsets

Requesting an event report for the execution of the next virtual machine instruction is performed through the usual EvGet() cset using the mask E_Opcode. VM instructions occur extremely frequently; dozens of them can occur as a result of the execution of a single line of source code. Consequently, performance is severely affected by the selection of all VM instruction events; the extent of this impact on performance is presented in Chapter 12.

However, a particular VM instruction or small subset of instructions may be of interest to a monitor. In that case, the EM need not receive reports for all instructions. The function opmask(cs, P) allows EM to select a subset of virtual machine instructions given by cs in P's task. Subsequent calls to EvGet() in which E_Opcode is selected reports events only for the VM instructions designated by cs.

5.3 Instrumentation in the Icon interpreter

This section describes the instrumentation used by MT Icon to produce events at various points in the run-time system. Significant points in interpreter execution where transfer of control might be warranted are explicitly coded into the run-time system with tests that result in transfer of control to an EM when they succeed. When execution reaches one of these points, an event occurs. Events affect the execution time of the TP; execution is either slowed by a test and branch instruction (if the event is not of interest to the EM) or stopped while the event is reported to the EM and it processes information. Minimizing the slowdown incurred due to the presence of monitoring instrumentation has been a focus of the implementation; inherent costs and framework performance are presented in Chapter 12.

There are several major classes of events that have been instrumented in the MT Icon intepreter. Most of these events correspond to explicit elements within the source code; others designate actions performed implicitly by the run-time system that the programmer may be unaware of. A third class of event that has been instrumented supports user interaction with the EM rather than TP behavior.

Explicit source-related execution events include:

- **Program location changes** in terms of line numbers and columns.
- **Procedure activity** including calls, returns, failures, suspensions, and resumptions. In addition to these explicit forms of procedure activity, events occur for implicit removals of procedure frames.
- **Built-in functions and operations** including structure accesses and assignments. Like procedures, events are produced for function and operator calls, returns, suspensions, resumptions, and removals.
- **String-scanning activity** including scanning environment creation, entry, change in position, and exit.

Implicit run-time system events include:

- **Memory allocations** from the heap string and block regions, including size and type information. This instrumentation is based on earlier instrumentation added to Icon for a memory monitoring and visualization system [Gris89].
- **Garbage collections** including the storage region being collected (Icon has separate regions for strings and data structures), the memory layout after compaction, and the completion of garbage collection.
- **Type conversions** performed on parameters to functions and operators. Information is available for conversions attempted, failed, succeeded, and found to be unnecessary.
- **Virtual machine instructions** executed by the Icon virtual machine [Gris86]. The program can receive events for all virtual machine instructions, or an arbitrary subset.
- **Clock ticks** for the passage of CPU time.

Most EMs, except completely passive visualizations and profiling tools, provide the user with some degree of control over the monitoring activity and must take user interaction into account. For example, the amount of detail or the rate at which the monitor information is updated may be variables under user control. Since an EM's user input occurs only as often as the user presses keys or moves the mouse, user interaction is typically far less frequent than events in TP. Even if no user input occurs, polling for user input may impose a significant overhead on the EM because it adds code to the central event processing loop.

In order to avoid this overhead, the event monitoring instrumentation includes support for reporting user activity in the EM window as part of the TP's event stream. Monitor interaction events are requested by the event code E_MXevent. An example of the use of monitor interaction events is presented further in this chapter in the section entitled "Handling user input". A complete list of event codes is presented in Appendix C in order to indicate the extent of the instrumentation.

5.4 Artificial events

As described above, the MT Icon co-expression model allows interprogram communication via explicit co-expression activation or implicit event reporting within the run-time system. *Artificial events* are events produced by explicit Icon code; they can be viewed at the language level as co-expression activations that follow the same protocol as implicit events, assigning to the keyword variables &eventcode and &eventvalue in the co-expression being activated.

There are two general categories of artificial events, *virtual events* meant to be indistinguishable from implicit events and *pseudo events* that convey control messages to an EM. Virtual events are generally used either to produce event reports from manually instrumented locations in the source program, to simulate event reports, or to pass on a real event from the primary EM that received it to one or more secondary EMs. Pseudo events, on the other hand, are used for more general inter-tool communications during the course of monitoring, independent of the TP's execution behavior.

Virtual events using event()

The MT Icon function event(code, value, recipient) sends a virtual event report to the co-expression recipient, which defaults to the &main co-expression in the parent of the current task, the same destination to which implicit events are reported.

There are times when a primary EM wants to pass on its events to a secondary EM. An example would be an event transducer that sits in between the EM and TP, and uses its own logic to determine which events are reported to EM with more precision than is provided by the masking mechanism. A transducer might just as easily report extra events with additional information it computes, in addition to those received from TP. A more substantial application of virtual events is a monitor coordinator, an EM that coordinates and produces events for other monitors. Such a tool is presented in Chapter 11.

Pseudo events for tool communication

EMs generally have an event-processing loop as their central control flow mechanism. The logical way to communicate with such a tool is to send it an event. In order to distinguish a message from a regular event report, the event code must be distinguishable. In the monitoring framework this is achieved simply by using an event code other than a one-letter string, such as an integer. Since not all EMs handle such events, they are not delivered to an EM unless it passes a second argument to EvGet(), such as EvGet(mask, 1).

The framework defines a minimal set of standard pseudo events, which well-behaved EMs should handle correctly; these pseudo events are described in Chapter 11. Beyond this minimal set, pseudo events allow the execution monitor writer to explore communication between EMs as another facility to ease programming tasks within the monitoring framework.

5.5 Monitoring Techniques

The next few chapters demonstrate the potential of MT Icon's execution monitoring facilities with examples of a variety of monitoring techniques. The examples are actual program fragments (rather than pseudocode) that show how to program various forms of monitoring in MT Icon. The purpose of this demonstration is to present MT Icon as a practical language in which to develop exploratory monitors. The examples all follow a common outline and use a common set of facilities, which are described below.

Anatomy of an execution monitor

The execution monitoring interface presented in this chapter uses a form of *event-driven* programming: the central control flow of EM is a loop that executes the TP for some amount of time, and then returns control to EM with information in the form of an event report. The central loop of an EM typically looks like:

```
while EvGet(eventmask) do
   case &eventcode of {
      # a case clause for each code in the event mask
      }
```

Event-driven programming is more commonly found in programs that employ a graphical user-interface, where user activity dominates control flow. Because monitoring employs a programming paradigm that has been heavily studied, many coding techniques developed for graphical user interface programming, such as the use of callbacks [Clar85], are applicable to monitors. Several of the example EMs in subsequent chapters use a callback model to take advantage of a higher-level monitoring abstraction available by means of a library procedure.

Handling user input

An EM that handles user input could do so by polling the window system after each event in the main loop:

```
while EvGet(eventmask) do {
   case &eventcode of {
      # a case clause for each code in the event mask
      }
   # poll the window system for user input
   }
```

If the events being requested from the TP are relatively infrequent, this causes no great problem. However, the more frequent the event reports are, the more overhead is incurred by this approach relative to the execution in TP. In typical EMs polling for user events may slow execution from imperceptibly to as much as 15%. Chapter 13 provides figures on the relative frequency of various types of events.

Since the slowdown is a function of the frequency of the event reports and not just the cost of the polling operation itself, techniques such as maintaining a counter and only polling every *n* event reports still impose a significant overhead. In addition such techniques reduce the responsiveness of the tool to user input and therefore reduce the user's control over execution.

Monitor interaction events, presented earlier in this chapter, address this performance issue by allowing user input to be supplied via the standard event stream produced by EvGet(). Since the E_MXevent event normally occurs far less frequently than other events, it makes sense to place it last in the case expression that is used to select actions based on the event code. Using this feature the main loop becomes:

```
while EvGet() do
   case &eventcode of {
      # other cases update image to reflect the event
      E_MXevent: {
         # process user event
         }
      }
```

EvGet() reports pending user activity immediately when it is available; the control over execution it provides is comparable to polling for user input on each event.

Querying the target program for more information

After each event report, EMs can use MT Icon's inter-task data access functions to query TP for additional information, such as the values of program variables and keywords. The access functions can be used in several ways, such as

- applying a predicate to each event report to make monitoring more specific,
- *sampling* execution behavior not reported by events by polling the TP for information unrelated to the event reports [Ogle90], or
- to present detailed information to the user, such as the contents of variables.

Visualization techniques

Program visualization employs the high-bandwidth processing capabilities of the human visual system in order to mitigate the volume problem inherent in execution monitoring. Because of the amount of information most EMs need to present, support for development of new visualization techniques is essential to support the claim that EMs developed in an exploratory manner can be useful and practical.

The fundamental issues in visualization are concerned primarily with effective use of the screen, maximizing the amount of information displayed, its understandability, and the rate at which it is updated. Thorough treatment of these topics is beyond the scope of this dissertation; they are briefly mentioned here because they motivate many of the examples to follow.

Mapping to a geometry – Visualizations map the information to be presented onto a geometry for presentation on the screen. In program visualization this often is difficult because the information described has no natural geometry. The artificial geometry that is constructed may be unintuitive or even misleading to the viewer. In order to avoid this, many EMs employ familiar visual metaphors.

Space limitations – Screen space limits the amount of detail that can be portrayed. If several views are presented simultaneously, screen space in any one view may be limited to a few square inches. Given limited space, scaling and miniaturization are important, but careful graphic design is just as important.

Animation – Smooth transitions between the states presented by the visual display are important for user orientation. Animation implies real-time updates as the program is executing. The performance of the underlying window system software limits the kind and quality of the views that can be animated.

There are trade-offs inherent in these issues. For example, the more complex the geometric mapping or scaling/miniaturization technique, the less satisfactory the animation may be.

5.6 Icon graphics capabilities

Icon is best known as a string and list processing language, but it also includes graphics facilities [Jeff91, Jeff93]. Visualization tools written in Icon present their output using the type `window`. This section describes aspects of Icon's window system facilities that are used in subsequent chapters. It presents only a small subset; see the reference manual [Jeff93] for a complete description of Icon's graphics facilities.

Windows allow both text and graphic input/output to be freely mixed. While on-screen, windows may be moved, resized, and iconified by the user or the Icon program. Window exposure (also known as "redraw" or "paint") events are handled automatically and do not have to be handled by the programmer; the window contents are *retained* until the window closes. If the keyword &window has a window value, it serves as a default window for all graphic functions. The remaining examples in this chapter assume &window is the window of interest.

Icon's window interface uses a raster graphics model based on that of Xlib, the X Window System C language interface [Gett88]. In this model, a window is a two-dimensional array of points, also called picture elements (*pixels*) in the x- and y-coordinates starting from the pixel (0,0) in the upper-left corner and moving positive to the right and down the window. Several functions take pixel coordinates and draw geometric figures on the window. Pixels are drawn with a window's current *foreground color*.

Some useful functions are given in Figure 5.1; other graphics functions are described as they are used in examples.

XClearArea()	clears a rectangular area
XDrawArc()	draws an arc
XDrawPoint()	draws a point
XDrawLine()	draws a line
XDrawRectangle()	draws a rectangle
XDrawString()	draws a string
XEvent()	returns the next user event
XFg()	sets the color used in subsequent drawing
XFillArc()	draws a filled arc
XFillRectangle()	draws a filled rectangle
XGotoRC()	moves text cursor position
XPending()	returns a list with user events awaiting processing

Figure 5.1: Some useful Icon graphics functions

Many visualization tools make extensive use of color in graphics operations to encode information about related data types or program operations. Such tools could change the output drawing color by repeated calls to XFg(), but it is much faster to ask the window system to set up several window values that draw with different colors. The call XBind(&window, "fg=" || s) creates a window value that draws on the window using foreground color s. All graphics functions may be prefixed with such a window argument w to draw with a non-default color, for example

```
w_red := XBind(&window, "fg=red")
XDrawPoint(w_red, x, y)
```

draws a red point at (x, y).

When an encoding of colors is used in a visualization tool, a table is typically used to store a mapping from a source domain such as string type names to window bindings with various colors.

5.7 Some useful library procedures

As mentioned in Section 5.3.1, several library procedures are useful in EMs. This section presents those library procedures that are used in the examples in the rest of this dissertation; the rest are described in the evinit library reference [Gris92c].

Location decoding and encoding procedures are useful in processing location change event values, but they are also useful in other monitors in which two-dimensional screen coordinates must be manipulated. Besides program text line and columns, the technique can variously be applied to individual pixels, to screen line and columns, or to screen grid locations in other application-specific units.

In addition, various EMs use utility procedures. Figure 5.2 lists the library procedures that are used in this dissertation.

location()	encodes a two-dimensional location in an integer
vertical()	returns the y/line/row component of a location
horizontal()	returns the x/column component of a location
prog_len()	returns the number of lines in the source code for TP
procedure_name()	returns the name of a procedure
XColumns()	returns the window width in text columns
XHeight()	returns the window height in pixels
XRows()	returns the window height in text rows
XWidth()	returns the window width in pixels

Figure 5.2: Library procedures used in this dissertation

CHAPTER 6

Following the Locus of Execution

Perhaps the most basic monitoring act is following along in the source code as execution progresses. Locus of execution information is used in various tools such as source-code viewers and profilers. Frequently, location information is used in combination with other execution information to inform the user of the specific source code line and column responsible for some behavior of interest.

This chapter presents simple example EMs that monitor location information and present it graphically. The first set of tools shows recent line number changes. These tools are primarily useful in detecting irregular control flow patterns that merit investigation, and in detecting major phases in program execution. Following the line number activity monitors, a graphical location profiler that displays cumulative location information is presented. Profilers are primarily useful in performance tuning.

The examples in this and the next several chapters are intended to demonstrate the broad capabilities of the monitoring framework. Actual source code is given in order to demonstrate useful techniques and affirm the claim that the framework supports an exploratory programming style. While the examples are often suggestive of monitors which are useful in their own right, they are necessarily kept simple for exposition. The development of more sophisticated monitors is an open-ended research domain for future work that this framework was designed to facilitate.

6.1 Location events

An event report with the code E_Loc occurs whenever the source line or column changes. Tracking the execution locus minimally involves selecting this event code in the event mask that is passed to EvGet() along with any others that may be of interest.

The value associated with a change in location is a 32-bit integer encoding of the line and column numbers. The line number is given in the least-significant 16 bits, and the column number in the most-significant 16-bits.

6.2 A simple line-number monitor

The code segment that follows outlines a simple line-number monitor that presents the sequence of source-code lines on a strip chart. The y coordinate is used to denote the line number; successive line numbers are plotted adjacently along the x axis. Line numbers are scaled to fit the available screen space. A sample screen image is shown in Figure 6.1. The tool is animated, showing the last *n* line number changes, where *n* is the width of the monitor window. As the animation progresses, ordinary sequential execution of successive expressions appears in the window as a downward-sloping line. Periodic repetitions of patterns in the window indicate the execution of loops.

The EM starts by initializing the event monitoring system and opening a window on which to display its output. Local variables x and y refer to screen coordinates; scale is used to adjust the y coordinate to fit within the bounds of the window. Real numbers are used in the scaling arithmetic in order to use all of the available window space.

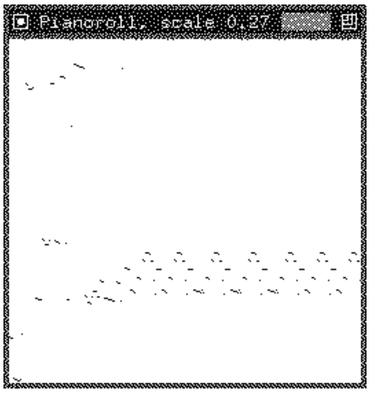


Figure 6.1: A simple line-number monitor

```
&window := open("LineMon", "x", "height=250", "width=250") |
    stop("can't open window")
scale := real(XHeight()) / prog_len()
x := 0
```

The program's main loop reads a location event with a call to EvGet(), computes and scales the line number to the window height, and plots it in the window with a call to XDrawPoint(). After the point is plotted, x is advanced to plot the next line number in the next pixel column to the right. When the plot reaches the right edge of the window, the EM wraps around to the left edge. Because pixel columns are reused, a rectangle one pixel wide is erased at each iteration (XClearArea()'s height argument defaults to the entire window).

```
while EvGet(E_Loc) do {
    y := vertical(&eventvalue) * scale
    XDrawPoint(x, y)
    x := (x + 1) % XWidth()      # advance x, wrapping from right to left
    XClearArea(x, 0, 1)         # clear pixel column for subsequent plot
    }
```

Variations on the line number monitor are presented in Figure 6.2 and Figure 6.3. Figure 6.2 draws a segment between the current source line and the preceding source line at each step. The effect emphasizes large jumps in program location that otherwise might not be noticed due to extremely short visits to certain locations. This phenomenon occurs more frequently in procedures that generate multiple results from a single expression than it does in ordinary procedural code. Figure 6.3 plots all the lines that execute in a single CPU clock tick (a hardware-dependent value; typically 4-20 milliseconds) in a single column. This view compresses much more location information onto a single screen, but loses the ordering between specific location events within a clock tick.

6.3 A location profile scatterplot

Another location-monitoring example, presented below, renders a continuously updated animated scatterplot of program activity by source program line and column number. A sample screen image is presented in Figure

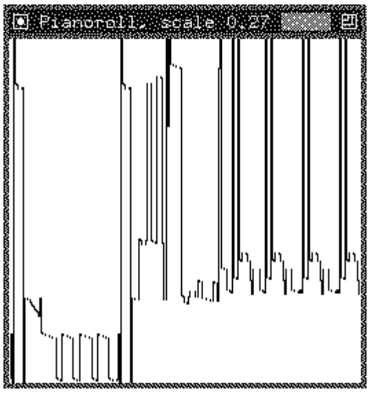


Figure 6.2: Monitoring adjacent pairs of lines

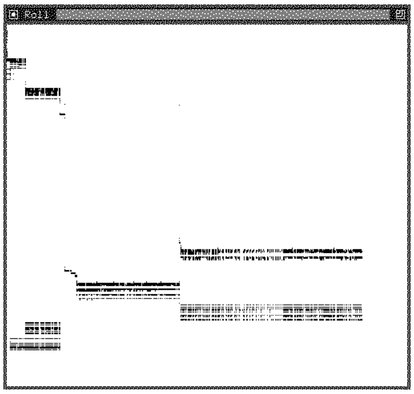


Figure 6.3: Mapping CPU clock ticks to pixel columns

6.4. The tool's animation does not employ motion, but rather changes in color as execution commences. The colors are rendered as grayscales for publication.

This EM maps source code columns and lines onto the x- and y- dimensions, one line or column per pixel. This mapping may be useful or already familiar to the user because it is a miniaturized view of the program text itself. Each source location at which the TP executes is highlighted, with the number of times that location has been executed given by a color progression on a logarithmic scale, from gray and blue through green and yellow and on to orange and red for locations that have executed many times.

The EM starts with standard initialization code and then creates a list of bindings with the various colors. A table, counts, maintains the number of times execution has occurred at each location.

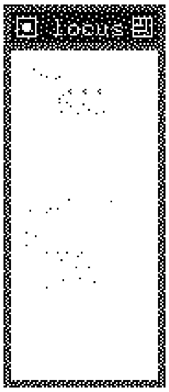


Figure 6.4: A location profile scatterplot

```
&window := open("locus", "x", "bg=white", "width=80", "height=500") |
    stop("can't open window")
Color := [ ]
every put(Color,
    XBind(&window, "fg="||("gray"|"blue"|"green"|"yellow"|"orange"|"red")))
counts := table(0)
```

With initialization completed, the main loop requests a location event, decodes its line and column, and increments the execution count for the location, stored in the table as counts[&eventvalue]. A point is then drawn in the window with a color encoding the log of the location's execution count. If the window height is not large enough to map the source file lines onto pixels, a bar is drawn at the bottom of the window to indicate it has been clipped. A more sophisticated version of this program scales the mapping from lines to pixels.

```
while EvGet(E_Loc) do {
    y := vertical(&eventvalue)
    x := horizontal(&eventvalue)
    counts[&eventvalue] +:= 1
    value := integer(log(counts[&eventvalue], 6)) + 1
    if Context := Color[ value ] then
        XDrawPoint(Context, x − 1, y − 1)
    if y > XHeight() then
        XFillRectangle(0, XHeight() − 4, 80, 4)
    }
```

CHAPTER 7

Monitoring Procedure and Generator Activity

Procedure activity is a major aspect of control flow, and it is especially significant in Icon because procedures can generate more than one result. This chapter describes the monitoring of procedure activity in detail. The techniques presented are important because they also apply to the monitoring of Icon's built-in functions and operators as well as string scanning environments. The examples given are intended to illustrate the framework's capabilities and are by no means the best or only way in which procedure activity may be portrayed.

