ENHANCING DEBUGGING TECHNOLOGY

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by

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I

dedicate this

thesis to my parent,

Chuchit and Ueychai Viravan.

It is my tribute to their constant

sacrifice, concern, encouragement, discipline, and love.

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ABSTRACT

Viravan, Chonchanok. Ph.D., Purdue University, May 1994. Enhancing Debugging Technology. Major Professor: Dr. Eugene H. Spafford.

This dissertation presents a new debugging assistant called a *Debugging Critic*. As an alternative to an automated debugging oracle, the debugging critic evaluates hypotheses about fault locations. If it cannot confirm that the code at the hypothesized location contains a fault, it formulates an alternative hypothesis about the location of a faulty statement or the location of omitted statements. The debugging critic derives knowledge of possible locations of a fault that manifested itself under a given test case from failure symptoms. It derives information about failure symptoms from programmers' replies to its questions. Therefore, it can operate without a line-by-line specification and a knowledge base of faults.

A prototype of our debugging critic has been implemented as an extension of an existing debugger, Spyder. An experiment with Spyder shows that programmers debug two to four times faster on the average with the debugging critic than without it. Ninety-two percent of the critic's users recommend the critic as an extension of conventional debuggers.

The research in this dissertation contributes to debugging and critic systems. In debugging, our experiment shows that an active debugging assistant can effectively improve debugging performance. Another contribution is our approach to evaluate and formulate hypotheses about fault locations, especially the locations of omitted statements. In critic systems, our contribution is the use of questions to present informative and non-insulting criticism.

1. INTRODUCTION

There are two ways to write error-free programs;
only the third one works.

– Perlis (*Epigrams on Programming*, 1982)

Program errors are a fundamental phenomenon in the real world of software [Sch71]. Because software designers and programmers are only human, they are likely to take inappropriate actions during software development that ultimately may cause the software to fail. These actions are what we call *errors* [IEE83]. The physical manifestations of errors in the program text are known as *faults* or *bugs* [IEE83]. We can realize the presence of errors if we can find *an error-revealing* test case that causes the program to fail. A *program failure* is a departure of program operation from program specification [IEE83]. A *program specification* is a document that prescribes in a complete, precise, and verifiable manner the requirements, design, behavior, or other characteristics of a program or a program component [IEE83].

The objective of testing is to explore the input space of a program to find *error-revealing* test cases that cause the program to fail, whereas the objective of debugging is to find and fix the faults responsible for failures [Agr91, Pan91]. Despite the fact that over 50% of total software development costs have been reported spent on the testing and debugging phases [Boe81, Mye79, Pre82], debugging remains one of the least developed areas in software engineering [AFC91].

Debugging, unlike testing, is an unstructured and spontaneous process [Tra79, Lau79]. The process is still human-oriented even when a debugging facility is used [Joh83]. It is regarded as more of an art than a science [GB85].

1.1 Debugging Background

Debugging is a process of locating and repairing faults. Research in cognitive aspects of programming characterizes debugging as an iterative process of synthesizing, testing, and refining hypotheses about fault locations and repairs [Ves85, Gou75, MW91]. A debugging process model proposed by Araki et al. [AFC91] (see Figure 1.1) echoes these aspects. A programmer develops his initial set of hypotheses when he observes a program failure. Hypotheses may concern the location of faults, the types and identity of faults, the expected program behavior, and the fault repairs, among many other things [AFC91]. Araki's hypothesis-set also includes the programmer's empirical knowledge of the software development process, the program, and its specifications. This hypothesis set evolves as a programmer selects and verifies the hypotheses. Araki called hypotheses that have been proven *fact hypotheses.* The process ends when the fault is fixed.

Current debugging tools and techniques support the evaluation of hypotheses about program behavior and the formulation of hypotheses about fault location and fault identity. Most debuggers help a programmer formulate and evaluate a hypotheses about program execution behavior by allowing him to observe actual program behavior. Conventional debuggers, such as Dbx [Dun86], Sdb [Kat79], and VAX Debug [Bea83], offer commands to step through the program execution, set break points, examine variable values at the break points, and trace program execution. Experimental debuggers, such as Spyder [Agr91], offer backward execution [Agr91]. Other prototype systems, such as Powell and Linton's OMEGA [PL83] and LeDoux's YODA [LeD85], allow the programmer to query program behavior.