In order to model the semantics of generators, most EMs maintain trees of suspended procedure activations that may be resumed. After presenting techniques to maintain these trees, the chapter describes an EM that draws an animated scatterplot of the number of results that each procedure produces; it quickly shows which procedures are generators, and shows when the number of results a procedure is producing changes significantly. Knowing which procedures are generators can be important for students and program maintainers that are unfamiliar with a program. For programmers that *are* familiar with the target program, knowing the number of results being produced per call to a given procedure can be valuable during debugging; it can confirm expected behavior and/or point out anomalies.

The chapter concludes with an EM that gives an abstract view of the actual tree of active and suspended procedures; it is useful for understanding the path that control flow took to get to the current place of execution. This EM is generalized to include string scanning operations in Chapter 9, and source code for a version that also allows monitoring of built-in functions and operators is presented in Appendix A as an example of a more sophisticated monitor.

As mentioned in Chapter 5, events take place at procedure calls, suspensions, resumptions, returns, failures, and implicit removals. The constant ProcMask contains a cset for all the event codes related to procedures; similar constants FncMask, OperMask, and ScanMask are used for other types of expression activity.

7.1 Activation Trees

The event value for calls and resumptions gives the procedure being activated, but other procedure events such as suspension and return give the Icon value being produced. In order to track the currently active procedure, the monitor must maintain a model of the program's procedure *activation tree* (Figure 7.1).

The procedure evaltree() described in this section maintains a simple model of procedure activation trees using records for tree nodes. Each record corresponds to an activation of a procedure. The record contains the procedure, the parent activation record from which the procedure was called, and a list of any children (including suspended ones) that this activation of the procedure has called:

```
record activation(value, parent, children)
```

When used in an EM, the record type may have additional fields to maintain other information about the procedure activation, such as the number of results it has produced. Figure 7.2 shows the Icon structures

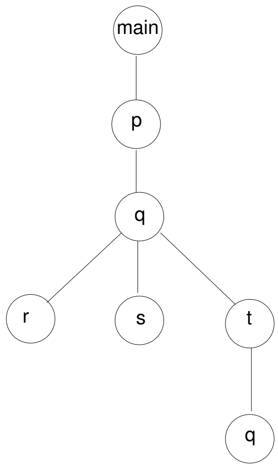


Figure 7.1: An activation tree

formed by evaltree() to model the activation tree in Figure 7.1. The source code for evaltree() is presented in Appendix A.

evaltree() maintains the complete activation tree as well as the current activation with the following monitor-event loop. It is called with an event mask parameter and two procedure parameters. The event mask parameter gives all the events needed by the EM. The procedure parameters consist of a callback procedure used to inform the monitor of changes in the tree, and a record constructor for a record type that has at least the fields declared above. The callback procedure is called with the activation record being entered as well as the activation record being exited.

```
procedure evaltree(mask, callback, activation_record)
    # ... compute codes for each branch of the case clause from mask
    while EvGet(mask) do
        case &eventcode of {
            # ... clauses maintain the activation tree and call client callback procedure
            }
end
```

In order to operate properly with any combination of procedure, function, operator, and scanning environment events, evaltree() examines its event mask and builds up lists of codes related to each of the six tree-modifying events. It stores these lists in the global variables CallCodes, SuspendCodes, ResumeCodes, ReturnCodes, FailCodes, and RemoveCodes. In addition, evaltree() creates a dummy root activation on which to build the activation tree.

The branches of evaltree()'s case clause perform the actual tree manipulations and then call the client callback procedure, supplying it with both the activation being entered and the activation being exited. For each call event, a new node is created and inserted as the right-most child of the current node. The new node becomes the currently executing node.

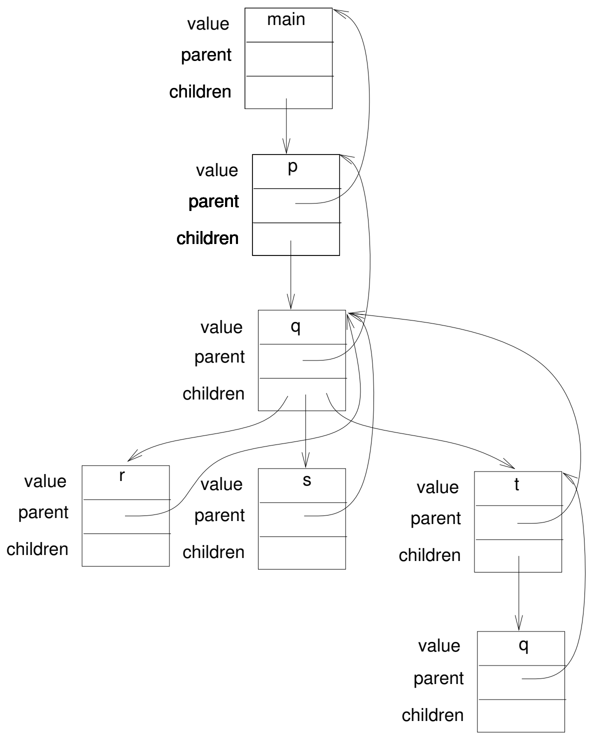


Figure 7.2: An Icon representation of an activation tree

```
!CallCodes: {
    entered := activation_record()
    entered.node := &eventvalue
    entered.parent := current
    entered.children := [ ]
    put(current.children, entered)
    current := entered
    callback(current, current.parent)
    }
```

Return and fail events result in the inverse of a call event: The current node is removed from the activation tree, and the parent of the current node becomes active. When an Icon return expression is executed, the instrumentation produces removal events for all descendants of the returning node preceding the resulting return event.

```
!ReturnCodes | !FailCodes: {
    exited := pull(current.parent.children)
    current := current.parent
    callback(current, exited)
    }
```

Suspend and resume events do not change the structure of the tree. For suspend events, the parent becomes the current (active) node; for resume events the right-most suspended child is resumed and becomes the current node. After the current node is updated, the client callback procedure is called.

```
!SuspendCodes: {
    current := current.parent
    callback(current, current.children[−1])
    }
!ResumeCodes: {
    current := current.children[−1]
    callback(current, current.parent)
    }
```

Removal events denote the implicit exit of a node in the activation tree as a result of control flow. Typically a removal event precedes the current node's return or failure and denotes the destruction of the current node's right-most child. If the current node has no children, removal indicates an implicit destruction of the current node, indicating that it will not be used in the surrounding expression evaluation context.

```
!RemoveCodes: {
    if exited := pull(current.children) then {
        while put(current.children, pop(child.children))
        callback(current, exited)
        }
    else {
        exited := pull(current.parent,children)
        current := current.parent
        callback(current, exited)
        }
    }
```

The default clause in this case expression simply calls the client callback procedure. The activation tree is not modified. This clause is useful because execution monitors that use evaltree() may be interested in other types of events besides those that involve the activation tree.

```
default:        callback(current, current)
```

7.2 An animated call-result scatterplot

To illustrate the use of evaltree(), the following example plots the number of times each procedure has been called along the x axis, while the number of results it has produced is plotted along the y axis. Points are moved whenever either a call or a resumption occurs. If the user presses a mouse button on one of the plotted points, the names of any procedures plotted at that point are listed. An example screen image from this program is given in Figure 7.3; the name GenMoves in the lower right corner is the name of the procedure plotted at the last location on which the mouse was clicked. The image does not convey the nature of the animation, in which plotted points start in the upper left corner and migrate down and to the right at varying speeds and directions.

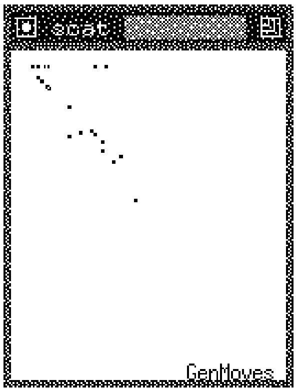


Figure 7.3: A scatterplot with motion

A call-result scatterplot serves several purposes. It serves as a basic procedure call profiler, revealing which procedures are used the most and are therefore most important in overall performance. Since this information is presented while the program is executing, it provides quicker feedback than profilers that present information only after execution has run to completion. Feedback during execution also shows temporal changes associated with major phases in the program. These uses are language-independent. The call-result scatterplot also serves two language-specific purposes: It shows the user which procedures are generators, and how many results the procedures are producing per call.

When a procedure consistently produces no results, it moves horizontally along the top edge. On the other hand, if a procedure generates results, it moves vertically straight down. If a procedure consistently returns with one result, it moves diagonally down and across. The slope of a line from the origin to a given procedure's point on this graph gives the average number of results that procedure has produced per call. If the motion of a point plotted for a procedure changes its direction substantially it may indicate unusual behavior that is worth further examination.

Two global tables, calls and results, store the dimensions' counts for each TP procedure. The global table loc2procs maintains a set of procedures plotted at each point on the graph; loc2procs is keyed by the integer-encoded locations introduced in the preceding chapter and is discussed in more detail later.

```
global  loc2procs,  # table of sets of procedures at a given location
        calls,      # table of call counts
        results     # table of result counts
```

Procedure main() performs initialization and calls evaltree(), which in turn obtains events, builds the activation tree, and calls scat_callback() for each event report. main() passes scat_callback() to evaltree() as a parameter, in addition to the event mask to use and the record type to use for activations. The event mask includes procedure events selected by the symbol ProcMask and monitor interaction events, indicated by the symbol E_MXevent. Monitor interaction events, described in Chapter 5, provide a convenient means of incorporating user input such as mouse clicks and button presses into EMs without a need for separately polling the EM window for activity.

```
# ... from procedure main()
&window := open("scat","x","width=150","height=180") |
    stop("can't open window")
calls := table(0)
results := table(0)
loc2procs := table()
evaltree(ProcMask ++ E_MXevent, scat_callback, activation)
```

scat_callback() updates the plotted location of a procedure whenever it is called or produces a result, calling plot() to increase the appropriate procedure's x- or y-coordinate, respectively. If the event is a call, the point corresponding to parameter new (the activation being entered) is updated, while if the event is a suspend or a return, the point corresponding to parameter old (the activation being exited) is updated.

If the event indicates user activity, a code indicating the user input is supplied in &eventvalue, and the keywords &x and &y are updated to indicate the mouse location. If the user presses the escape character "\e", monitoring is terminated; if the user presses a mouse button, write_names() is called to write the names of procedures plotted where the mouse indicates.

```
procedure scat_callback(new, old)
    case &eventcode of {
        E_Pcall:             plot(new.node, 1, 0)
        E_Psusp | E_Pret:    plot(old.node, 0, 1)
        E_MXevent: {
            case &eventvalue of {
                "\e": stop("execution halted")
                &lpress: repeat {
                    write_names()
                    if XEvent() === &lrelease then break
                    }
                }
            }
        }
end
```

The procedure plot() takes a procedure and updates the tables to reflect its new position. If the procedure is the only occupant of the screen coordinate it is leaving, the point is erased there; similarly if the new position is not already occupied, a point is drawn. “Points” are plotted two pixels wide and two pixels high because individual pixels provide poor visibility on some displays. An even larger size might improve visibility further at a cost of screen space. plot() uses a logarithmic scale in order to keep the screen size required by this application reasonable for large programs. A logarithmic scale is chosen over a linear scale because any linear scale would either plot the most important often-called procedures off the edge of the chart or else plot all the less frequently called functions together in one corner of the chart. The scaling process uses the distance of the point from the origin in order to preserve the ratio of calls to results in the scaled point; this is discussed in more detail below.

```
procedure plot(who, iscall, isrslt)
    loc := scaled_location(calls[who], results[who])
    if *delete(\loc2procs[loc], who) = 0 then
        XClearArea(horizontal(loc) * 2, vertical(loc) * 2, 2, 2)
    calls[who] +:= iscall
    results[who] +:= isrslt
    loc := scaled_location(calls[who], results[who])
    /loc2procs[loc] := set()
    if *insert(loc2procs[loc], who) = 1 then
        XFillRectangle(horizontal(loc) * 2, vertical(loc) * 2, 2, 2)
end
```

scaled_location(x, y) scales its arguments and produces an integer encoding of the point (x, y) with the x-coordinate in the most significant 16 bits and the y-coordinate in the least-significant 16 bits. scaled_location() also computes the distance from the origin for a point using the Pythagorean theorem; it is used during scaling.

```
procedure scaled_location(x, y)
    length := sqrt(x ^ 2 + y ^ 2)
    return location(scale(y, length), scale(x, length))
end
```

The procedure scale(coord, len) applies a logarithmic scaling factor to a coordinate. If logarithmic scales were applied separately to the x- and y- coordinates, the proportions of calls to results would not be preserved and the resulting points would be plotted artificially close to the central diagonal of slope 1. Instead, the logarithmic scale is applied to the distance from the origin. The coordinate is multiplied by the ratio of the scaled length to the original length. When both coordinates are so scaled, the scaled point forms a similar triangle to the original unscaled point; the slope of calls to results is preserved from the unscaled point.

```
procedure scale(coord, length)
    if length < 1 then return 0          # avoid divide by 0 error
    return integer(coord * log(length, 1.25) / length)
end
```

Procedure write_names() prints the names of all procedures plotted near a mouse click. It builds a list L of the names of all procedures in the loc2procs table located within one pixel of the current mouse location. When write_names() has built the list of procedures, it erases the last name list, and writes the new list of names in the lower left corner of the window.

```
procedure write_names()
    static maxrows, maxcolumns
    &x /:= 2
    &y /:= 2
    # build a list of names of procedures
    L := []
```

```
every i := -1 to 1 do
    every j := -1 to 1 do {
        loc := location(&y + j, &x + i)
        every put(L, procedure_name(!\loc2procs[loc]))
        }
# compute the geometry needed to erase last name list
if max := *L[1] then {
    every max <:= *!L
    maxcolumns <:= max
    }
maxrows <:= *L
&col := XColumns() - maxcolumns
&row := XRows() - maxrows - 1
XClearArea(&x, &y)
if *L > 0 then
    every i := 1 to *L do {
        XGotoRC(XRows() - *L + i, XColumns() - max)
        writes(&window, L[i])
        }
e := XEvent()
end
```

The scat program could be generalized in several ways; for instance, it is trivial to extend scat to accomodate Icon's built-in function and operator repertoire. If this information were cross-referenced with static knowledge of which functions and operators were generators, scat could show whether they are being used generatively, or only used to obtain single results as in conventional programming. Another useful way to extend scat would be to allow the user to specify lines (slopes) to indicate a procedure's expected result/call ratio; if the number of results were too low or too high, the user might want to stop execution and inspect the situation in closer detail.

7.3 Algae

A program named Algae illustrates one approach to displaying procedure and generation activity in a more connected fashion. Algae displays an animated representation of the activation tree for procedures, built-in functions, and/or string scanning environments as the TP executes, and serves as a basis for other more sophisticated EMs that are presented in later chapters.

Algae is designed to use little screen space and does not require rearrangement of nodes as the tree changes, like conventional approaches to tree layout do. This attempt to save screen space and animation time produces an approximation of the activation tree that sacrifices the details of parent-child relationships in the tree. The Algae metaphor is meant to complement more conventional layouts, not to replace them. The idea behind Algae is to present enough of the expression activity so that common goal-directed evaluation patterns in TP are identified and strange behavior can be noticed as an unfamiliar pattern in the animation.

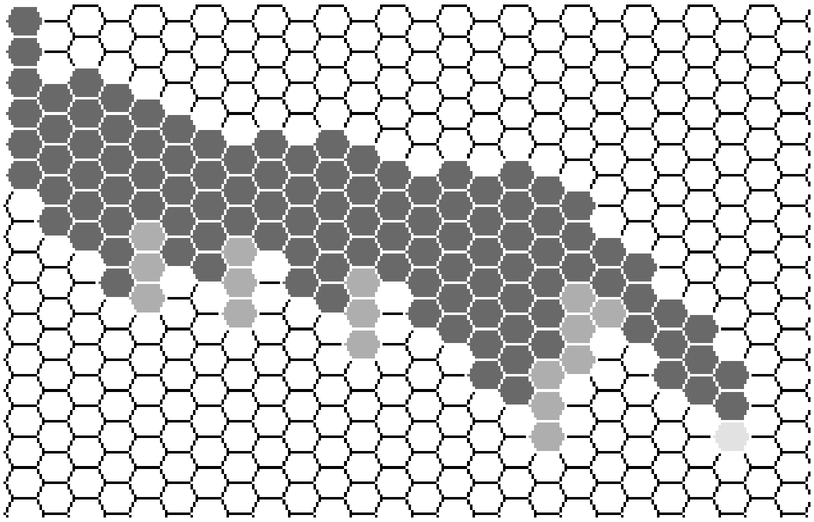


Figure 7.4: Algae

Algae geometry

The Algae window uses a simple two-dimensional grid of cells; the vertical dimension depicts expression nesting depth, such as calls and returns from procedures. The horizontal dimension depicts generator suspension width, such as procedure, function/operator, and scanning environment suspension. Whenever a computation is suspended, new computations at the same level start in the next cell column to the right, indicating the possibility of backtracking into the suspended computation. A sample image of Algae is shown in Figure 7.4. The target program being monitored is a recursive descent parser. Magenta (depicted as dark gray) cells represent suspended Icon procedures for the nonterminals of a parse that is being attempted. A yellow (light gray) cell in the bottom-right is the currently active procedure. Light blue (medium gray) is used to fill in cells when they are vacated; coloring these cells provides a "high water mark" for the computation up to any given point and gives it an overall characteristic shape.

In order to support the two-dimensional geometry, Algae's activation tree records have fields for the row and the column of the cell assigned for each activation:

```
record algae_activation(value, parent, children, row, column, color)
```

Since screen space is limited, each activation is depicted as a small hexagon in the window, color-coded by the kind of activation (procedure, function, operator, or string scanning environment). The size of the hexagons is scalable. Given this geometry it would be easier to plot Algae using rectangular points. Hexagons are used primarily for their visual effect – they provide a smoother animation as the tree grows and shrinks. Position changes in Algae are often diagonal, and in a square mapping, these changes appear to be a farther distance than horizontal or vertical position changes. A collection of Icon procedures totalling roughly 160 lines were written to manipulate hexagons; they are omitted here for the sake of brevity. In the code below, the procedure spot() fills a hexagon at a given location with a particular color.

Because screen space is limited and the activation tree is constantly changing, Algae does not lay out the tree in a way that spreads out nodes throughout the available screen space. Instead, Algae lays out tree nodes from the leftmost edge of the window, being careful to maintain the correct depth and breadth of the tree, and making sure that no two nodes occupy the same cell. When a new node is created, it is a assigned a cell with a row given by its level; the column is computed by inspecting the existing tree and finding the first position to the right of both the parent node and any nodes at the new node's level.

Since expression trees grow and shrink along their rightmost edge, the tree search to assign a column is a pre-order depth-first right-to-left search. An important special case is if the node's parent already has a child, in which case the newly-created node can immediately be assigned a column adjacent to its older sibling; this case is handled directly in algae_callback() for efficiency and often allows the tree search to be avoided entirely.

The code to compute the column is:

```
procedure computeCol(parent)
    node := parent
    while node.row > 1 do node := \node.parent # find root
    if node === parent then return parent.column
    if col := subcompute(node, parent.row + 1) then
        return max(col, parent.column)
    else
        return parent.column
end
procedure subcompute(node, row)
    # check this level for correct depth
    if \node.row = row then return node.column + 1
    # search children from right to left
    return subcompute(node.children[*node.children to 1 by −1], row)
end
```

Using evaltree() to incrementally update the display

Algae makes extensive use of colors to indicate the kind of activation, such as whether it is a procedure, function, or string scanning environment. In main(), several bindings are created with different foreground colors, as described in Chapter 5. The colors used are arbitrary and the user can determine the contents of the node by clicking on it if the color is not familiar.

After initialization, Algae calls evaltree() and passes it a reference to the procedure algae_callback(). The event mask used is variable and depends on command-line arguments. The body of algae_callback() performs the incremental animation of the tree. Each event that modifies the activation tree entails the updating of two display cells: a cell that is entered is drawn in yellow to mark it as the active cell, and a cell that is exited is either drawn in the color associated with the activation (if it is suspended) or in a background gray color (if the associated activation has returned or failed and no longer exists).

```
    case &eventcode of {
        !CallCodes: {
            new.column := (old.children[−2].column + 1 | computeCol(old))
            new.row := old.row + 1
            new.color := Color[&eventcode]
            spot(\old.color, old.row, old.column)
```

```
        }
    !RetCodes | !FailCodes: spot(background, old.row, old.column)
    !SuspCodes | !ResumCodes: spot(old.color, old.row, old.column)
    !RemCodes: {
        spot(black, old.row, old.column)
        XFlush(black)
        delay(100)
        spot(background, old.row, old.column)
        }
    E_MXevent: user_event(&eventvalue, new)
    }
spot(yellow, new.row, new.column)
```

Algae controls

User control of Algae consists of marking specific hexagons (using the left mouse button) or entire rows and columns (using the middle button) to pause execution. Pressing the right button atop an hexagon marked active or suspended prints the name of the associated procedure or function, or the subject of the associated string scanning environment. The input handling is performed by do_event() in response to an E_MXevent.