Fault recognition techniques help a programmer formulate hypotheses about fault identity and fault location. These techniques require either a knowledge base of faults or the program specification as their input. A knowledge base of faults contains common fault patterns. When part of a program matches a fault pattern in the knowledge base, the location becomes a hypothesized fault location. Lint [Dar90],

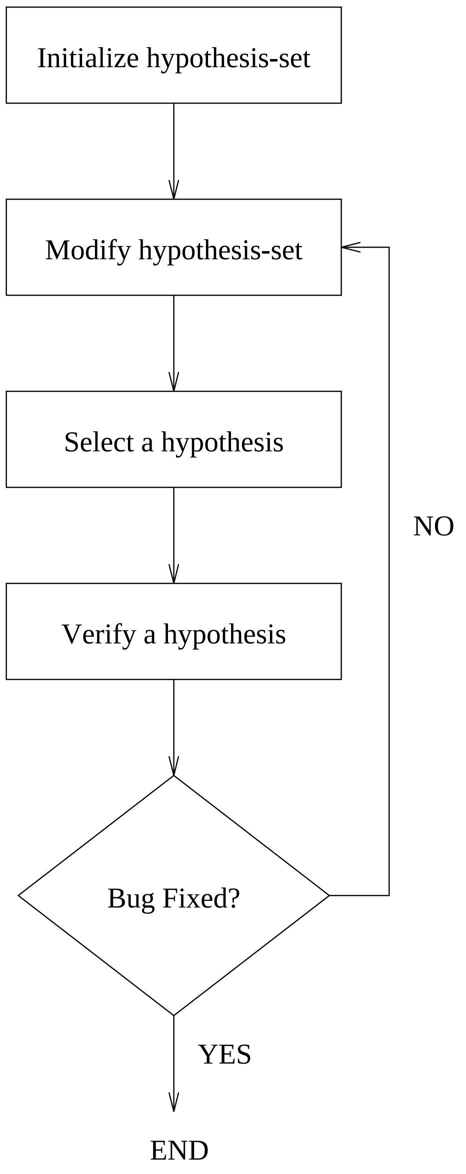


Figure 1.1 A debugging process model

relying on its knowledge of common errors, finds common portability problems and certain types of coding errors in C programs. Program specifications are used by systems such as Lukey's PUDSY [Luk80], Adam's LAURA [AL80], and Jackson's ASPECT [Jac93] to identify faults by identifying discrepancies between the program and its specification.

Fault localization techniques help a programmer formulate hypotheses about fault location. Program slicing techniques [Wei82, LW87, Agr91, OO84, HRB90, KL90, Ven91, YL88, Pan93] extract statements or procedures on which the specified variable or statement depends, according to predefined criteria. The programmer can select a location containing statements in a slice as his hypothesized location. Fault localization heuristics, such as Collofello and Cousins's decision-to-decision path-based heuristics [CC87b] and Pan's slicing-based heuristics [Pan93] use test-based knowledge to enhance their ability to locate a fault. Knowledge of *program plans*, as described in several papers [HN90, JS85, Rut76, Luk80, AL80, Let87, KLN91, KN89, RW88, Sha81, Wil90, Har90] can also be used to identify possible fault locations. Because a program plan describes a pattern of code to accomplish a specific task, the locations with a mismatch between the code and a program plan pattern are identified as possible fault locations. Fault localization binary search algorithms [Sha83, SKF91, KL88, Kup89] can also locate possible fault locations in side-effect-free programs.

Although debugging techniques to help formulate fault-related hypotheses are abundant, techniques to help verify these hypotheses are scarce. It is reasonable to investigate whether techniques to help verify fault-related hypotheses can enhance current debugging technology.