Each call to algae_callback() checks to see whether the cell being entered is one selected by the user to pause execution, and if it is, the callback procedure loops reading user events until the user indicates that execution should continue. algae_callback() concludes with the code for this test:

```
loc := location(new.row, new.column)
if \step | (new.column >= \maxcolumn) |
    (new.row >= \maxrow) | \ hotspots[loc] then {
    step := &null
    XWindowLabel("Algae stopped: (s)tep (c)ont ( )clear ")
    while e := XEvent() do
        if user_event(e, new) then break
    XWindowLabel("Algae")
    }
```

The procedure user_event() returns if execution should proceed, but fails if execution is still paused and another user event should be obtained. The code for user_event() is somewhat lengthy and is included in the complete text of Algae in Appendix A.

The techniques presented here apply not only to Icon's built-in functions, operators, and scanning environments — the evaltree() procedure can accomodate all of these kinds of events simultaneously and maintain one large expression activation tree. Some differences between the different kinds of activations exist; an obvious one is that function and operator events are so frequent that monitoring them in an EM like Algae vastly reduces the tool's effectiveness in monitoring the less-frequent procedure activity. It would be useful to explore variants of evaltree() that allow certain subtrees to be ignored, or do not plot activity at all unless interesting behavior such as generation or backtracking takes place.

CHAPTER 8

Monitoring Memory Usage

Memory usage is an important aspect of program behavior that is not directly evident from source code examination. The execution monitoring instrumentation produces events on every memory allocation with an event code that indicates the type allocated and a corresponding event value giving the size of the allocation in bytes. In addition, events occur at garbage collections, including the types and sizes of objects that survive reclamation. Allocation events are selected with the evinit symbol AllocMask.

This chapter presents a variety of EMs that portray aspects of memory usage. First, EMs are given that plot each individual allocation in relation to other recent allocations; they are useful in observing localized program behavior such as allocations of unusual size or changes in the major phases of execution. Later in the chapter, EMs that portray cumulative memory usage behavior are discussed; they provide a useful profiling service and a general understanding of the TP's use of memory. These simple examples illustrate only a few of many visual metaphors that have been developed for memory usage, ranging from literal views of the heap to completely abstract animations whose patterns reflect a program's memory allocations. Some of the other tools that portray memory activity are described in a separate document [Gris92b].

8.1 Allocation by type

Many visual metaphors can be used to depict allocation types or sizes, or both. Two allocation monitors are presented in this section. The first emphasizes frequencies and patterns of types in allocated memory, while the second emphasizes allocation size information. These examples also exhibit a clean separation of the data collection and graphics rendering tasks, enabling the visual metaphors to be used in other tools that monitor types of events other than memory allocations.

8.1.1 Pinwheel

The pinwheel metaphor presents a sequence of values, in this case the event codes associated with allocation event reports, encoded as colors or textures drawn in sectors around a circle. The *n* sectors of the circle represent a history of the last *n* allocation events in the TP's execution. A screen image from a program using this metaphor to present memory allocation patterns is given in Figure 8.1. In this example, event codes for Icon's allocated types are mapped onto colors. The view is updated on each allocation; the animation rate gives an indication of the frequency with which memory allocations occur.

Pinwheel and many other visual metaphors have been encapsulated in procedures for use by execution monitors. By using a common set of conventions, the metaphors can be applied interchangeably and to different types of data. The procedure pinwheel(), called with no arguments, starts with local variable declarations and then initializes several variables that scale the mapping.

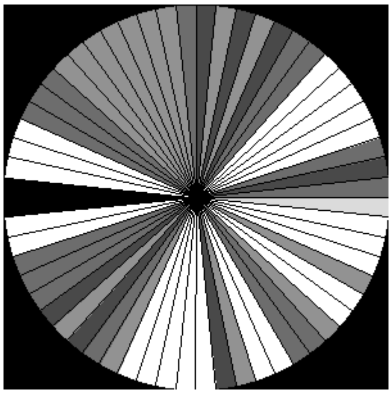


Figure 8.1: Pinwheel

```
procedure pinwheel()
   local clear, xorg, yorg, radius, radians
   local angle, arc, sector_units, fullcircle, blank, max, xratio, yratio

   max := real((XWidth() < XHeight()) | XWidth())
   xratio := XWidth() / max
   yratio := XHeight() / max
   fullcircle := 360 * 64
   angle := 0                              # initial degrees x 64
   radians := 0
   sector_units := fullcircle / Sectors    # amount to advance
   blank := 2 * sector_units               # amount to blank
   xorg := XWidth() / 2
   yorg := XHeight() / 2
   radius := max / 2
   while NextEvent() do {
      XFillArc(Background, 0, 0, XWidth(), XHeight(), angle + sector_units, blank)
      XFillArc(Binding, 0, 0, XWidth(), XHeight(), angle, sector_units)
      XDrawLine(Background, xorg, yorg, xratio * radius * cos(radians) +
         xorg, yratio * radius * sin(radians) + yorg)
      angle +:= sector_units
      angle %:= fullcircle
      radians := -dtor(angle / 64)
      }
end
```

Pinwheel's main loop reads a monitoring event, draws a filled arc in a binding that uses a color associated with the event, and erases the next slice of the pinwheel to mark the edge of motion. The local variable angle, the front edge of the pinwheel motion, is advanced at each iteration. The procedure NextEvent() encapsulates the task of reading a program event and selecting an appropriate color (or texture) to portray it so that the type of data being processed and the color used to draw the pinwheel are independent of the task of drawing the pinwheel itself. NextEvent() assigns the global variable Binding a window value with an appropriate foreground color for use in drawing the sector.

8.1.2 Nova

The nova metaphor is another example of a radial mapping of a sequence of event reports. Each allocation event report is plotted as a line segment from the center of the window in polar coordinates, with a radius given by the size of the allocation (&eventvalue), at a regular angular offset from the preceding value. Like pinwheel, the graphic is drawn in a color that indicates the allocation type, based on the event code, and the display is animated at the rate at which memory allocations take place. An example screen image from nova is shown in Figure 8.2.

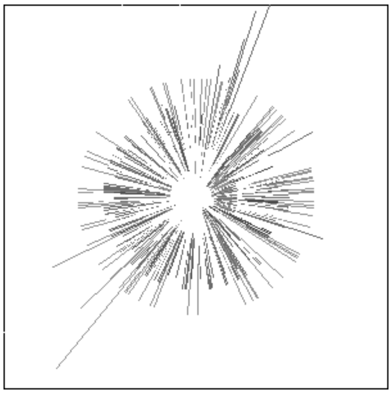


Figure 8.2: Nova

Like pinwheel, nova begins with an initialization section, followed by a loop that reads an event (again using NextEvent()) and draws a line at the appropriate angle and of the appropriate length.

```
procedure nova()
    local clear, xorg, yorg, radius, radians
    local angle, arc, sector_units, fullcircle, erase, oldvalue
    initial gclear := 1
    erase := list(Sectors)
    fullcircle := 360 * 64
    angle := 0                              # initial degrees * 64
    radians := 0
    sector_units := fullcircle / Sectors   # amount to advance
    xorg := XWidth() / 2
    yorg := XHeight() / 2
    radius := ((XHeight() < XWidth()) | XHeight()) / 2.0
    while NextEvent() do {
        put(erase, Value)
        oldvalue := get(erase)
```

```
        XDrawLine(Background, xorg, yorg, \oldvalue * cos(radians) + xorg,
            oldvalue * sin(radians) + yorg)
        XDrawLine(Binding, xorg, yorg, Value * cos(radians) +
            xorg, Value * sin(radians) + yorg)
        angle +:= sector_units
        angle %:= fullcircle
        radians := −dtor(angle / 64)
        }
end
```

The following example demonstrates how memory allocation monitors may be of practical use. A poetry-scrambling program submitted by a user produced the visual signature given in Figure 8.3 when run under a tool using the nova metaphor (the wedge shaped gap in Figure 8.3 is present simply because the nova's sweep has not completed its first revolution). The program builds up very long lists by repeated concatenation, resulting in the frequent very large allocations shown in the figure. After changing two lines of code to replace a list concatenation with calls to Icon's put() function, the visual signature became "normal" and program execution speed doubled (Figure 8.4).

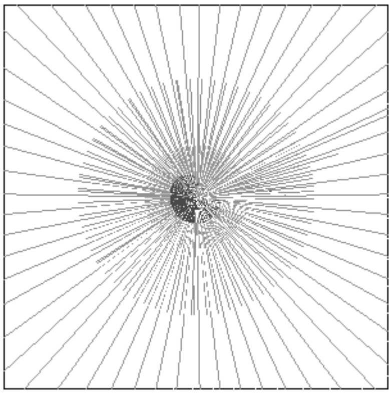


Figure 8.3: Frequent large allocations suggest a problem

8.2 Cumulative allocation by type

Visualizing individual allocation events is useful for understanding local phenomena, but an overall summary of memory allocation is also useful in understanding program behavior. The following code segment totals the amount of memory allocated in the program by data type, building a table of sums that is keyed by the allocation event codes for each type. The sums are cumulative, that is, garbage collections are not taken into consideration.

```
t := table(0)
while EvGet(AllocMask) do
    t[&eventcode] +:= &eventvalue
```

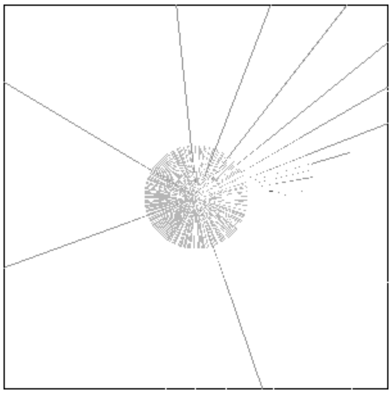


Figure 8.4: The target program runs twice as fast after a two-line change

8.2.1 Animating a bar graph

The following procedure renders a list of non-negative numbers in a window as a bar graph. Each bar in the graph is given a string name in a list called labels whose indices match those of the list of numbers.

```
procedure bar_graph(L, labels, scale)
    local height, x, y, i
    XClearArea()
    height := XHeight()
    bar_width := real(XWidth()) / *L
    XWindowLabel("Bar Graph, scale " || left(scale, 6))
    every i := 1 to *L do {
        x := (i – 1) * bar_width
        y := L[i] * scale
        XFillRectangle(x, height – y + 1, bar_width – 2, y)
        XDrawString(x, 15, labels[i])
        }
end
```

If bar_graph is called frequently, such as every time an event occurs in an execution monitoring setting, the frequent window updates create a distracting amount of screen flicker. In such an animation, an incremental approach is more appropriate.

The following program updates a bar graph incrementally. The bar graph presents cumulative memory allocation by type. An example screen image from this animated bar chart is given in Figure 8.5.

The cumulative allocations are stored in list bars, in the order they appear on the screen. A parallel list of labels for each bar is maintained in labels; it is built from a table evs that maps event codes to their string names. The table is constructed by the standard evinit library procedure evsyms(). The mapping from event codes to screen position is maintained by the table typecode2bar. The animated bar graph scales itself as cumulative allocations increase.

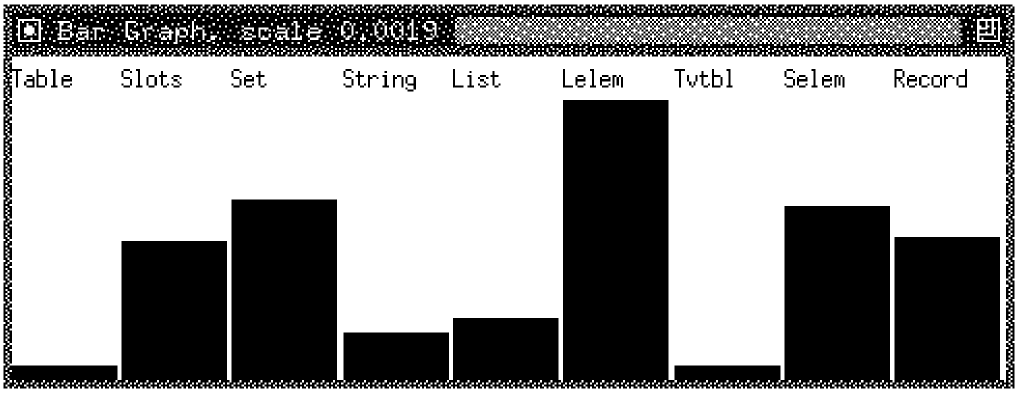


Figure 8.5: An animated bar graph

```
&window := open("barmem","x") | stop("can't open window")
height := XHeight()
evs := evsyms()
typecode2bar := table()
bars := []
labels := []
scale := 4.0
```

The main loop requests an allocation event and calls procedure bar() to update the size of the bar that corresponds to the event. A new bar is created when a type's first allocation takes place. No screen space is devoted to types for which no allocation occurs. As each bar's label is obtained from the event names table evs, the event's E_ prefix is stripped by the string subscript [3:0].

```
while EvGet(AllocMask) do {
    if /event2bar[&eventcode] := *put(bars,0) then
        put(labels, evs[&eventcode][3:0] | "?")
    extent := (bars[event2bar[&eventcode]] +:= &eventvalue) * scale
    if extent > height - 20 then
        bar_graph(bars, labels, scale /:= 2)
    else
        bar(extent, event2bar[&eventcode])
    }
```

The procedure bar() simply fills in a rectangle for the added space.

```
procedure bar(extent, i)
    x := (i – 1) * bar_width
    y := height – extent + 1
    XFillRectangle(x, y, bar_width – 2 , &eventvalue * scale + 1)
end
```

8.2.2 Pie charts

The following procedure draws a pie chart from a table shares in which each portion of the pie represents a key and their relative size is the key's table value. A parallel table colors of window bindings contains the color, grayscale, or texture that is used to distinguish each of the parts.

```
procedure draw_pie(shares, colors, sum, x, y, width, height)
    local start, fraction, k, path
    start := 0
    fraction := 360 * 64.0 / sum
    every k := key(shares) do {
        path := fraction * shares[k]
        XFillArc(colors[k], x, y, width, height, start, path)
        start +:= path
        }
end
```

Unless the update rate is high, a visualization tool using this procedure can be animated by brute-force by redrawing the entire image each time rather than incrementally. If the update rate is high, the chart might only be redrawn when a constituent's size changes by a significant amount, such as more than one percent of the total. A sample screen image from such a program is given in Figure 8.6.

8.3 Running allocation by type

In order to take garbage collections into account, the program must select E_Collect and E_EndCollect events. The E_Collect event is produced prior to a garbage collection. The E_EndCollect event occurs after a garbage collection, and if it is selected, the monitoring instrumentation also produces (re)allocation events in between the E_Collect and E_EndCollect for the objects that survived the collection.

```
codes := AllocMask ++ E_Collect ++ E_EndCollect
t := table(0)
while EvGet(codes) do
    if &eventcode === E_Collect then t := table(0)
    else t[&eventcode] +:= &eventvalue
```

A more complex example of monitoring allocation by type is the following strip chart. It uses the approach as the preceding example, but portrays a continuous animation in a window. In the following example, the y axis is used to show the proportions of memory used by all types. An example screen image from this program is given in Figure 8.7.

The program monitors all memory allocation and garbage collection information, maintains a table of running sums of memory by type, and draws each vertical line in the graph as a set of segments that are color

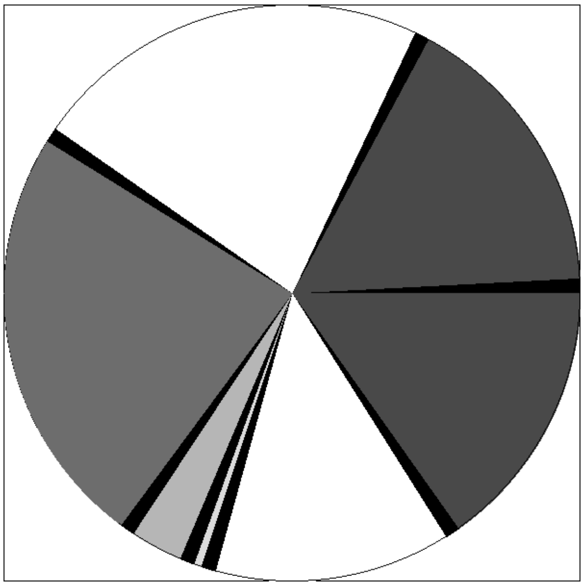


Figure 8.6: A pie chart

coded by type and whose length corresponds to the proportion of memory used by that type. An external library procedure, typebind(), is linked and used to provide the color encoding. typebind() returns a table whose keys are type allocation event codes and whose values are window bindings with foregrounds set to various colors; the table is stored in global variable Colors. Since colors vary from device to device, several palettes are available from typebind(), depending on the output device to be used. The global variable tallies refers to a table of sums of allocations keyed by type. Global variable heapsize stores the total amount of available memory. The event processing loop in procedure main() calls redraw() to update the window on each allocation and clears the window on garbage collection.

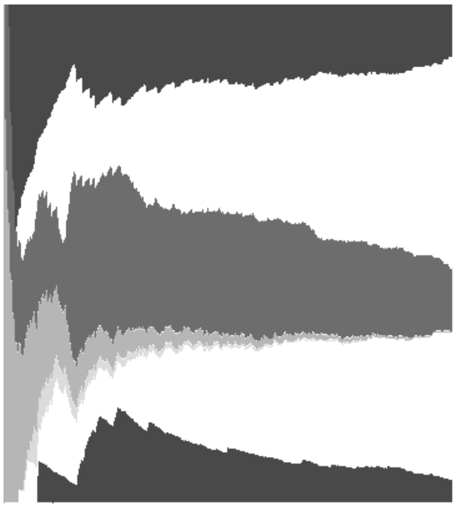


Figure 8.7: A memory allocation strip chart

```
tallies := table(0.0)
heapsize := 0
every heapsize +:= keyword("regions", Monitored)
&window := open("MemoryType", "x")
Colors := typebind(&window, AllocMask)
mask := AllocMask ++ E_Collect
while EvGet(mask) do
    case &eventcode of {
        E_Collect: {
            XClearArea()
            tallies := table(0.0)
            }
        default: {
            tallies[&eventcode] +:= &eventvalue
            redraw()
            }
        }
```

The procedure redraw() updates the display when needed. Real arithmetic is used to minimize numeric errors in the mapping.

```
procedure redraw()
   static x
   initial x := 0
   start := 0
   every k := key(t) do {
      segment := XHeight() * real(tallies[k]) / heapsize)
      XFillRectangle(Colors[k], x, start, 1, segment)
      start +:= segment
      }
   x := x + 1 % XWidth()
   XClearArea(x + 1, 0, 1)
end
```

It is possible to substantially improve on this trivial example; redundant calls and type conversions can be avoided, and many variations on the mapping from the problem space onto the image geometry are possible. In particular it may be worth avoiding screen updates when the change to be reported is very small.

8.4 Survival rates across collections

If a garbage collection reclaims only a small amount of storage, the TP may quickly run out of free memory and collect again. As the frequency of collections rises, overall system performance declines rapidly. This information can be obtained by selecting E_Collect and E_EndCollect events and reading TP's &storage keyword.

```
while EvGet(E_Collect) do {
   L := [ ]
   every put(L, keyword("storage", Monitored))
   EvGet(E_EndCollect)
   L2 := [ ]
   every put(L2, keyword("storage", Monitored))
   write("reclaimed ",integer(real(L[2] - L2[2]) / L[2] * 100),
      " percent of the string region")
   write("reclaimed ",integer(real(L[3] - L2[3]) / L[3] * 100),
      " percent of the block region")
   }
```

CHAPTER 9

Monitoring String Scanning

As a descendant of SNOBOL4, Icon has a natural orientation towards text processing and includes a control structure devoted to that task. This chapter presents a brief overview of Icon's string scanning facilities and then gives example execution monitors that portray the target program's use of this control structure. The examples are themselves relatively simple, but demonstrate the framework's capabilities in this area and are suggestive of more advanced possibilities to be explored in this domain using the framework. Techniques for monitoring string scanning can be built by extending the techniques presented for monitoring procedure and operator activity in Chapter 7.