1.2 Debugging Oracle Problem

According to Weinberg [Wei71], programmers have difficulty finding errors because their conjectures become too prematurely fixed, blinding them to other possibilities.

This problem occurs when the programmer spends too much time looking for errors in the wrong place [Gou75, MM83, SV93]. This problem is called "fixation on the wrong location."

As a fault localization process can consume up to 95% of the overall debugging effort [Mye79], it is desirable to overcome the problem of "fixation on the wrong location." Current debugging assistance methods do not yet address this problem adequately for three reasons:

- Traditional assistance which helps programmers to observe program execution behavior does not prevent the problem of "fixation on the wrong location." A programmer inspects the program execution to find anomalous behavior. Our studies [SV93] show that programmers can confuse a location with anomalous behavior with a fault location. This leads to, rather than solves, the problem of "fixation on the wrong location."

- Fault recognition tools cannot recognize all faults. When the code does not match any fault pattern in the knowledge base of faults, the code location can neither be confirmed nor rejected as a fault location. This is because the knowledge base of faults is always incomplete (see page 6). Also, when the tool generates an error message or a warning message about a non-faulty location, it can cause rather than solve the problem of "fixation on the wrong location".

- A programmer with access to program slices for erroneous variables can still develop a fixation on the wrong location within program slices [SV93]. When the fault is the result of omitted statements, a location that contains no statement in a program slice for an erroneous variable can neither be confirmed nor rejected as a fault location.

A *debugging oracle* is a person or a system that decides whether hypotheses about fault location, fault identity, and fault repair are true [SV93]. A programmer is usually responsible for making these decisions. If a debugging oracle can be automated, its ability to verify a location has the potential to overcome the problem of "fixation on the wrong location."

However, automating a debugging oracle is made difficult by several factors. To answer "Is the statement at the given location faulty?" automatically, an oracle would need a line-by-line formal specification of the program, a complete knowledge of possible faulty patterns, and/or a capability to prove correctness of the code.

- A line-by-line specification can be used to evaluate every execution of the given code to identify discrepancies. The problem with this approach is the lack of line-by-line specifications in practice.

- Knowledge of possible fault patterns can be used to recognize whether a location contains a fault. The problem with this approach is the incompleteness of any knowledge base of faults. A knowledge base of faults is complete when no new fault and no new program can be introduced. As one can always write a new program and introduce new programming language constructs, a complete knowledge of all possible fault patterns cannot be attained.

- A capability to prove correctness of code can be used to verify whether the code is faulty. The problem with this approach is that the time required to prepare the input for a proof-checker can outweigh debugging time saved by the oracle. The difficulty in proving correctness of the code is that it may not always be feasible to characterize many real-life programs mathematically [DLP79]. Also, existing automatic program provers, such as the one defined by Goldschlag [Gol90], act as proof-checkers rather than proof-generators, as they take a rough draft of a proof as input. Proofs, even in a draft format, are generally much more difficult to construct and understand than the programs themselves [DLP79]. Debugging time may even increase if a programmer has to construct a proof draft for every hypothesis he makes.

This dissertation approaches the debugging oracle problem with the conjecture that it is possible to construct an alternative, automatable tool that can operate in the absence of both a line-by-line specification and a knowledge-base of fault patterns. It is desirable for such an alternative assistant to overcome the problem of "fixation on the wrong location."

1.3 Statement of Thesis

Thesis

Programmers can debug faster when they have a tool to help evaluate hypotheses about fault locations in addition to tools that help formulate fault-related or program behavior-related hypotheses.

To support the statement of thesis, we propose an alternative to a debugging oracle. This alternative answers the question, "Is it conclusive that the statement at location *loc* contains the fault that was manifested under the given test case *t*?" instead of "Is the statement at location *loc* faulty?"

The primary mechanism of our proposed assistant is to evaluate hypotheses about fault location. Given a hypothesized location of a fault and a test case, the assistant evaluates whether the statement contains the fault that causes the program to fail under the given test case. This method can work in the absence of a formal specification and a knowledge base of common fault patterns.