9.1 Overview of string scanning

Icon's string scanning facility provides high-level text processing capabilities that free the programmer to think in terms of patterns in the text instead of character-by-character handling of indices and subscripts. String scanning operations work within the context of a string being scanned, the *subject*, and a current *position* of interest within that subject. Together, the subject and position form a *scanning environment* (Figure 9.1).

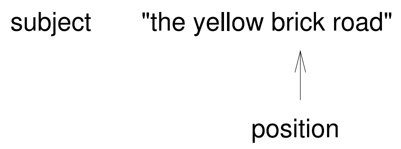


Figure 9.1: A string scanning environment

The Icon expression

```
s ? expr
```

evaluates *expr* in a scanning environment that consists of subject `s` and an initial position of 1 (the beginning of the string). Scanning environments remain in effect inside any procedure calls within *expr*. Scanning environments may be nested; the outer scanning environment is saved and restored when the inner environment is entered and exited.

Operations on scanning environments include absolute and relative movement of the position as well as various forms of string and character set matching and searching. Relatively sophisticated parsing is performed by using these operators in conjunction with goal-directed evaluation and backtracking. In particular, the functions that change position within an environment, `move()` and `tab()`, undo their effects if they are resumed by backtracking.

9.2 String scanning events

Since a TP may suspend from and later resume a scanning environment, string scanning instrumentation includes a set of events for environment creation, suspension, resumption, failure, and removal, analogous to the events that occur as a result of procedure activity. Monitoring string scanning may entail the maintenance of a scanning environment tree using code similar to the procedure activity tree presented in Chapter 7.

In addition to these events, string scanning position changes result in the occurrence of E_Spos events. If the scanning position is restored by move() or tab() during backtracking, a second E_Spos event occurs.

Scanning environment activity including position change events can be selected by an EM using the library symbol ScanMask as the argument to EvGet(). In addition to ScanMask events, a string scanning monitor may be interested in calls to the built-in string-scanning functions that comprise Icon's pattern matching primitives, such as find() and upto().

9.3 Absolute and relative position changes

This section gives two simple EMs that present position change information with different emphases: (1) a view that portrays absolute position, and (2) a view that emphasizes relative position changes.

Visualizing absolute positions within the subject

String scanning operations move the position of interest within the subject forward or backward. Moving the position forward is common; moving the position backward is less common and usually is triggered by backtracking during goal-directed evaluation. It is useful to be able to observe when the position moves forward or backward and how large the changes in position are relative to the size of the string.

The following program displays an animated strip chart with subject lengths and position change information. For each position change event, the length of the subject is drawn down from the top and filled with two or three colors: a red segment indicates the current position or the number of characters already processed, while a white segment indicates the remainder of the string not yet processed. If backtracking has occurred, a gray segment in between the red and the white indicates the furthest forward that the scanning position has reached or the extent of the backtracking. A sample screen image is given in Figure 9.2.

The program starts with standard initialization code, including the creation of window bindings for drawing segments in red and gray. The width of each bar is determined by variable barwidth, and the number of pixels drawn per character in the various segments is specified in the variable scale.

The program's main loop requests position change events, and plots a segment on the window for each change. XDrawRectangle() draws a black outline to indicate the size of the scanned subject; calls to XFillRectangle() plot the red and gray segments. A variable max holds the furthest position reached during scanning of a particular subject string; the gray segment is only drawn if backtracking has moved the position backwards into parts of the subject that have already been scanned.

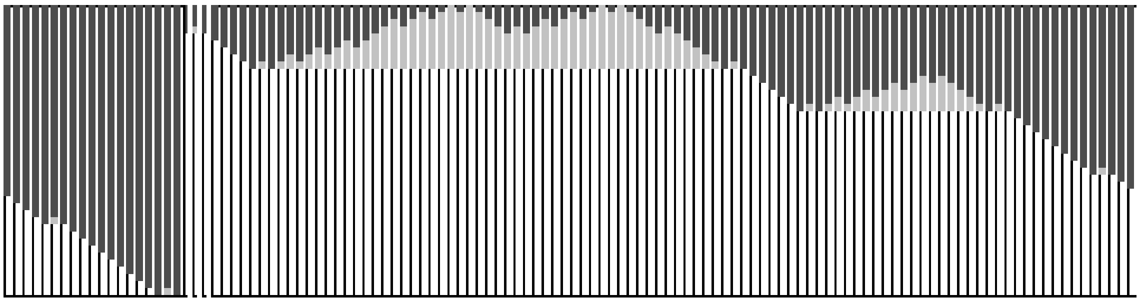


Figure 9.2: Absolute string position

```
while EvGet(E_Spos) do {
    s := keyword("subject", Monitored)
    position := &eventvalue
    if s == s_old then max <:= position
    else max := 1
    if *s > 0 then {
        XDrawRectangle(x, 0, barwidth, scale * *s)
        XFillRectangle(red, x, 0, barwidth, scale * (position − 1))
        if max > position then
            XFillRectangle(gray, x, scale * (position − 1),
                barwidth, scale * (max − position))
        }
    x := (x + barwidth + 1) % XWidth()
    XClearArea((x + barwidth + 6) % XWidth(), 0, barwidth + 6)
    s_old := s
    }
```

This simple EM does not scale its output to fit the window; in the event a very long subject is scanned, output is clipped to window boundaries. An additional limitation is that backtracking information is not saved and restored for nested scanning environments.

Visualizing relative position changes

By tracking relative position changes, backward motion is highlighted and large position changes are emphasized. The following EM plots relative position change as distance from the middle of the window, with forward position change going below the midpoint and backward position change going up from the midpoint. A sample screen image is shown in Figure 9.3.

After initialization, the main loop reads E_Spos events and uses the keyword() function to obtain the corresponding subject. If the subject is unchanged since the last event, the relative position change is noted. Like the previous example, this tool would provide more accurate information if it saved and restored the subject for nested scanning environments. The next section provides a method for doing so.

Figure 9.3: Relative string position

```
barwidth := 3
&window := open("pos", "x") | stop("can't open window")
x := 0
while EvGet(E_Spos) do {
    s := keyword("subject", Monitored)
    p := &eventvalue
    XFillRectangle(x, XHeight() / 2, barwidth, 1)
    if s === s_old then
        if p > p_old then
            XFillRectangle(x, XHeight() / 2, barwidth, p − p_old)
        else if p_old > p then
            XFillRectangle(x, XHeight() / 2 − (p_old − p), barwidth, p_old − p)
    x := (x + barwidth + 1) % XWidth()
    XClearArea((x + barwidth + 6) % XWidth(), 0, barwidth + 6)
    s_old := s
    p_old := p
    }
```

9.4 Scanning operations and the environment tree

Since scanning environments may be nested in much the same way as procedures, functions, and operators, it makes sense to use a tool similar to the Algae tool presented in Chapter 7 to portray nested scanning environments. One way to make use of such a tool is to display scanning activity such as calls and results of string scanning functions and operators as graphical manipulations inside the hexagon allocated by Algae to the active scanning environment.

A modified version of Algae that displays string functions and operators encoded as colors is shown in Figure 9.4. The program uses the pinwheel metaphor from Chapter 8 to animate the sequence of operations independently within each scanning environment. Around the pinwheels' outside borders, circles are drawn in red, white, and gray segments to show current position and positional backtracking, similar to the absolute string positions example given earlier. The border around the pinwheel in the second column of Figure 9.4 is almost entirely dark (the grayscale depiction of red), indicating that the scanning position is almost to the end of the string, while the border around the pinwheel in the fourth column is only slightly dark above the three o'clock position, showing that the scanning position is still near the front of the scanned string.

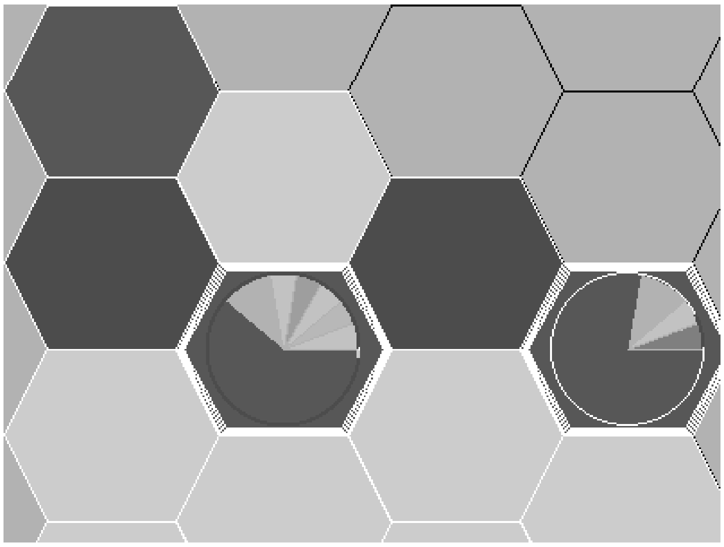


Figure 9.4: Scanning environment trees and operations

In order to add this kind of detailed information about string scanning environments, extra fields are added to Algae's activation record type for the current scanning position, the farthest scanning position reached in the scanning environment, and the environment's pinwheel angle (expressed in units of 1/64th of a degree).

```
record activation(node, parent, children, row, column, color, pos, maxpos, angle)
```

Updating position in the current scanning environment

Position change events are added to the event mask passed to evaltree(). The case expression of the callback procedure for E_Spos events updates the current scanning environments position fields, and draws red and gray arcs around the outside of the hexagon to show position information. Global variables HexWidth and HexHeight are used to determine the region inside the hexagon that is available for drawing.

Note that a callback static variable, scanenv, is used rather than the current activation (new), which can be a procedure, function, or operator called within the current scanning environment. scanenv is maintained by code added to the case expression branches of Algae's evaltree() callback procedure, described below.

```
case &eventvalue of {
    # ... other Algae case branches as given in Chapter 7
    E_Spos: {
        scanenv.pos := &eventvalue
        scanenv.maxpos <:= &eventvalue
        unit := fullcircle / *scanenv.node
        XDrawArc(red, hexcolumn_x(scanenv.col) + 5,
            hexrow_y(scanenv.row, scanenv.col) + 5,
            HexWidth – 10, HexHeight – 10, 0, (&eventvalue – 1) * unit)
        if scanenv.maxpos > scanenv.pos then
            XDrawArc(gray, hexcolumn_x(scanenv.col) + 5,
                hexrow_y(scanenv.row, scanenv.col) + 5,
                HexWidth – 10, HexHeight – 10,
                (&eventvalue – 1) * unit, (scanenv.maxpos – scanenv.pos) * unit)
        XDrawArc(wwhite, hexcolumn_x(scanenv.col) + 5,
            hexrow_y(scanenv.row, scanenv.col) + 5,
            HexWidth – 10, HexHeight – 10,
            (scanenv.maxpos – 1) * unit, fullcircle – (scanenv.maxpos – 1) * unit)
        }
    }
```

Drawing pinwheel sectors for string scanning functions

The global table of colors is extended to map important string scanning functions onto window bindings with foreground colors that indicate which function is being performed. Activity that involves these functions is captured by adding code to the callback procedure's case expressions. The code for suspension events is shown here; similar code is added to the other cases.

```
!SuspCodes: {
    pinwheel(scanenv, \Colors[new.node])
    # ... rest of code for suspension events
    }
```

Maintaining pinwheels for nested scanning environments

The added fields of an activation record are initialized whenever a new scanning environment event is received. The modified code looks like:

```
!CallCodes: {
    # ... code as given in Chapter 7
    if &eventcode === E_Snew then {
        new.pos := new.maxpos := 1
        new.angle := 0
        }
    }
```

The pinwheel drawing procedure from Chapter 8 is revised to take an activation record and a window binding with a foreground color to encode the string operation being performed, and draw a single sector in that foreground each time it is called.

```
procedure pinwheel(arecord, win)
    static full_circle, sector_units
    initial {
        full_circle := 360 * 64
        sector_units := full_circle / 16 # 16 sectors in the circle
        }
    radians := −dtor(arecord.angle / 64)
    x := hexcolumn_x(arecord.col) + 6
    y := hexrow_y(arecord.row, arecord.col) + 6
    width := HexWidth − 12
    height := HexHeight − 12
    center_x := x + width / 2
    center_y := y + height / 2
    XFillArc(arecord.color, x, y, width, height, arecord.angle + sector_units, blank)
    XFillArc(win, x, y, width, height, arecord.angle, sector_units)
    XDrawLine(arecord.color, center_x, center_y,
        radius * cos(radians) + center_x, radius * sin(radians) + center_y)
    arecord.angle +:= sector_units
    arecord.angle %:= full_circle
end
```

9.5 Conclusions

String scanning is an important feature in Icon. In order to monitor it correctly, an EM must not only handle position changes, but also handle nested and suspended scanning environments. The extra attention required to monitor scanning correctly parallels the effort required to implement scanning correctly in the language.

Although string scanning is important, most programs use string scanning in extremely simple ways. Although detailed views will always be useful in debugging situations, in more general program-understanding efforts the information provided by literal text-oriented views of string scanning may be less useful than might be expected. A better approach may be to view string scanning within a larger context of program operation, such as the modified Algae example. It is not clear how to best monitor and visualize string scanning; this is still an open area for research.

CHAPTER 10

Monitoring Data Structures and Variable Usage

Previous chapters have demonstrated techniques for monitoring various aspects of program control and memory usage. Although some aspects of TP data usage are observable by means of memory allocation and garbage collection events, key aspects of program behavior are often characterized in terms of operations on program data, such as manipulations of program data structures or variable references.

This chapter presents techniques for monitoring data from both program-wide and narrower, variable-oriented viewpoints. Example EMs include list access monitors that show usage of Icon's built-in list data type on a program-wide scale, and variable reference monitors that show activity within individual procedure activations. There are many other ways to present data structure activity and this is an open area of research. The examples in this chapter illustrate the capabilities and possible uses of the framework in this domain.

10.1 List Accesses

On a program-wide scale, a tool that visualizes list activity is representative of techniques needed to monitor Icon's list, table, record, and set data types. Icon's list data type is used for a variety of purposes. Some programs use a few large lists, while other programs may use hundreds or thousands of small lists. Lists can change in size dynamically using both queue and stack operations, and they can also be accessed randomly similar to arrays in other languages.

The following EM portrays an overall view of list behavior in a TP. TP's lists are presented as a sequence of vertical bars, with each bar's length proportional to the size of the corresponding list. Vertical segments of the bars are color-coded by the types of the lists' elements. If all of a list's elements are of the same type, this forms a solid bar of that type's color; if a list is heterogeneous, its appearance is "candy-striped" with the various colors of its elements' types. The horizontal position of a list's bar on the display is given by the list's serial number. A serial number is an integer associated with each list when it is created. Using serial numbers to determine screen position orders the lists from left to right by time of creation.

Queue, stack, and array-style random accesses are portrayed by changing the size of the bar (in the case of queue and stack accesses) or briefly painting a segment of the bar black and then redrawing it (in the case of random accesses). An example image from this program is given in Figure 10.1. Empty columns in this view indicate serial numbers at which no list has yet been created (on the far right) or lists that are empty or have been garbage collected (in the middle of the figure).

One of the key features of this program is a high degree of scalability necessary in order to accomodate programs with very large numbers of lists and yet present as much detail as screen space allows. In particular, if the number of lists is too large to fit in the window, the window is split into two rows and the number of vertical pixels per element is halved; this generalizes to n rows of as few as one vertical pixel per list element. Figure 10.2 depicts a view in which the number of lists has caused a split into two rows. Figure 10.3 depicts a scaled image for a larger number (around 400) of lists requiring eight rows. Spaces in the figures again generally indicate empty or garbage-collected lists.

This scalability is achieved by maintaining a number of interdependent variables to describe the screen geometry. The window is divided into a matrix of size `rows` by `cols` corresponding to individual lists; each

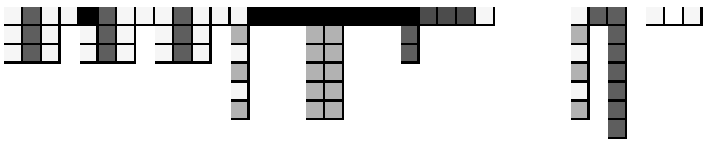


Figure 10.1: A list access monitor

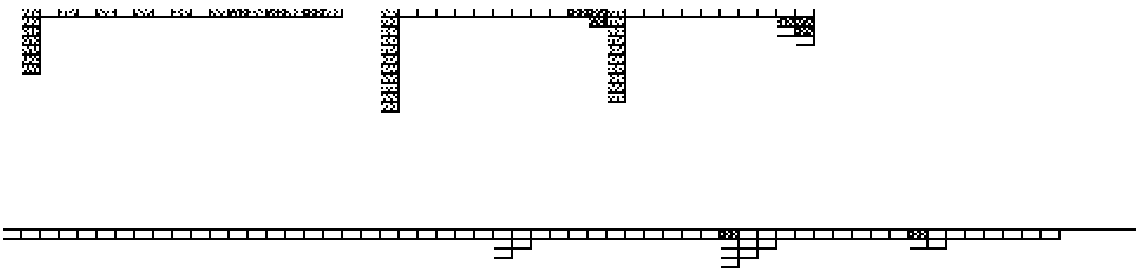


Figure 10.2: A moderate number of lists

element of the matrix is in turn divided into vertical segments of height elem_height.

```
global
    rows,           # number of rows of entire lists
    cols,           # number of lists displayed per row
    elem_height     # height of an individual list element
```

In addition to this basic screen geometry, a count of the number of lists in TP is kept in number_active, and the mapping from lists to window (row,column) coordinates is maintained in table list_locations. The mapping from lists to window coordinates uses list serial numbers as keys, rather than list values themselves. If the EM retained references to the TP lists instead of their serial numbers, none of the TP lists could be reclaimed by garbage collection.

Procedure redraw() draws an entire picture of all the lists in the program. It uses the MT Icon function structure() to generate all the allocated structures in the program, and assigns each list a row and column.

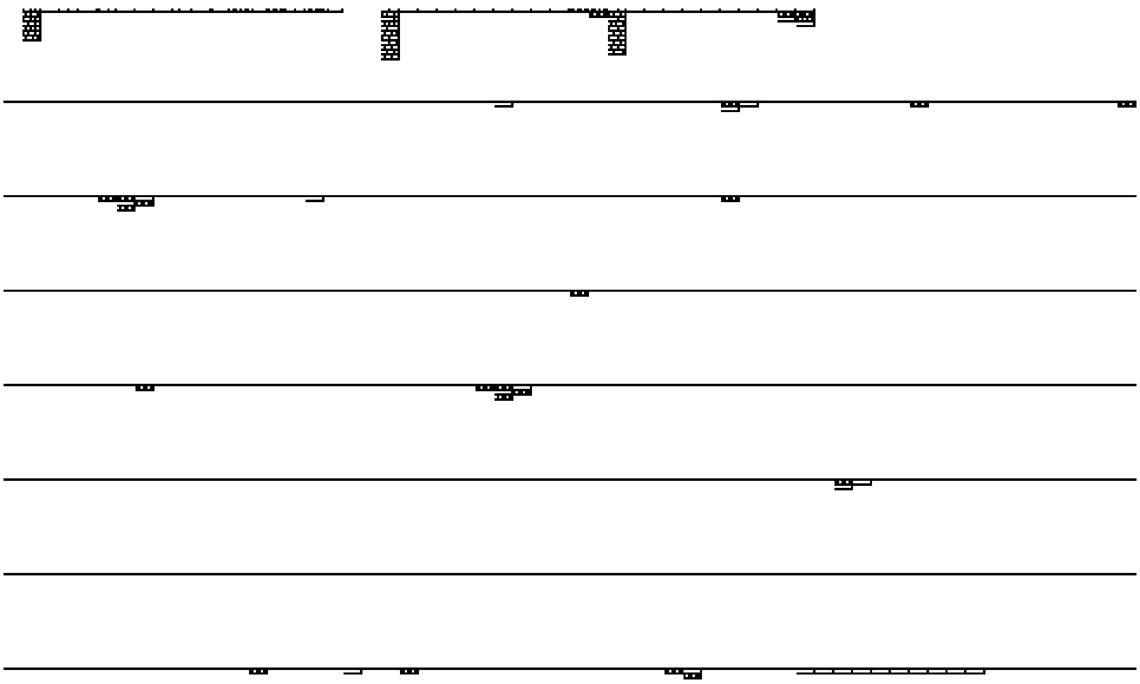


Figure 10.3: A large number of lists

Each element of each list is then drawn by XFillRectangle() in a color determined by the element's type by a call to objcolor().

```
procedure redraw()
    XClearArea()
    column_width := XWidth() / cols
    row_height := XHeight() / rows
    every i := 1 to rows − 1 do XDrawLine(0, i * row_height, XWidth(), i * row_height)
    number_active := 0
    list_locations := table()
    every type(L := structure(Monitored)) == "list" do { # for every list in the heap...
        number_active +:= 1
        row := 1 + number_active / cols
        col := number_active % cols
        list_locations[serial(L)] := location(row, col)
        every index := 1 to *L do
            XFillRectangle(objcolor(L[index]), col * column_width, (row − 1) * row_height +
                (index − 1) * elem_height + 1, column_width, elem_height)
        }
end
```

Procedure redraw() is called whenever the scaling must be changed. The view it establishes can be updated incrementally for ordinary list construction and access by drawing one or more individual list elements with procedure plot(). plot() draws a rectangle, first with a black rectangle to highlight the access, and then with a rectangle of a specified color.

```
procedure plot(w, row, col, index, del)
    /del := 40
    x := col * column_width
    y := (row − 1) * row_height + (index − 1) * elem_height + 1
    if del > 0 then {
        XFillRectangle(vblack, x, y, column_width, elem_height)
        XFlush(vblack)
        delay(del)
        }
    XFillRectangle(w, x, y, column_width, elem_height)
end
```

The main loop fetches list events and updates by calling plot(). redraw() is called when the screen becomes full or the window size changes. One significant detail of list access monitoring is that a list access results in two events, one with the list itself for an event value, and a second event with an integer event value that gives the index accessed within the list. EM saves the list value in the first event and uses it when the second is reported. Since the events come in pairs, TP does not do anything in between the two events, but after the second event, EM must use and then destroy its reference to the list or it might spuriously prevent the list from being garbage collected.

```
while EvGet(ListMask) do
    case &eventcode of {
        E_Lref : L := &eventvalue
        E_Lsub : {
            index := &eventvalue
            if index < 0 then
                index +:= *L + 1
            loc := list_locations[serial(L)]
            plot(objcolor(L[index]), vertical(loc), horizontal(loc), index)
            L := &null
            }
        # ... other events handled similarly
        }
```

Although this example uses some sophistication to scale well to larger numbers of lists, it can be enhanced in various ways. For example, relaxing the direct mapping from serial number to screen location would allow screen-space to be reclaimed whenever a list was garbage collected. Another improvement would be to portray list operations in a visually distinct way instead of simply maintaining an accurate representation of the lists' contents.

10.2 Monitoring variable references

Monitoring structure accesses with techniques such as those described in the previous section is useful, but in many EMs, notably debuggers, data monitoring is driven from the variables used in the program. We consider two examples of variable monitoring, one that visualizes all variables and one that identifies references to specific variables of interest.

10.2.1 Assignment events

One of the most common monitoring techniques is the observation of assignments, where the user is informed or monitoring code is executed whenever an assignment to a particular variable or set of variables is made. The instrumentation reports an E_Assign event on each assignment. E_Assign has a string event value equivalent to calling name(v) on the assigned variable, suffixed by a *scope code*. The scope codes are

Code	Scope
`"+"`	global
`":"`	static
`"-"`	local
`"^"`	parameter

Statics, locals, and parameters are followed by the name of the procedure in which they are defined. For example, a local variable i in procedure main() would produce an E_Assign event value "i-main". Variable references to structure elements have no scope code.

For assignments to named variables and keywords, the name and scope are sufficient to perform reference detection; the name and scope may be augmented by procedure activity information in order to provide finer detail for local (and especially recursive local) variables. For assignments to structure elements, the event value cannot produce the name. A given structure element might be assigned by means of any of several variables that reference the structure. For this reason, reference detection techniques are different for named variables and for structure-element variables.

10.2.2 Monitoring variables by name

Figure 10.4 shows a window image of a tool that displays the names and types of variables associated with procedure activations; the names are written in multiple columns in the case of a procedure with a larger number of variables. As its appearance indicates, the tool is an enlarged version of the Algae program from Chapter 7. The names of procedure parameters and local variables are displayed within each activation, drawn in a color that indicates the type of the variable. Colors are updated after each assignment. One useful extension to this tool is to show the values of integers. This is useful because integers are common, because they do not require much space, and because they are not heap-allocated and therefore do not appear in other data-oriented monitors.

The required modifications to Algae source code are omitted here for the sake of brevity; they are comparable to the extensions for string scanning given in the preceding chapter. The technique used is the monitoring of assignment events, considering only those events whose scope code indicates either a local variable or parameter assignment.

The use of source-text names creates serious spatial problems. Another reasonable way to extend this EM would be to modify it to use smaller rectangles for each variable and omit the names. Specific variables'

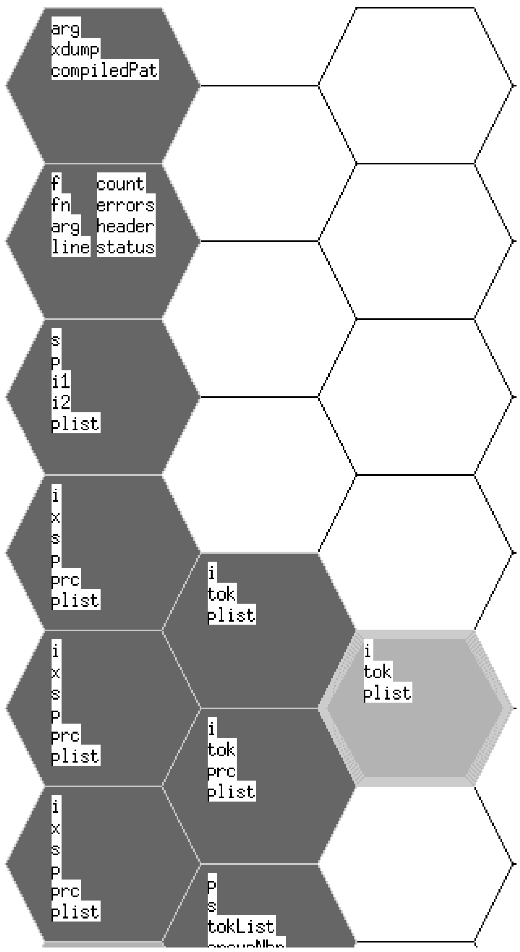


Figure 10.4: Monitoring variables in active procedures

names could be shown when the user clicks the mouse atop a particular variable.

10.2.3 Monitoring individual variables

A named variable is identified by its name and scope, or by its instantiating procedure activation if recursively created local variables are considered distinct. For such variables, reference detection is implemented using the E_Assign event values and some additional logic. Two examples below illustrate cases where (1) the EM acts on any assignment to a variable defined within a given procedure, and (2) the EM acts on assignments only within a specific activation record.

In the non-recursive case, variables can be identified by their name and scope. A collection of variable names of interest might be stored in an Icon set ("trapped_variables" in the code below). Variable traps require selection of assignment events and maintenance of current procedure information using the evaltree() procedure as described in Chapter 7 on following procedure activity. The correct invocation of evaltree() is:

```
evaltree(ProcMask ++ E_Assign, trap_callback, activation_record)
```

Procedure trap_callback() detects variable references with a set membership test.

```
procedure trap_callback(current_proc)
    if &eventcode === E_Assign then
        if member(trapped_variables, &eventvalue) then {
            # perform trap
            }
end
```

In some EM's, the handling of recursive procedure calls requires a more sophisticated form of variable trapping in which each individual local variable within each procedure activation record is treated as a distinct entity and can be trapped separately. This is relevant in recursive procedure calls. This form of trapping can be implemented by adding a field to the structure maintained for activation records:

```
record trapped_activation(p, parent, children, trapped_variables)
```

The variable reference detection is performed using this record type in an evaltree() invocation of the form:

```
evaltree(ProcMask ++ E_Assign, trap_callback, activation_record)
```

and replacing the line

```
        if member(trapped_variables, &eventvalue) then {
```

in trap_callback() with the line

```
        if member(new.trapped_variables, &eventvalue) then {
```

10.2.4 Detecting structure variable references

Icon structures have pointer semantics. Consequently, if two variables refer to the same structure, a trap on the name of an element of one of the variables will not catch an assignment using the other variable name. In the code

```
L1 := list(2)
L2 := L1
L2[1] := "foo"
```

a trap on variable L1[1] will not catch the assignment even though assignment is made to it. In order to trap structure elements, the information provided in assignment events need to be mapped down to the underlying structure.

Unfortunately, name(v) for a structure variable produces only a type code letter and a string image of the subscripting element. Without resorting to data intrusive techniques such as altering the internal representation of Icon structures, monitors cannot tell from an assignment to an element which structure the element is in. Instead monitors use the framework's extensive access to the program state.

Given the information E_Assign events provide about structure assignments, one way to trap structure elements is to check if a structure assignment *might* be a variable trap, and then compare all structures that might have been changed, after the assignment has been performed. In general, non-intrusive techniques for monitoring assignment are inefficient: this particular approach imposes a cost on structure variable assignment proportional to the number of trapped structure variables of the same type and index; if a large number of variables are to be trapped, data intrusive techniques may be needed for performance reasons. An appropriate trapped variable technique has been developed for SNOBOL4 [Hans78].

For every trapped structure variable, a triple consisting of the structure, the index or key, and the old value is maintained.

```
record trapped_structvar(struct, index, value)
```

These records are stored in a table, indexed by the string name that is reported by E_Assign when the variable is assigned.

Structure variable traps use not only E_Assign events, but also the E_Value events that are produced following the assignment. If the structure indexed by the key does not still equal the old value, the assignment has taken place. This technique is not capable of detecting assignments of the same value replacing itself in structures. The code is

```
codes := E_Assign ++ E_Value
while EvGet(codes) do
    case &eventcode of {
        E_Assign : {
            if match("T[" | "L[" | "R.", &eventvalue) then
                struct_asgn := trapped_structs[ &eventvalue ]
            else struct_asgn := &null
            }
        E_Value : {
            every tv := !\struct_asgn do
                if tv.struct [ tv.index ] ~=== tv.value then {
                    # the trapped structure element has been assigned
                    }
            }
        }
```

This technique works directly for tables and lists. It also works for record fields as long as the field is translated into its corresponding index for insertion into the trapped_structvar record.

CHAPTER 11

Monitor Coordination and Communication

As illustrated in the preceding chapters, MT Icon and its execution monitoring interface make it easy to develop new EMs. In this model, monitors are free to specialize in particular aspects of program execution, and the user selects the aspects to monitor in a given execution. When multiple EMs come into play, the selection of which EMs to use, the execution of those EMs, and their communication interface are the responsibility of a program called a monitor coordinator (MC).

This chapter presents monitor coordination as another domain within the scope of the exploratory program development features provided by the execution monitoring framework. After a general discussion of monitor coordinators, an example monitor coordinator is presented that implements a generalization of the *selective broadcast* communication paradigm advocated by Reiss [Reis90a]. Other paradigms of monitor coordination are possible within the framework. In addition, other generalizations of selective broadcast proposed in the literature may prove complementary to the one presented in this chapter [Garl90].

11.1 Some monitoring configurations

MT Icon execution events are always reported to the parent program that loaded the TP being monitored. This means that the normal event reporting mechanism handles simple relationships such as monitoring a monitor or monitoring multiple TPs (Figure 11.1).

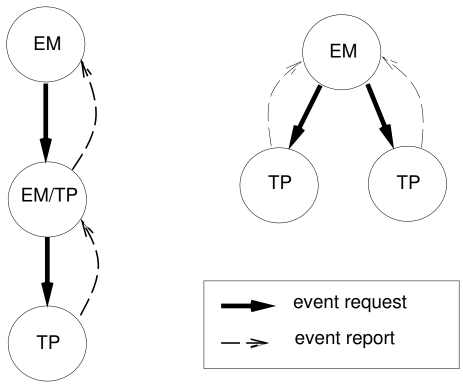


Figure 11.1: Monitoring a monitor; monitoring multiple TPs

On the other hand, the parental event report relationship means that if more than one EM is to monitor a TP, the TP's parent must provide other EMs with artificial copies of the TP events; MT Icon's event() function provides this service. Figure 11.2 depicts a parent EM that forwards TP events to an assisting EM.

Monitor coordinators are specialized EMs whose primary function is to forward events to other client EMs. A monitor coordinator is an event monitoring *kernel* that integrates and coordinates the operation of

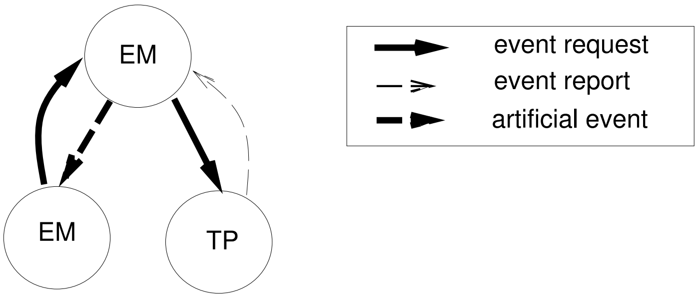


Figure 11.2: Forwarding events to an assistant

multiple stand-alone tools. By analogy to operating systems, the alternative to a kernel design would be a monolithic program execution monitor that integrates all operations into a single program.

Figure 11.3 depicts some relationships among MCs. Figure 11.3(a) is similar to Figure 11.2 and shows that a MC is just an execution monitor that forwards events. Figure 11.3(b) shows the main purpose for MCs, the execution of multiple EM's on a single TP. Figure 11.3(c) shows a MC monitoring a MC.

MC configurations and logic generally are limited to and revolve around parent-child relationships. For example, it is impossible to monitor events in a TP loaded and being monitored by another EM or MC unless that parent is configured to forward such events.

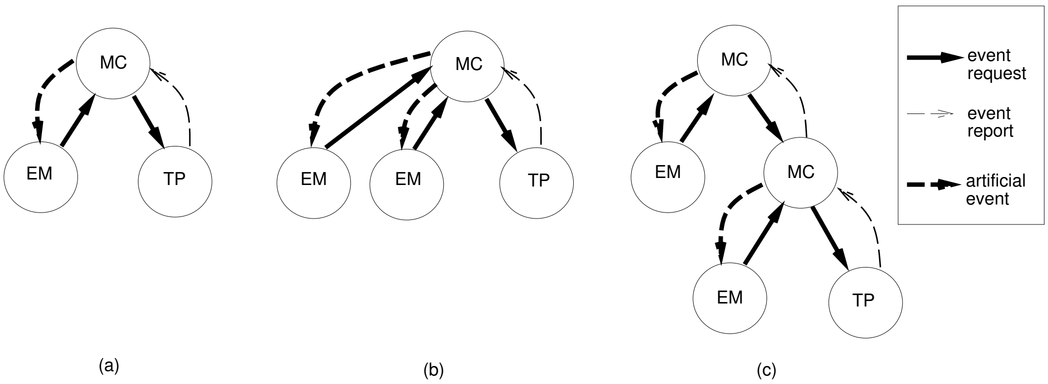


Figure 11.3: Monitor coordinators

Since event reports also transfer control, MCs also are schedulers for EMs, relinquishing the CPU to them by forwarding events to them. In the simplest case the MC forwards an event and waits for the EM to request another event before continuing; this scheduling is a form of cooperative multi-tasking. If the MC is the parent that loaded the EM in question, it can request event reports (such as clock ticks) from the EM in order to preempt its execution. Since MCs are special-purpose EMs, development of efficient MC designs falls within the scope of exploratory programming support provided by MT Icon.

11.2 Advantages and disadvantages of the MC approach

The three primary advantages of monitor coordinators are:

Modularity With a MC, monitors can be developed independently of one another and of the MC itself; they can run as stand-alone monitors, directly loading and executing the program to be monitored. This allows monitors to be debugged separately and puts "fire-walls" between monitors when they monitor the same program at the same time.

Specialization Support for multiple monitors allows EMs to be written to observe very specific program behavior and still be used in a more general setting. This in turn reduces the burden of generality placed on EM authors. Specialization also simplifies the task of presenting information, since each EM uses its own window and the user decides how much attention and screen space to devote to each EM.

Extensibility Extensibility refers to the ease with which new tools are added to the visualization environment. Adding a new tool to run under a MC does not require recompiling or even relinking the MC or any of the other visualization tools.

Monitor coordinators do have disadvantages. The implementation of MCs poses serious performance problems that require careful consideration. Although unsuitable for exploratory monitor development and experimental work, a single monolithic EM provides better performance than a MC that loads multiple EMs.

The primary problem with MCs is the number of context switches among tasks; on some architectures, notably RISC architectures such as the Sun SPARC, switching between coroutines is an expensive operation. Minimizing the number of switches required must be a goal of most MC designs.

11.3 Eve, an execution monitor coordinator

Eve is an example of a MC that allows the user to execute one or more EMs selected from a list and forwards TP events to those EMs that the user selects. The communication provided by Eve represents a generalization of the selective broadcast communications paradigm, because EMs may change the set of events at any time during execution; in Reiss's FIELD system, tools can specify the set of events they are interested in only when they are started. Unlike Forest's generalization of selective broadcast in which dynamic control is achieved by placing a greater computational load on the coordinating message server, Eve maintains an extremely simple message dispatch mechanism and passes policy changes on to the TP by recomputing the TP's event mask whenever needed. By suppressing events as early as possible, the higher performance required for execution monitoring is attained. This technique of continually minimizing the set of events reported by the TP could be used in conjunction with a Forest-style policy mechanism in the monitor coordinator if that were desired.

Eve is a cooperative multi-tasking scheduler. Figure 11.4 shows an image of Eve's control window. On the left-hand side are buttons that pause and terminate TP execution and a slider that controls execution speed. The main area of the window consists of a configurable list of EMs, and for each EM a set of buttons allow the tool to be controlled during TP execution. In the figure, two EMs are loaded and enabled. The source code for Eve is presented in Appendix B.

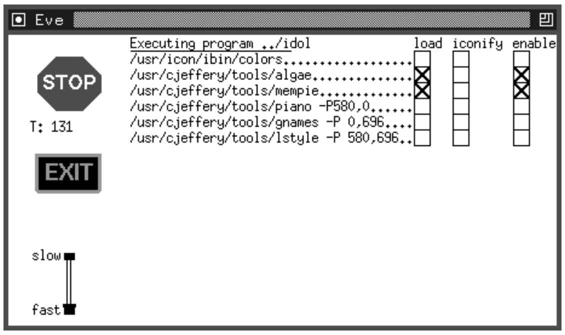


Figure 11.4: Eve's control window

11.4 Writing EMs to run under Eve

Eve supplies events to client EMs using the standard EvGet() interface [Gris90b]. This section describes a few differences between the stand-alone interface and the Eve environment. Note that programs written for the Eve environment run without change or recompilation as stand-alone tools.

Client environment

After each EM is loaded, Eve initializes it with references to its event source (the Eve program itself) and the TP. The former is necessary so that EMs yield control to Eve to obtain each event. The latter is provided so that the state of the TP may be examined or modified directly by all EMs. These references in the form of co-expression values are assigned to the keyword &eventsource and the global variable Monitored, respectively; the global variable Monitored is declared in each EM when it links to the evinit event monitoring library.

Since under Eve &eventsource is *not* the TP, EMs should always use Monitored to inspect program state. For example, to inspect the name of the current source file in the executing program an EM should call keyword("file", Monitored) rather than keyword("file", &eventsource).

Aside from the fact that &eventsource is not Monitored under Eve, from a programmer's standpoint, Eve's operation is implicit. Just as monitoring does not inherently affect TP behavior (other than slowing execution), within the various EMs Eve's presence normally is not visible; the EM can call EvGet() as usual.

General-purpose artificial events

Eve sends certain artificial events when directed by the user (in the Eve control window). These include the disable and enable events discussed above, E_Disable and E_Enable. A tool can pass a second parameter to EvGet() in order to receive these pseudo-events, for example EvGet(mask, 1). When an E_Disable event is received, a tool is requested to disable itself. Tools that do not maintain any state between events can simply shut off their event stream by calling EvGet('', 1):

```
case &eventcode of {
    # ... more frequent events come first
    E_Disable: while EvGet('', 1) ~=== E_Enable
    }
```

Tools that require events in order to maintain internal consistency might at least skip their window output operations while they are disabled. An E_Enable event informs the tool that it should resume operation, updating its display first if necessary.

Monitor communication example

In addition to the use of artificial events for communication between Eve and other EMs, artificial events can be used by EMs to communicate with each other, using Eve as an intermediary. For example, a line-number monitor such as the one shown in Figure 6.1 is more useful if the user can inquire about a section of interest in the line-number graph and see the corresponding source text. This functionality can be built into the line-number monitor, but since many visualization tools can make use of such a service, it makes more sense to construct an EM to display source lines, and use virtual events to communicate requests for source code display from other EMs.

Communication using Eve starts with the definition of an artificial event code for use by the communicating EMs. Some of these codes such as E_Disable are defined in the standard library, but in general EMs can use any artificial event codes that they agree upon. In this case, an event code, E_ALoc, is defined for artificial location display events. Communicating EMs also agree on the type and meaning of the associated event value. In this case the associated event value is an integer encoding of a source line and column number, similar to that produced by E_Loc events.

The source-code display EM is similar to other EMs, except that it is not interested in TP events, but only in E_ALoc events. Its main loop is

```
while EvGet('', 1) do
    if &eventcode === E_ALoc then {
        # process requests for source code display
        }
```

Any EM that wishes to request source location display services sends an E_ALoc event to Eve. Eve then broadcasts this event to those tools that requested artificial event reports. The code to send a location request event to Eve from within an EM is

```
loc := location(line, column)
event(E_ALoc, loc, &eventsource)
```

11.5 Eve in operation

This section describes the primary techniques employed in Eve to obtain good performance. The key ideas are to filter events at the source and to precompute the set of EMs to which each event code is distributed.

Different EMs require different kinds of events. After obtaining a list of client EMs to execute, Eve loads each client. It then activates each EM for the first time; when the EM completes its initialization, it calls EvGet(), passing Eve an event mask.

11.5.1 Computation of the minimal event set

Each time an EM requests its next event report from Eve, it transmits a cset event mask indicating what events it is interested in. Eve could simply request all events from the TP, and forward event reports to each

EM based on its current mask. The interpreter run-time system is instrumented with so many events that this brute-force approach is too slow in practice. In order to minimize the cost of monitoring, Eve asks the TP for the least set of events required to satisfy the EMs.

From the event masks of all EMs, Eve computes the union and uses this cset to specify events from the TP. The code for this union calculation is

```
unioncset := ''
every monitor := !clients do
    if monitor.enabled === E_Enable then
        unioncset ++:= monitor.mask
```

Although every EM can potentially change its event mask every time it requests an event, constant recomputation of the union mask would be unacceptably expensive. Fortunately, most tools call EvGet() with the same event mask cset over and over again. Eve does not recompute the union event mask unless an EM's event mask changes from the EM's preceding event request.

11.5.2 The event code table

The minimal event set described above greatly reduces the number of events actually reported from the TP. When an event report is received from the TP, Eve dispatches the report to those EMs that requested events of that type. The larger the number of EMs running, and the more specialized the EMs are, the smaller the percentage of EMs that typically are interested in any given event.

Eve could simply test the event code with each EM's cset mask with a call any(mask, &eventcode). This test is fast, but performing the test for each EM is inefficient when the number of EMs is large and the percentage of EMs interested in most events is small. Instead, the list of EMs interested in each event code is precomputed as the union mask is constructed. These lists are stored in a table indexed by the event code. Then, after each event is received, a single table lookup suffices to supply the list of interested EMs. For each enabled monitor, the code for union mask computation is augmented with:

```
every c := !monitor.mask do {
    /EventCodeTable[c] := [ ]
    put(EventCodeTable[c], monitor)
    }
```

11.5.3 Event handling

Eve requests three types of events whether or not any client EM has requested them: E_Tick, E_MXevent, and E_Error. Eve uses these events to provide basic services while execution is taking place; since these events occur relatively infrequently they do not impose a great deal of overhead.

E_Tick events allow Eve to maintain a simple execution clock on the control panel. E_MXevent events allow Eve to receive user input (such as a change in the slider that controls the rate of execution) in its control panel. E_Error events allow Eve to handle run-time errors in the TP and notify the user when they occur, allowing errors to be converted to expression failure at the user's discretion.

11.5.4 Eve's main loop

Eve's main loop activates the TP to obtain an event report, and then dispatches the report to each EM whose mask includes the event code. Since this loop is central to the performance of the overall system, it is coded carefully. Event dispatching to client EMs costs one table lookup plus a number of operations performed for each EM that is interested in the event – EMs for whom an event is of no interest do not add processing time for that event. The code for Eve's main loop is:

```
while EvGet(unioncset) do {
    #
    # Call Eve's own handler for this event, if there is one.
    #
    (\ EveHandlers[&eventcode]) ()
    #
    # Forward the event to those EM's that want it.
    #
    every monitor := !EventCodeTable[&eventcode] do
        if C := event( , , monitor.prog) then {
            if C ~=== monitor.mask then {
                while type(C) ~== "cset" do {
                    #
                    # The EM has raised a signal; pass it on, then
                    # return to the client to get his next event request.
                    #
                    broadcast(C, monitor)
                    if not (C := event( , , monitor.prog)) then {
                        unschedule(monitor)
                        break next
                        }
                    }
                if monitor.mask ~===:= C then
                    computeUnionMask()
                }
            }
        else
            unschedule(monitor)
        # if the slider is not zero, insert delay time
    }
```

11.6 Interactive error conversion

Normally execution terminates when a run-time error occurs. Icon supports a feature called *error conversion* that allows errors to be converted into expression failure. Error conversion can be turned on and off by the source program by assigning an integer to the keyword &error. &error indicates the number of errors to convert to failure before terminating the program; on each error the value of &error is decremented and if it reaches zero the program terminates. A program can effectively specify that all errors should be converted by setting &error to a small negative integer. The mechanism is limited in that it does not allow the user or the program to inspect the situation and determine whether error conversion is appropriate: error conversion is either on or it is off.

Eve catches run-time errors in the TP and allows the user to decide whether to terminate execution, or convert the error into expression failure and continue execution (Figure 11.5).

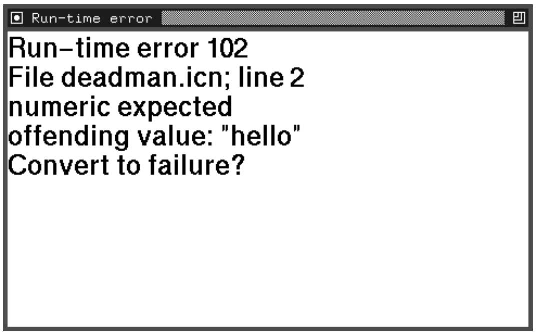


Figure 11.5: Eve's interactive error converter

An E_Error event occurs upon a run-time error. A monitor that requests E_Error events is given control before the error is resolved. Eve requests these events, presents the user with the error, and asks for an appropriate action. The code in Eve that does interactive error conversion is:

```
procedure eveError()
    win := open("Run-time error " || &eventvalue, "x")
    write(win, "Run-time error ", &eventvalue)
    write(win, "File ", keyword("file", Monitored), "; line ", keyword("line", Monitored))
    write(win, keyword("errortext", Monitored))
    writes(win, "Convert to failure? ")
    if read(win)=="y" then
        keyword("error", Monitored) := 1
    close(win)
end
```

CHAPTER 12
Performance

In the absence of specialized hardware support, monitoring imposes significant performance overhead on TP execution. In practice, the user of the system usually is unable to observe execution behavior in any detail at the rate at which it is generated by the monitoring system, and must frequently stop or slow down execution in order to inspect details. Similarly, the more sophisticated the execution monitor's analysis of execution behavior, the more overall execution speed directly relates to time spent in the monitor. In light of these facts, performance considerations for the monitoring framework are not as important as the quality and utility of the information provided by EMs.

Nevertheless, many of the systems discussed in Chapter 2 are reported to experience performance problems, especially tied to the rate at which information is extracted from the target program. Execution monitoring is useful only if the performance of the implementation is fast enough so that the system can be applied successfully to medium and large programs and solve real-world problems. Empirically, the framework developed for monitoring Icon programs meets this criterion.

The purpose of this chapter is to measure the performance overhead associated with monitoring in MT Icon. Since the general execution model may be relevant to the monitoring of other high-level languages, costs are provided for separable components such as the implementation of multi-tasking and the interpreter instrumentation. The evaluation is concerned primarily with time measures, rather than space requirements; space has not been an issue in practice.

The performance results provided in this chapter start with baseline measurements of the cost of multi-tasking support and instrumentation, followed by measurements of the relative costs of monitoring different types of language events. The chapter concludes with a note on the effect of CPU type upon the cost of monitoring, and a discussion of the costs incurred by monitor coordinators.

12.1 Costs of multi-tasking and of interpreter instrumentation

The reference point for measurements presented in this chapter is the Version 8.10 Icon interpreter, which can be conditionally compiled with no tasking or monitoring support, with multi-tasking, or with multi-tasking and monitoring support.

The first cost to be considered is that of the multi-tasking implementation employed by MT Icon. The implementation is optimized for detailed monitoring in which many event reports take place and task switching is therefore extremely frequent. In order to minimize the cost of the task switch, an extra memory reference is imposed when accessing task-specific global variables in the run-time system. The overhead on these extra memory references is insignificant compared with overall interpreter execution costs.

Timings for the Icon benchmark suite [Gris90a] run on a Sun Sparcstation IPX under the Icon interpreter compiled without and then with multi-tasking support are shown in the two leftmost columns of Figure 12.1 (the remaining columns are discussed below). Generally the benchmarks' execution differences under Icon and MT Icon are small enough to fall within the margins of error in the measurements due to variations in machine load.

In addition to multi-tasking, execution monitoring depends on the presence of instrumentation added

TP	Icon	MT Icon	MT Icon with events	... with VM
concord	5.5	5.7	8.9	10.2
deal	6.6	6.6	8.0	9.1
ipxref	1.3	1.4	2.1	2.2
queens	8.1	8.2	12.4	13.2
rsg	8.2	8.1	11.5	12.8

Figure 12.1: MT Icon benchmark timings (seconds)

in-line to the interpreter and run-time system code under conditional compilation. When compiled with instrumentation, the interpreter performs tests to determine whether to report each event, even if monitoring is not being performed. The column of Figure 12.1 labeled "MT Icon with events" gives Icon benchmark suite timings using an interpreter built with monitoring instrumentation. Since instrumentation of virtual machine instructions imposes a significant cost all by itself, the figures in the rightmost column show timings with virtual machine instructions included. Generally, the presence of pervasive instrumentation increases execution time thirty to fifty percent even when it is not used.

This measure is independent of the co-expression model and the use of independently written and translated Icon programs as monitors; it would be incurred due to the presence of the instrumentation even if entire execution monitoring system including visualizations were tightly integrated into the Icon interpeter itself.

12.2 Relative costs of monitoring different language features

Some classes of events are much more costly to monitor than others. This is roughly proportional to the frequency with which an event occurs. For example, garbage collection events occur very seldomly, so it costs very little to monitor garbage collection events. Line number changes are far more frequent; virtual machine instructions are the most common of all. The classes of events covered are memory allocations, assignments, type conversions, structure accesses, procedure activity, built-in function activity, operator activity, string scanning activity, program source code location changes, and virtual machine instruction execution.

Figure 12.2 gives benchmark suite event counts in the leftmost column, followed by percentages for each of the major categories of events, and Figure 12.3 gives execution times for monitors that request those events but do no computation of their own. The timings are generally proportional to the amount of work actually performed by the computation, and not a direct function of any particular class of events. Generally, however, the more events monitored the greater the slowdown imposed by monitoring. Comparison of Figures 12.1 and 12.3 shows that on a Sparc, monitoring typically imposes an overhead of one order of magnitude for infrequent event categories, or two orders of magnitude for virtual machine instructions, compared with execution under the standard Icon interpreter. Computations performed by the EM or EMs as they process events further slow TP execution.

With the exception of garbage collections, there are 1.18 events per virtual machine instruction on average, typically ranging from one (the virtual machine instruction event itself) to around twelve. The number of events that occur per virtual machine instruction is not strictly bounded, since a garbage collection can result in a number of events proportional to the number of data objects that survive collection in the block region.

	total #	alloc	assign	conv	struct	proc	func	op	scan	loc	VM instr
concord	3782971	1.7	4.9	20.5	0.2	0.2	9.1	8.8	1.8	8.2	44.6
deal	1963019	3.2	5.7	26.5	1.4	1.1	2.1	12.8	0	7.9	34.7
ipxref	1044476	0.6	1.7	21.1	3.4	0.5	1.3	18.9	0	8.7	43.8
queens	6835489	0.1	4.0	29.9	4.3	0.2	0	18.0	0	8.0	35.3
rsg	5367792	0.9	2.7	4.0	3.7	0	3.7	13.5	0	10.0	61.5

Figure 12.2: Total event counts and percent of events in each category

	alloc	assign	conv	struct	proc	func	op	scan	loc	VM instr
concord	33.2	72.4	225.3	14.6	14.5	107.1	107.8	34.7	114.7	386.2
deal	52.2	47.8	153.3	17.9	16.3	21.6	80.6	10.0	71.8	184.1
ipxref	4.5	8.1	63.4	12.4	4.2	6.5	56.1	2.6	41.4	102.6
queens	19.2	108.7	584.8	101.4	21.5	16.1	362.4	16.0	208.7	534.8
rsg	29.8	59.8	74.7	71.9	16.0	72.9	205.1	15.5	214.5	761.7

Figure 12.3: Execution times for no-op monitors by category (seconds)

For each virtual machine instruction in the TP, an EM potentially receives several event reports resulting in arbitrarily lengthy computations on its part. Since event reporting is built around the Icon co-expression context switch, the CPU-dependent speed of the context switch operation compared with normal program activities is important in determining the cost of using a multi-tasking model of execution monitoring instead of a one-process model. Figure 12.4. compares timings of ordinary operations, context switches, and event reporting on the Sun Sparcstation IPX and an Intel 486 processor. The figures are the average from one million executions of each operation. The first three columns give timings for the null operation, integer addition, and procedure call. The fourth column times the Icon co-expression context switch, while the fifth column times the event reporting mechanism including its context switch.

The first and third rows report timings taken using Icon's built-in timing mechanism, while the second and fourth rows give times observed by the UNIX shell `time` command. Although the Sparcstation performs almost twice as fast as the i486 on normal computations, its advantage is greatly reduced for execution monitoring because its context switch is very slow — the context switch executes a software trap that flushes register windows to memory. When this system time is taken into account (adding the two figures given in each column of the second and fourth rows) the i486 outperforms the Sparc by a factor of 4 for the co-expression context switch, and by roughly 50 per cent on the event reporting mechanism. Of course, the Sparc's performance advantage on the rest of the TP and EM execution translates into faster execution overall.

12.3 Limitations of graphics hardware and software

Experience has shown that in many program visualization applications, the window system software is not able to perform window output at the rate at which it is produced by an EM; this is observed when monitors written using asynchronous window system calls complete execution noticeably before animation stops in the monitor window. For such applications, writing EMs in Icon instead of a lower-level language does not

CPU	no-op	i + j	p(x)	@x	event()...EvGet()
Sparc (&time)	10.4	38.8	33.6	97.5	277.8
Sparc (u+s time)	10.2+0.1	39.4+0.4	33.6+0.2	79.5+93.5	222.0+113.0
i486/33 (&time)	19.5	63.8	58.5	78.0	363.7
i486/33 (u+s time)	11.7+0.2	38.2+0.2	34.9+0.1	46.5+0.1	235.2+1.6

Figure 12.4: Costs of various operations (microseconds, average)

cost as much in terms of performance as might be expected. In contrast, MT Icon is least suitable for EMs with complex graphics requiring significant numeric computation, because such applications' performance is less likely to be limited by window system capabilities and because Icon is not oriented towards numeric applications.

12.4 Cost incurred by monitor coordinators

Although MC's offer great flexibility, the use of a MC to execute multiple EMs instead of writing a single monolithic EM imposes additional overhead, primarily increasing the number of task switches required. The MC Eve can be used to illustrate this cost.

In the worst case, all EMs request a report for every event. Under Eve, if there are N tools then there are 2 * N + 2 task switches per event report. A monolithic EM would incur only two switches per event report, from TP to EM, and from EM to TP. Eve therefore imposes 2 * N additional switches in the worst case.

In the best case, the event masks are disjoint and only one EM is interested in any event to be reported. In this case Eve incurs four task switches per event report – twice as many as in the monolithic case. Since users typically employ multiple EMs to provide information about a variety of aspects of program behavior, the expected normal case is closer to this best case behavior than the worst case in which the EMs are all observing the same events.

CHAPTER 13
Conclusions and Future Work

MT Icon and its instrumentation provide a framework in which it is possible to take a program monitoring idea from conception to implementation in a short period of time. The primary contribution in this framework is the exploitation of coroutines and dynamic loading to provide EMs with program state information at the source level instead of at the machine level.

13.1 Successes of the framework

The framework demonstrates the viability of:

- exploratory development of execution monitors, given suitable language support,
- a synchronous task model for the monitoring of programs written in high-level languages,
- application of monitors developed under the framework to obtain useful performance tuning information.

MT Icon's execution monitoring interface has proven simple enough to be programmed even by novice Icon programmers. In one semester, students with no prior Icon programming experience were able to the framework in a university course to construct sophisticated program visualization tools. Expert users can construct experimental EMs in hours instead of days.

Exploratory monitor programming is of limited usefulness if it does not scale up to accomodate the development of larger full-featured monitoring services. MT Icon allows the execution of multiple EMs on a single TP using a monitor coordinator as an attractive alternative to monolithic all-encompassing tools such as traditional debuggers and profilers. Performance degrades gracefully as tools are added.

Dynamic loading and synchronous, shared-address space tasks have proven to be a robust model in which TP and EMs can co-exist. Task switching between TPs and EMs provides acceptable performance while minimizing the impact of monitoring upon the behavior of the TP.

The implementation of dynamic loading and multi-tasking in MT Icon builds upon Icon's implementation of co-expressions. The execution monitoring framework is therefore portable to most of the platforms that Icon runs on with the exception of personal computers with small memory sizes. The system has been run on a variety of UNIX platforms as well as OS/2 2.0. Many of the more powerful EMs make extensive use of Icon's graphics facilities; use of graphics is a greater portability limitation than MT Icon and the execution monitoring interface.

The execution monitoring framework has been used to implement a variety of profiling tools for tuning performance, such as tools that count the number times a given line or given procedure has been executed. Of particular interest are language-specific tools that profile behavior that is not related directly to the program source code, but rather takes place in the run-time system, such as garbage collection or type-conversion. Such costs may not be readily apparent to a programmer writing or reading the code.

One such profiler simply indicates in a small window whenever a garbage collection takes place. For normal programs this monitor imposes little overhead and is unobtrusive, while programs that are exhibiting thrashing heap behavior flash repeatedly, drawing attention to the problem. Upon observing such behavior, the user may be able to adjust heap size parameters so that thrashing does not occur in future executions.

A more sophisticated profiler cross-references type-conversion information with program source locations and applies simple heuristics to select locations where frequent conversions are likely to be unnecessary or redundant. The user then can manually inspect the locations found to determine whether a simple modification can eliminate the conversions. The redundant conversions profiler has resulted in speedups of 0-15 percent on real programs, with useful results on programs written both by novice and expert users.

In addition to profiling tools, program tuning often results from the observation of behavior presented by more general EMs. For example, inefficient structure manipulations can frequently be inferred by observing allocation patterns or structure access activity, as in the nova tool example in Chapter 8.

Success in target program tuning suggests the related issue of language implementation tuning. MT Icon's execution monitoring framework was not built with the objective of providing information for improving the implementation. Nevertheless, prior research in the monitoring and visualization of memory usage led to improved allocation heuristics [Gris89], and observation of EMs under MT Icon also suggested improvements to the implementation. For example, monitoring of list-creation events led to a change in list concatenation with the result that it is faster and allocates less space than before.

Instrumentation also can find problems in the implementation. Modifications to the implementation during the construction of the Icon compiler at one point introduced a bug into the implementation of the built-in string analysis function `many()`. The bug allowed `many()` to produce string indices beyond the bounds of the subject string. The bug was observed in a string scanning EM, where position events appeared past the end of the subject string.

13.2 Limitations of the framework

Although the framework addresses the construction of monitors for a broad spectrum of program behavior, the techniques it uses are of limited applicability to other languages, and the ability to monitor implementation behavior does not extend into the realm of observing activity during garbage collection. In addition, there are inherent limitations in the use of non-intrusive monitoring techniques: some kinds of debugging require intrusion into the target program, and the framework is not oriented towards intrusive techniques.

The approach to execution monitoring presented here is not applicable to programming languages and systems in which the implementor of the execution monitoring facilities does not "own" the implementation of the language. Beyond access to source code, instrumentation of a language run-time system generally requires intimate knowledge of the implementation and represents a major investment of effort. Because instrumentation is spread throughout the code, it poses added maintenance problems in the implementation and must be added to the primary source if it is to remain functional in future language updates and versions.

The technique of capturing program behavior via run-time system instrumentation is not appropriate for low-level compiled languages, where instrumentation is more appropriately embedded in generated code via a preprocessor or compiler modifications. Instrumentation of an interpreter is generally simpler and easier than modifying a compiler code generator.

MT Icon's dynamically loaded coroutines do not have ready equivalents in most other languages and would have to be added, as they were to Icon, before the exploratory execution monitor development provided by MT Icon can be realized. The implementation of a portable dynamic loading mechanism was much simpler for an interpreter than would be the case for a compiled language. In some cases, notably SmallTalk, the language has the requisite features but the implementation may require added features such as separately-collected heap spaces before EMs can execute without interfering with TP behavior.

Another limitation of the framework is in the area of garbage collection monitoring. The MemMon system is able to provide very detailed information about Icon's marking and compaction algorithms through a file-based event stream [Gris89]. This information has proven useful in practice, but there is no way to safely report events during a garbage collection in MT Icon. An event report causes transfer of control and execution in an EM. During a garbage collection, TP data may not be in a valid format and if an EM were free to inspect it, system failure would result.

This is one inherent penalty in the one-process and thread models in which EMs directly access TP data through pointers. Since this limits the monitoring of implementation behavior, rather than TP behavior, it is not an unacceptable loss. If the garbage collection algorithm is under study, a two-process model or file-based monitoring system should be employed rather than the MT Icon task model.

13.3 Enhancements and future directions

The execution monitoring framework for Icon was motivated by a desire to explore new types of execution monitors, particularly program visualization tools. The framework is an enabling technology and its success should result in the development of various experimental monitoring tools. In addition, some general problems in execution monitoring have been observed that further work may mitigate or solve. A third future direction is the application of concepts from this work to the monitoring of other languages. A fourth future direction consists of further tuning the framework and integrating it with Icon compiler technology.

Update variation in simultaneous animations

As detailed in the chapter on system performance, some events occur very frequently compared with others. Since graphic output is often a bottleneck in the present system, animations based on frequent events such as location changes reduce or preclude the effectiveness of animations based on less frequent events.

Mitigating the effects of this problem is an open area for research. Clearly, the faster the overall execution is, the faster the slowest animation in a group runs, but then faster animations' motion will be too fast to be useful. One possible way for monitors of frequent kinds of events to coexist with monitors of infrequent events is if the monitors of frequent events sample their events at some rate determined by the less frequently updated monitors. For EMs that do not maintain a model of TP state this may work; for EMs such as Algae that do maintain a model, it will not. The best such EMs can hope to do is implement a reduced output mode in order to improve slower EMs' animation rates by improving overall execution speed.

Concurrency among monitors

Our monitoring framework is interactive and allows full debugging unlike most event-based monitoring and debugging systems. This degree of interaction means that by design, the TP cannot continue its execution concurrently while an EM is processing an event and/or user input.

On the other hand, EMs are typically independent of one another and if MT Icon were extended to allow true concurrency on multiprocessor hardware, all the EMs interested in any given event could run concurrently. As more and better EMs are developed, the growing motivation to run more EMs more of the time will create an interest in shared-memory multiprocessors.

Integrating monitors into coordinators

Our framework allows EMs to be compiled and executed separately, or in conjunction with one another using an MC. Under an MC, a large number of task switches may take place with each event. Although this has not been prohibitive in practice, the possibility of merging commonly used EM functionality directly into the MC and avoiding the task switching overhead is attractive. For example, the interactive run-time error conversion and elapsed CPU time features of Eve were first implemented as stand-alone EMs and later added to Eve.

Less commonly-used EMs can remain stand-alone and be loaded separately. The ability to add EM functionality into an MC is also attractive in light of Icon compiler technology discussed below, in which the MC performance may be substantially increased. Merging functionality could be accomplished relatively easily for EMs that use callbacks. EMs that utilize their own flow of control to change states from event to event would require more effort to integrate.

Integrating the Icon interpreter and compiler

The MT Icon facilities are specific to the Icon interpreter and are not supported by the Icon compiler [Walk91]. On the other hand, the Icon compiler offers significant performance improvements over the interpreter. The two systems share the same run-time code and data representation, and there is no fundamental reason why an EM cannot be compiled by the Icon compiler and linked with interpreter code so that it is able to load and execute interpreted Icon programs. Since the vast majority of time spent in most monitoring situations is spent in the EM, the ability to execute EMs at compiled speeds would dramatically improve monitoring performance. This improvement could apply to monitor coordinators such as Eve without losing the flexibility of the current system, in which dynamically-loaded EMs can be selected from a menu and run together under an MC.

More execution monitors

The purpose of the research presented in this dissertation was to facilitate the development of new EMs. The collection of EMs implemented so far in testing the framework is in no way exhaustive. Now that the framework is implemented and has been proven useful, more EMs should be developed. As of yet relatively few EMs provide user-control over the details of the information presented. Existing EMs are oriented towards general program understanding (and particularly visualization) tasks. The development of exploratory execution monitors using this framework still has large unexplored potential. EMs that provide more specific debugging facilities have yet to be written, and have obvious utility. In addition, EMs have application areas in special contexts that have not been treated, such as the education of novice programmers.

More types of events; finer selection controls

The event monitoring instrumentation in the present system is extensive, but in a language with as much built-in behavior as Icon, it will almost always be possible to add more types of events. For example, no instrumentation is currently available to monitor certain control structures such as alternation and limitation, to monitor the dynamic hash table activity used in Icon's built-in set and table data types, or to monitor I/O such as file and window activity.

The existing system has certain events that would benefit from further subdivision into different event codes. Conversion events might usefully be coded by destination type the way allocation events are, for example. There are other events for which finer selections than the event mask mechanism may be appropriate, similar to the selection of virtual machine instructions of interest via opmask(). Generally these are just performance enhancements, and the current system performs satisfactorily. Nevertheless, events for which this finer selection might be useful include location events and operator and function events.

Language support for trapped variables

The non-intrusive techniques for the monitoring of individual variables that are presented in Chapter 10 do not scale well when large numbers of variables need to be monitored. For such applications, data intrusive language support for *trapped variables* would provide a better alternative.

There are two primary operations on variables that are of interest: assignments and dereferencing operations. A variable trap mechanism might insert a layer of indirection into a trapped variable reference; the intermediate block inserted between the variable descriptor and its value would cause a side-effect such as an event to occur when the variable was assigned or dereferenced. Trapped variables are data intrusive, but not problematically so, since the intermediate block might be allocated in the EM rather than the TP.

The concept of a trapped variable is old [Gris72], and underlies such mechanisms as the SNOBOL4 variable association facility [Hans78]. Adding trapped variable support to Icon is non-trivial but not impractical. Since the technique is complementary to the approaches presented in this dissertation, adding it would improve the overall capabilities of the framework.

Preemptive scheduling monitor coordinators

No event mask is used when Eve sends an event report to an EM; the EM runs until it requests its next event. Under some circumstances an MC may want to regain control from an EM that consumes excessive resources by monitoring the EM, requesting event reports for clock ticks, for example. This would enable a MC to give priority to some EMs over others, or ensure that all EMs receive regular CPU time in order to handle user interaction promptly.

13.4 Final thoughts

It is illustrative of the neglect of execution monitoring in the literature that no major programming language has been designed with explicit *linguistic* support (as opposed to library packages and other extra-linguistic forms of support) for monitoring; such support has at best come after the fact and is more often entirely missing. Without such support, the literature is filled with articles on how to implement crude forms of monitoring using low-level techniques and nonportable operating system and machine architecture capabilities and articles that present high-level abstractions of monitoring with no demonstration of their application to practical problems.

MT Icon represents a successful grafting of support for execution monitoring onto an existing language. Being an afterthought, its design and implementation are naturally somewhat constrained. The question arises: In a new high-level language language, if linguistic support for execution monitoring is an explicit design goal, what language features should be present? MT Icon suggests some of them (dynamic loading, synchronous tasks), but it may be possible to conceive of better services than MT Icon provides, and a better execution model with which to perform monitoring.

Appendix A: Algae

This appendix presents the Icon source code for Algae, the example execution monitor introduced in Chapter 7 and enhanced in Chapters 9 and 10.

```
############################################################################
#
# File: algae.icn
#
# Subject: Program to show expression evaluation as “algae”
#
# Author: Clinton Jeffery
#
# Date: 5/1/92
#
############################################################################
#
# Press ESC or q to quit
# Left mouse assigns specific (row,column) break "points"
# Middle mouse assigns absolute depth and width break lines
# Right button erases assigned break "points"
#
# When paused due to a break, you can:
#
# c to continue
# s to single step
# C to clear one point and continue
# " " to clear everything and continue
#

$include "evheader.icn"
link evinit
link evutils
link options
link optwindw
link hexlib
link evaltree

global scale,                         # cell (hexagon or square) size
    step,                             # single step mode
    numrows,                          # number of cell rows
    numcols,                          # number of cell columns
    spot,                             # cell-fill procedure (hex or square)
    mouse,                            # cell-mouse-locator procedure
    Visualization,                    # the window
    wHexOutline,                      # binding for drawing cell outlines
    depthbound,                       # call-depth on which to break
    breadthbound,                     # suspension-width on which to break
    hotspots                          # table of individual cells on which to break

record algae_activation(node, row, column, parent, children, color)


#
# main() - program entry point. The main loop is in evaltree().
#
procedure main(av)
    local codes, algaeoptions
    #
    # pull off algae options (don’t consume child’s options in this call
    # to options()).
    #
    algaeoptions := [ ]
```

```
    while av[1][1] == "-" do {
        put(algaeoptions, pop(av))
        if algaeoptions[-1] == "-f" then put(algaeoptions, pop(av))
        }
    EvInit(av) | stop("Can't EvInit ",av[1])
    codes := algae_init(algaeoptions)
    evaltree(codes, algae_callback, algae_activation)
    XAttrib("windowlabel=Algae: finished")
    EvTerm(&window)
end

#
# algae_init() - initialization and command-line processing.
# This procedure supplies default behavior and handles options.
#
procedure algae_init(algaeoptions)
    local t, position, geo, codes, i, cb, coord, e, s, x, y, m, row, column
    t := options(algaeoptions,
                  winoptions() || "P:S:-geo:-square!-func!-scan!-op!-noproc!")
    /t["L"] := "Algae"
    /t["B"] := "cyan"
    scale := \t["S"] | 12
    if \t["square"] then {
        spot := square_spot
        mouse := square_mouse
        }
    else {
        scale /:= 4
        spot := hex_spot
        mouse := hex_mouse
        }
    codes := cset(E_MXevent)
    if /t["noproc"] then codes ++:= ProcMask
    if \t["scan"] then codes ++:= ScanMask
    if \t["func"] then codes ++:= FncMask
    if \t["op"] then codes ++:= OperMask
    hotspots := table()
    &window := Visualization := optwindow(t) | stop("no window")
    numrows := (XHeight() / (scale * 4))
    numcols := (XWidth() / (scale * 4))
    wHexOutline := Color("white")    # used by the hexagon library
    if /t["square"] then starthex(Color("black"))
    return codes
end

#
# algae_callback() - evaltree callback procedure for algae.
# Called for each event, it updates the screen to correspond
# to the change in the activation tree.
#
procedure algae_callback(new, old)
    local coord, e
    initial {
        old.row := old.parent.row := 0; old.column := old.parent.column := 1
        }
    case &eventcode of {
        !CallCodes: {
            new.column := (old.children[-2].column + 1 | computeCol(old)) | stop("eh?")
            new.row := old.row + 1
            new.color := Color(&eventcode)
            spot(\old.color, old.row, old.column)
            }
        !ReturnCodes |
```

```
        !FailCodes: spot(Color("light blue"), old.row, old.column)
        !SuspendCodes |
        !ResumeCodes: spot(old.color, old.row, old.column)
        !RemoveCodes: {
            spot(Color("black"), old.row, old.column)
            XFlush(Color("black"))
            delay(100)
            spot(Color("light blue"), old.row, old.column)
            }
        E_MXevent: do1event(&eventvalue, new)
        }
    spot(Color("yellow"), new.row, new.column)
    coord := location(new.column, new.row)
    if \step | (\breadthbound <= new.column) | (\depthbound <= new.row) |
        \ hotspots[coord] then {
        step := &null
        XAttrib("windowlabel=Algae stopped: (s)tep (c)ont ( )clear ")
        while e := XEvent() do
            if do1event(e, new) then break
        XAttrib("windowlabel=Algae")
        if \ hotspots[coord] then spot(Color("light blue"), new.row, new.column)
        }
end


#
# procedures for the "-square" option, display Algae using squares
# instead of hexagons.
#

# Draw a square at (row, column)
procedure square_spot(w, row, column)
    XFillRectangle(w, (column - 1) * scale, (row - 1) * scale, scale, scale)
end


# encode a location value (base 1) for a given x and y pixel
procedure square_mouse(y, x)
    return location(x / scale + 1, y / scale + 1)
end

#
# clearspot() removes a "breakpoint" at (x,y)
#
procedure clearspot(spot)
    local s2, x2, y2
    hotspots[spot] := &null
    y := vertical(spot)
    x := horizontal(spot)
    every s2 := \!hotspots do {
        x2 := horizontal(s2)
        y2 := vertical(s2)
    }
    spot(Visualization, y, x)
end

#
# setspot() sets a breakpoint at (x,y) and marks it orange
#
procedure setspot(loc)
    hotspots[loc] := loc
    y := vertical(loc)
    x := horizontal(loc)
    spot(Color("orange"), y, x)
```

```
end

#
# do1event() processes a single user input event.
#
procedure do1event(e, new)
    local m, xbound, ybound, row, column, x, y, s
    case e of {
        "q" |
        "\e": stop("Program execution terminated by user request")
        "s": {                              # execute a single step
            step := 1
            return
            }
        "C": {                              # clear a single break point
            clearspot(location(new.column, new.row))
            return
            }
        " ": {                              # space character: clear all break points
            if \depthbound then {
                every y := 1 to numcols do {
                    if not who_is_at(depthbound, y, new) then
                        spot(Visualization, depthbound, y)
                    }
                }
            if \breadthbound then {
                every x := 1 to numrows do {
                    if not who_is_at(x, breadthbound, new) then
                        spot(Visualization, x, breadthbound)
                    }
                }
            every s := \!hotspots do {
                x := horizontal(s)
                y := vertical(s)
                spot(Visualization, y, x)
                }
            hotspots := table()
            depthbound := breadthbound := &null
            return
            }
        &mpress | &mdrag: {             # middle button: set bound box break lines
            if m := mouse(&y, &x) then {
                row := vertical(m)
                column := horizontal(m)
                if \depthbound then {   # erase previous bounding box, if any
                    every spot(Visualization, depthbound, 1 to breadthbound)
                    every spot(Visualization, 1 to depthbound, breadthbound)
                    }
                depthbound := row
                breadthbound := column
                #
                # draw new bounding box
                #
                every x := 1 to breadthbound do {
                    if not who_is_at(depthbound, x, new) then
                        spot(Color("orange"), depthbound, x)
                    }
                every y := 1 to depthbound - 1 do {
                    if not who_is_at(y, breadthbound, new) then
                        spot(Color("orange"), y, breadthbound)
                    }
                }
```

```
            }
        &lpress | &ldrag: {             # left button: toggle single cell breakpoint
            if m := mouse(&y, &x) then {
                xbound := horizontal(m)
                ybound := vertical(m)
                if hotspots[m] === m then
                    clearspot(m)
                else
                    setspot(m)
                }
            }
        &rpress | &rdrag: {             # right button: report node at mouse location
            if m := mouse(&y, &x) then {
                column := horizontal(m)
                row := vertical(m)
                if p := who_is_at(row, column, new) then
                    XAttrib("windowlabel=Algae " || image(p.node))
                }
            }
        }
end

#
# who_is_at() - find the activation tree node at a given (row, column) location
#
procedure who_is_at(row, col, node)
    while node.row > 1 & \node.parent do
        node := node.parent
    return sub_who(row, col, node)      # search children
end

#
# sub_who() - recursive search for the tree node at (row, column)
#
procedure sub_who(row, column, p)
    local k
    if p.column === column & p.row === row then return p
    else {
        every k := !p.children do
            if q := sub_who(row, column, k) then return q
        }
end

#
# computeCol() - determine the correct column for a new child of a node.
#
procedure computeCol(parent)
    local col, x, node
    node := parent
    while \node.row > 1 do              # find root
        node := \node.parent
    if node === parent then return parent.column
    if col := subcompute(node, parent.row + 1) then {
        return max(col, parent.column)
        }
    else return parent.column
end

#
# subcompute() - recursive search for the leftmost tree node at depth row
#
procedure subcompute(node, row)
    # check this level for correct depth
```

```
     if \node.row = row then return node.column + 1
     # search children from right to left
     return subcompute(node.children[*node.children to 1 by -1], row)
end

#
# Color(s) - return a binding of &window with foreground color s;
# allocate at most one binding per color.
#
procedure Color(s)
  static t, magenta
  initial {
       magenta := XBind(&window, "fg=magenta") | stop("no magenta")
       t := table()
       /t[E_Fcall] := XBind(&window, "fg=red") | stop("no red")
       /t[E_Ocall] := XBind(&window, "fg=chocolate") | stop("no chocolate")
       /t[E_Snew] := XBind(&window, "fg=purple") | stop("no purple")
       }
  if *s > 1 then
       / t[s] := XBind(&window, "fg=" || s) | stop("no ",image(s))
  else
       / t[s] := magenta
  return t[s]
end

procedure max(x,y)
     if x < y then return y else return x
end
```

```
###########################################################################
#
# Name: evaltree.icn
#
# Title: Maintain activation tree
#
# Author: Clinton Jeffery
#
# Date: July 28, 1992
#
###########################################################################
#
# Usage: evaltree(cset, procedure, record constructor)
#
# Requires: MT Icon and event monitoring.
# the record type must have fields node, parent, children
#
###########################################################################
#
$include "evheader.icn"

global CallCodes,
    SuspendCodes,
    ResumeCodes,
    ReturnCodes,
    FailCodes,
    RemoveCodes

procedure evaltree(mask, callback, activation_record)
    local c, current

    CallCodes := string(mask ** cset(E_Pcall || E_Fcall || E_Ocall || E_Snew))
    SuspendCodes := string(mask ** cset(E_Psusp || E_Fsusp || E_Osusp || E_Ssusp))
    ResumeCodes := string(mask ** cset(E_Presum || E_Fresum || E_Oresum || E_Sresum))
    ReturnCodes := string(mask ** cset(E_Pret || E_Fret || E_Oret))
    FailCodes := string(mask ** cset(E_Pfail || E_Ffail || E_Ofail || E_Sfail))
    RemoveCodes := string(mask ** cset(E_Prem || E_Frem || E_Orem || E_Srem))

    current := activation_record()
    current.parent := activation_record()
    current.children := [ ]
    current.parent.children := [ ]

    while EvGet(mask) do {
        case &eventcode of {
            !CallCodes: {
                c := activation_record()
                c.node := &eventvalue
                c.parent := current
                c.children := [ ]
                put(current.children, c)
                current := c
                callback(current, current.parent)
                }
            !ReturnCodes | !FailCodes: {
                p := pull(current.parent.children)
                current := current.parent
                callback(current, p)
                }
            !SuspendCodes: {
                current := current.parent
                callback(current, current.children[-1])
                }
            !ResumeCodes: {
```

```
                current := current.children[−1]
                callback(current, current.parent)
                }
            !RemoveCodes: {
                if child := pull(current.children) then {
                    while put(current.children, pop(child.children))
                    callback(current, child)
                    }
                else {
                    if current === current.parent.children[−1] then {
                        p := pull(current.parent.children)
                        current := current.parent
                        callback(current, p)
                        next
                        }
                    else stop("evaltree: unknown removal")
                    }
                }
            default: {
                callback(current, current)
                }
            }
        }
end
```

Appendix B: Eve

This appendix presents the Icon source code for Eve, the example monitor coordinator presented in Chapter 11.

```
############################################################################
#
# File: eve.icn
#
# Subject: Program to control multiple execution monitors
#
# Author: Clinton Jeffery
#
# Date: November 17, 1992
#
############################################################################
#
# Version: 3.2
#
############################################################################
#
# An execution monitor coordinator
#

$include "evheader.icn"
link evutils
link options
link optwindw
link vidgets
link vbuttons
link vslider
link vstyle
link vtext
link vtools
link vstopsgn

global
    cmd,                        # target program file name
    clients,                    # list of client objects
    unioncset,                  # union of client's csets
    root,                       # root of the widget tree
    msg,                        # main message widget
    enabled,                    # list of checkbox widgets
    stopSign,                   # state of the stop sign widget
    stopstate,                  # state of the stop sign widget
    EventCodeTable,             # table of EM's to call for each event
    loaded,                     # list of checkbox widgets
    delayval,                   # amount of slowdown to insert per event
    verbose,                    # switch to make Eve explain itself
    candidates,                 # list of potential EM's to run
    ticksum,                    # number of clock ticks elapsed in TP
    EveHandlers,                # Eve's procedures for each event
    EveBroadcastQueue           # queue used for EM - EM communication


#
# main() - initializes TP, EM's, Eve's own tables, then enters the main loop
#
procedure main(av)
    local optable, all, i, aborter, monitor,
        arglist, C, eveoptions

    optable := initializeTP(av)
```

```
    if \verbose then write("Eve: Monitoring ", cmd, " (", image(&eventsource), ")")

    all := optable["all"]
    initializeEMs(optable)

    initializeEve()
    if \verbose then write("Eve: executing monitored program")

    mainLoop()
end

#
# mainLoop() − Eve's main loop
#
procedure mainLoop()
    while EvGet(unioncset) do {
        #
        # Call Eve's own handler for this event, if there is one.
        #
        (\ EveHandlers[&eventcode]) ()
        #
        # Forward the event to those EM's that want it.
        #
        every monitor := !EventCodeTable[&eventcode] do
            if C := event( , , monitor.prog) then {
                if C ~=== monitor.mask then {
                    while type(C) ~== "cset" do {
                        #
                        # The EM has raised a signal; pass it on, then
                        # return to the client to get his next event request.
                        #
                        broadcast(C, monitor)
                        if not (C := event( , , monitor.prog)) then {
                            unschedule(monitor)
                            break next
                            }
                        }
                    if monitor.mask ~===:= C then
                        computeUnionMask()
                    }
                }
            else
                unschedule(monitor)
        delay(6 < delayval)
        }
    set_Vstrset_coupler(stopstate, , "done")
    stopsigndone(stopSign)
    drawtime()
    eveQuit()
end

#
# initializeTP() − initialize the target program
#
procedure initializeTP(av)
    local optable
# EvGlobals()

    delayval := 0
    *av>0 | stop("usage: eve [−f eveconfig] [−s] [−all] icon−command−line")
    #
    # pull off eve options (don't consume child's options in this call
    # to options()).
    #
```

```
    eveoptions := [ ]
    while av[1][1] == "−" do {
        put(eveoptions, pop(av))
        if eveoptions[−1] == "−f" then put(eveoptions, pop(av))
        }
    optable := options(eveoptions, "P:V!−geo:f:s−all!")
    /optable["P"] := "0,0"
    /optable["f"] := getenv("HOME") || "/.eve"
    /optable["L"] := "Eve"
    /optable["T"] := "*helvetica−bold−r−*−−17*"
    /optable["H"] := 100
    /optable["W"] := 100
    verbose := optable["V"]

    cmd := pop(av) | stop("Eve: Icon program command−line argument is missing!")
    &eventsource := load(cmd, av) | stop("can't load ", image(cmd))
    return optable
end

#
# intializeEMs − initialize the execution monitors
#
procedure initializeEMs(optable)
    local all, i, titles, title, wantheight, maxwidth
    all := optable["all"]
    candidates := getClientList(optable["f"], all)
    titles := getTitles()
    &window := optwindow(optable) | stop("no &window")
    maxwidth := calcWidth(titles)
    wantheight := XAttrib("fheight") * (*candidates + 1) + XAttrib("ascent")
    wantheight <:= 80
    XAttrib("width=" || (maxwidth + 101 + XTextWidth("loadiconifyenable") + 16))
    XAttrib("height=" || wantheight)
    wantheight <:= 240
    # build buttons and sliders on Eve's window
    root := Vroot_frame(&window)
    attachClientControls(titles,maxwidth)
    VResize(root)
    # allow user to select EMs
    while(pop(XPending()))
    until stopstate.value ~=== "startup" do
        run()
    if wantheight ~= XAttrib("height") then XAttrib("height="||wantheight)
    attachSlider()
    while(pop(XPending()))
    clients := [ ]
    every i := 1 to * candidates do
        if \all | \loaded[i].callback.value then {
            arglist := titledparse(candidates[i])
            put(clients, client(pop(arglist), arglist, i))
            }
    # the first time through we activate the clients with no useful value
    if \verbose then write("Eve: initializing ", *clients, " clients")
    every i := 1 to *clients do
        clients[i].mask := @ clients[i].prog
end

#
# initializeEve() − initialize Eve's own state variables
#
procedure initializeEve()
    ticksum := 0
    EveHandlers := table()
```

```
    EveHandlers[E_Tick] := eveTick
    EveHandlers[E_MXevent] := eveEvent
    EveHandlers[E_Error] := eveError
    computeUnionMask()
end

#
# calcWidth() - compute the width needed for Eve window, in pixels
#
procedure calcWidth(titles)
    local maxwidth
    maxwidth := 0
    every maxwidth <:= XTextWidth(!titles)
    maxwidth <:= XTextWidth("Executing program " || cmd) + 4
    maxwidth +:= XTextWidth("..")
    return maxwidth
end

#
# getTitles() - from a list of candidates, build a list of titles
#
procedure getTitles()
    local titles, i
    titles := list(*candidates)
    every i := 1 to *candidates do
        if candidates[i][1] == "\"" then
            candidates[i] ? {
                move(1)
                titles[i] := tab(find("\""))
                }
        else
            titles[i] := candidates[i]
    return titles
end

#
# attachClientControls() - attach controls for each possible EM,
# as well as Eve's stopsign and exit button
#
procedure attachClientControls(titles,maxwidth)
    local fheight, y, dotwidth
    fheight := XAttrib("fheight")
    descent := XAttrib("descent")
    dotwidth := XTextWidth(".")
    loaded := list(*candidates)
    enabled := list(*candidates)
    every i := 1 to *candidates do {
        y := i * fheight + descent
        title := left(titles[i], maxwidth / dotwidth, ".")
        while XTextWidth(title) > maxwidth do title := left(title, *title - 1)
        Vmessage(root, 101, y, &window, title)
        loaded[i] :=
            FixedCheckbox(all, root, 101 + maxwidth, y,
                          &window, loadedChange, i, fheight)
        FixedCheckbox(&null, root, 101 + maxwidth + XTextWidth("load") + 8,
                          y, &window, iconicChange, i, fheight)
        enabled[i] :=
            FixedCheckbox(all, root, 101 + maxwidth + XTextWidth("loadiconify") + 16,
                          y, &window, enableChange, i, fheight)
        }

    stopstate := Vstrset_coupler(if /all then "startup" else "running",,,,,,
                                 ["startup","running","stopped","done"])
```

```
    stopSign := stopsign(&window, stopstate)
    aborter := stopsign(&window, Vstrset_coupler("abort",,,,,["abort"]))

    insert(Vrecset, "stopsign_rec")
    VInsert(root, stopSign, 10, 0, 80, 80)
    msg := Vmessage(root, 101, 0, &window, "Select client monitors")
    VInsert(root, Vline(&window, 101, fheight,
                    101 + XTextWidth("Select client monitors"), fheight))
    Vmessage(root, 101 + maxwidth, 0, &window, "load")
    Vmessage(root, 101 + maxwidth + XTextWidth("load") + 8, 0, &window, "iconify")
    Vmessage(root, 101 + maxwidth + XTextWidth("loadiconify") + 16, 0,
        &window, "enable")
    VInsert(root, aborter, 0, 80, 100, 70)
end

#
# attachSlider() - attach slider for execution speed control
#
procedure attachSlider()
    VRemove(root, msg)
    Vmessage(root, 101, 0, &window, "Executing program " || cmd)
    Vvert_slider(root, 45, 180, &window, speed, , XHeight() - 190, 10, 0, 100, 0)
    Vmessage(root, 20, 175, &window, "slow")
    Vmessage(root, 20, XHeight() - 20, &window, "fast")
    VResize(root)
end

#
# speed() - set the speed from the slider value. A vidget callback.
#
procedure speed(foo, newdelay)
    delayval := integer(newdelay ^ 1.5)
end

#
# run() - vidget event handler; yields control after every event by suspending
#
procedure run(e, x, y)
    local return_value

    if \e then {
        if return_value := VEvent(root, e, x, y) then suspend return_value
        else suspend
        }
    repeat {
        e := XEvent()
        if return_value := VEvent(root, e, &x, &y) then
            suspend return_value
        else suspend
        }
end

#
# titledparse() - parse command lines with an optional string title
# at the front. The syntax of .eve file lines is
# ["title"] cmd [options]
#
procedure titledparse(s)
    if s[1] == "\"" then
        s ? {
            move(1)
            tab(find("\""))
            move(1)
            tab(many(' '))
```

```
            return parse(tab(0))
            }
    else return parse(s)
end

#
# Trivial command line (string) argument --> list conversion.
#
procedure parse(s)
    local l, s2
    l := [ ]
    s ? {
        while s2 := tab(upto(' ')) do { put(l, s2) ; tab(many(' ')) }
        if *(s2 := tab(0))>0 then put(l, s2)
        }
    return l
end

#
# unschedule(EM) - remove EM from those that are receiving events.
#
procedure unschedule(EM)
    local newclients, monitor
    newclients := [ ]
    every monitor := !clients do {
        if monitor ~=== EM then put(newclients, monitor)
        else write("unscheduled ", image(EM.name))
        }
    clients := newclients
    computeUnionMask()
end

#
# computeUnionMask() - determine the set of events required by the
# union of all EM's -- including Eve's tick, error and user input needs
#
procedure computeUnionMask()
    static tickset
    local monitor, c
    initial tickset := cset(E_Tick || E_MXevent || E_Error)

    EventCodeTable := table()
    EventCodeTable["noop"] := ""
    EventCodeTable[E_Tick] := [ ]
    EventCodeTable[E_MXevent] := [ ]
    EventCodeTable[E_Error] := [ ]
    unioncset := tickset
    every monitor := !clients do
        if monitor.enabled === E_Enable then {
            unioncset ++:= monitor.mask
            every c := !monitor.mask do
                if c ~=== E_MXevent then {
                    /EventCodeTable[c] := [ ]
                    put(EventCodeTable[c], monitor)
                    }
            }
    if \verbose then write("Eve: union mask ", image(unioncset))
end

#
# getClientList(s) - read the .eve file and return a list containing
# its contents.
#
```

```
procedure getClientList(s, all)
    local fin, line, candidates
    candidates := [ ]
    if \s then fin := open(s) | stop("can't open ", s)
    else if not (fin := open(getenv("HOME") || "/.eve")) then {
        fin := &input
        write("Enter a list of client command lines.  A blank line terminates")
        }
    while *(line := read(fin))>0 do
        put(candidates, line)
    if fin ~=== &input then close(fin)
    return candidates
end

#
# During execution, Eve's knowledge about EMs is stored in a list of
# records of type "client_rec".
#

record client_rec(name, args, eveRow, prog, state, mask, enabled)

#
# client() - create and initialize a client_rec.
#
procedure client(args[ ])
    local self
    self := client_rec ! args
    if /self.name then stop("empty client?")
    self.prog := load(self.name, self.args) | stop("can't load ", image(self.name))
    variable("&eventsource", self.prog) := &current | stop("no EventSource?")
    variable("Monitored", self.prog) := &eventsource | stop("no Monitored?")
    /self.state := "Running"
    /self.mask := ''
    /self.enabled := E_Enable
    return self
end

#
# eveEvent() - event handler for E_MXevent user input event.
# If the user pressed the stop sign, the stop sign changes into a green light;
# wait until the user presses the green light before continuing.
#
procedure eveEvent()
    run(&eventvalue, &x, &y)
    while stopstate.value === "stopped" do
        run()
    &eventcode := "noop"
end

#
# eveTick() - event handler for E_Tick clock tick event.
#
procedure eveTick()
    drawtime(ticksum +:= &eventvalue)
end

#
# eveError() - event handler for E_Error TP run-time error event.
#
procedure eveError()
    local w
    if keyword("error", &eventsource) = 0 then
        #
        # this error would be fatal, handle it
```

```
        #
        if w := open("Run−time error", "x",
             "font=*helvetica−bold−r−*−−24*", "lines=10" ) then {
             write(w, "Run−time error ", image(&eventvalue))
             write(w, "File ", keyword("file", &eventsource),
                  "; line ", keyword("line", &eventsource))
             write(w, keyword("errortext", &eventsource))
             write(w, "offending value: ", image(keyword("errorvalue", &eventsource)))
             writes(w, "Convert to failure? ")
             if XEvent(w)===("y"|"Y") then
                  variable("&error", &eventsource) := 1
             }
end

#
# drawtime() − write the current elapsed TP clock time
#
procedure drawtime(val)
    /val := ticksum
    XGotoXY(18, 82)
    writes(&window, "T: ", val)
end

#
# loadedChange() − vidget callback for the "loaded" buttons
#
procedure loadedChange(i, val)
    local arglist
    if stopstate.value === "running" then {
        if /val then {
             # trying to turn off a load while running? Sorry...
             loaded[i].callback.V.toggle(loaded[i].callback, i, 1)
             }
        else {
             arglist := titledparse(candidates[i])
             write("arglist:")
             every write(!arglist)
             put(clients, client(pop(arglist), arglist, i))
             enabled[i].callback.V.toggle(enabled[i].callback, i, val)
             if /enabled[i].callback.value then enabled[i].D.draw_off(enabled[i])
             else enabled[i].D.draw_on(enabled[i])
             write(image(enabled[i].callback.value), ",", clients[*clients].enabled)
             clients[*clients].mask := @ clients[*clients].prog
             computeUnionMask()
             }
        }
    else {
        enabled[i].callback.V.toggle(enabled[i].callback, i, val)
        if /enabled[i].callback.value then enabled[i].D.draw_off(enabled[i])
        else enabled[i].D.draw_on(enabled[i])
        }
end

#
# enableChange() − vidget callback for the "enable" buttons.
# Update Eve’s state, and inform client of disable/enable.
#
procedure enableChange(i, val)
    local C, monitor
    if stopstate.value ~== "running" then fail
    val := if val === &null then E_Disable else E_Enable
    every monitor := !clients do {
        if monitor.eveRow === i then {
```

```
            monitor.enabled := val
            (C := event(val, , monitor.prog)) | (write("failing") & fail)
            if monitor.mask ~===:= C then
                computeUnionMask()
            }
        }
end

#
# iconicChange() – vidget callback for the "icon" buttons.
#
procedure iconicChange(i, val)
    local cl, v, v2
    val := if val === &null then "window" else "icon"
    every cl := !clients do
        if cl.eveRow === i then {
            if not (v := variable("Visualization", cl.prog)) then
                write("Visualization: failed")
            if find("window",image(v)) then XAttrib(v,"iconic=" || val)
            else if type(v) == "list" then
                every v2 := !v do XAttrib(v2,"iconic=" || val)
            else write("Visualization: ", type(variable("Visualization", cl.prog))|"failed")
            }
end

#
# eveQuit() – TP execution completion handler
#
procedure eveQuit()
    local c
    if \verbose then write("Eve: Monitored program has terminated execution")
    every c := (!clients).prog do
        cofail(c)
    GetEvents(root)
end

#
# broadcast() – sent event to interested EMs
#
procedure broadcast(x, except)
    /EveBroadcastQueue := []
    put(EveBroadcastQueue, x)
    put(EveBroadcastQueue, except)
    flush_broadcast_queue()
end

#
# flush events produced during EM – EM communcation.
# This code appears similar to Eve's main loop.
#
procedure flush_broadcast_queue()
    local c, C, x, except, monitor
    while *EveBroadcastQueue > 0 do {
        x := pop(EveBroadcastQueue)
        except := pop(EveBroadcastQueue) | stop("malformed broadcast queue")
        if x === "quit" then eveQuit()
        every monitor := (except ~=== !clients) do
            if C := event( , , monitor.prog) then {
                if C ~=== monitor.mask then {
                    while type(C) ~== "cset" do {
                        #
                        # The EM has raised a signal.
                        # Pass it on to all the others except the client.
```

```
                #
                put(EveBroadcastQueue, C)
                put(EveBroadcastQueue, monitor)
                if not (C := event( , , monitor.prog)) then {
                    unschedule(monitor)
                    if \verbose then
                        write("Eve warning: broadcast of ",
                            image(&eventcode), " aborted")
                    }
                    break next
                }
            if monitor.mask ~===:= C then
                computeUnionMask()
            }
        }
    else {
        unschedule(monitor)
        if \verbose then
            write("Eve warning: broadcast of ", image(&eventcode), " aborted")
        break
        }
    }
end
```

Appendex C: Event Codes

The following list of event codes is provided in order to give a general indication of the extent of instrumentation discussed in Chapter 5. More information on these codes is presented in [Gris92c].

Classes of events

AllocMask	Memory allocation events
AssignMask	Assignment events
TypeMask	Events related to Icon data types
ConvMask	Type conversion events
ListMask	List operation events
RecordMask	Record operation events
ScanMask	String scanning events
SetMask	Set operation events
TableMask	Table operation events
StructMask	Structure operation events (lists, records, sets, and tables)
ProcMask	Procedure activity events
FncMask	(Built-in) Function activity events
OperMask	Operator activity events

Individual events

E_Lrgint	Large integer allocation
E_Real	Real allocation
E_Cset	Cset allocation
E_File	File allocation
E_Record	Record allocation
E_Tvsubs	Substring trapped variable allocation
E_External	External allocation
E_List	List allocation
E_Lelem	List element allocation
E_Table	Table allocation
E_Telem	Table element allocation
E_Tvtbl	Table-element trapped variable allocation
E_Set	Set allocation
E_Selem	Set element allocation
E_Slots	Hash header allocation
E_Coexpr	Co-expression allocation
E_Refresh	Refresh allocation
E_Alien	Alien allocation
E_Free	Free region
E_String	String allocation
E_Lrgint	Large integer allocation
E_Real	Real number allocation

E_Cset	Cset allocation
E_File	File allocation
E_Record	Record allocation
E_Tvsubs	Substring trapped variable allocation
E_External	External allocation
E_List	List allocation
E_Lelem	List element allocation
E_Table	Table allocation
E_Telem	Table element allocation
E_Tvtbl	Table element trapped variable allocation
E_Set	Set allocation
E_Selem	Set element allocation
E_Slots	Hash header allocation
E_Coexpr	Co-expression allocation
E_Refresh	Refresh allocation
E_Alien	Allien alien allocation
E_Free	Free region
E_String	String allocation
E_Integer	Integer value pseudo-event
E_Null	Null value value pseudo-event
E_Proc	Procedure value pseudo-event
E_Kywdint	Integer keyword value pseudo-event
E_Kywdpos	Position value pseudo-event
E_Kywdsubj	Subject value pseudo-event
E_Pid	Symbol name
E_Sym	Symbol table entry
E_Tick	Clock tick
E_Loc	Location change
E_Opcode	Virtual-machine instruction
E_Aconv	Conversion attempt
E_Tconv	Conversion target
E_Nconv	Conversion not needed
E_Sconv	Conversion success
E_Fconv	Conversion failure
E_Lsub	List subscript
E_Rsub	Record subscript
E_Snew	Scanning environment creation
E_Sfail	Scanning failure
E_Ssusp	Scanning suspension
E_Sresum	Scanning resumption
E_Srem	Scanning environment removal
E_Spos	Scanning position
E_Assign	Assignment
E_Intcall	interpreter call
E_Intret	interpreter return

E_Stack	stack depth
E_Ecall	Call of operation
E_Efail	Failure from expression
E_Eret	Return from expression
E_Bsusp	Suspension from operation
E_Esusp	Suspension from alternation
E_Lsusp	Suspension from limitation
E_Eresum	Resumption of expression
E_Erem	Removal of a suspended generator
E_Coact	Co-expression activation
E_Coret	Co-expression return
E_Cofail	Co-expression failure
E_Pcall	Procedure call
E_Pfail	Procedure failure
E_Pret	Procedure return
E_Psusp	Procedure suspension
E_Presum	Procedure resumption
E_Prem	Suspended procedure removal
E_Fcall	Function call
E_Ffail	Function failure
E_Fret	Function return
E_Fsusp	Function suspension
E_Fresum	Function resumption
E_Frem	Function suspension removal
E_Ocall	Operator call
E_Ofail	Operator failure
E_Oret	Operator return
E_Osusp	Operator suspension
E_Oresum	Operator resumption
E_Orem	Operator suspension removal
E_Collect	Garbage collection
E_EndCollect	End of garbage collection
E_TenureString	Tenure a string region
E_TenureBlock	Tenure a block region
E_Error	Run-time error
E_Exit	Program exit
E_MXevent	monitor input event
E_Comment	Comment

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