This method works under the assumptions that (1) the program is sequential and structured, (2) when the program may contain multiple faults, only one fault is manifested by a given error-revealing test case, (3) the program is written in statement-oriented language, (4) the program has no in-line side-effects (such as i++ in the C language), and (5) the programmer has access to the high-level natural language specification of the program. This method is operational in the absence of a formal specification and a knowledge base of faults.

As this alternative is also a debugging assistant, we proposed addition mechanisms to support the hypotheses evaluation process in ways that can improve debugging speed:

Maintain knowledge about the program.

> Araki suggested that knowledge about the program is enhanced when a hypothesis is evaluated, even if it can be neither confirmed nor rejected [AFC91]. It is desirable to identify what types of knowledge can be collected and applied to enhance the assistant.

Formulate an alternative hypothesis about fault location.

> When the programmer's hypothesis cannot be confirmed, our assistant formulates an alternative hypothesis. This alternative hypothesis may indicate either a possible location of a faulty statement or of omitted statements. This assistance is desirable because it has a potential to help remedy the "fixation on the wrong location" problem.

Augment existing fault localization or fault recognition tools.

> If our proposed assistant can augment other existing fault localization or fault recognition tools, then it can be integrated into other debuggers. For this research, the fault localization tool used is a program slicing tool. The fault recognition tool used is a pattern matching tool for which the programer can define a fault pattern to search.

1.4 Overview

Chapter 2 describes terminology and work related to both debugging and to our alternative to a debugging oracle. Chapter 3 describes an empirical study to identify the form of an oracle's assistance that can improve debugging speed and accuracy. As this study involved expert programmers who debugged a program with omitted statements, the methods they used to locate omitted statements are also reported. Chapter 4 describes a debugging critic as an alternative to a debugging oracle. It describes how the critic system evaluates hypotheses about fault locations, maintains knowledge about the program, and formulates an alternative hypothesis. The method of formulating a hypothesis about the location of omitted statements is also described. Chapter 5 describes a prototype of a debugging critic and an experimental study to evaluate its effectiveness. Chapter 6 presents the summary, the contributions, and suggestions for future research directions.

2. TERMINOLOGY AND RELATED WORK

This chapter presents terminology and work related to debugging and our alternative assistant to a debugging oracle. Our alternative assistant is categorized as a critic system.

2.1 Terminology

This section presents terms pertaining to programs, program specifications, faults, failures, and program slicing used in this dissertation.

2.1.1 Program

A program $\mathcal{P}$ is a triple (S, A, Σ), where S is a set of states, A is a set of actions, and Σ is a set of a finite execution sequences of the form

$$\sigma = s_0 \xrightarrow{\alpha_0} s_1 \xrightarrow{\alpha_1} s_2 \xrightarrow{\alpha_2} s_3 \ldots \xrightarrow{\alpha_{\$-1}} s_{\$}$$

where $s_i \in S$, $\alpha_i \in A$, and i is an index identifying an *execution step.* Step i uniquely determines state s_i in a given execution sequence. The last execution step is denoted by \$, as the last state is denoted by $s_{\$}$.

A *state* s_i represents a "snapshot" of the program at execution step i. A state, $(\pi, v_1, v_2, \ldots, v_n)$, is a vector of values of all variables (v_i) and of the control point in the program (π). A control point π represents the location of the code to be executed next.

An *action* α_i represents a single indivisible statement that is reached at step i. A *statement* is an instruction written in a programming language that can change values in states as the program executes. A *procedure* contains a set of statements. The *location* of an action is the position of a statement in the program text. This position is identified by a *line number*. The *location* of a set of actions is identified by a procedure name.

A *state transition* $s_i \xrightarrow{\alpha_i} s_{i+1}$ represents an execution of a statement reached at step i that transforms state s_i to state s_{i+1}. An execution of one or more statements that transform state s_i to s_j, where $i < j$, is abbreviated as $s_i \xrightarrow{\alpha} s_j$.

An *execution sequence*, σ_t, denotes a series of state transitions when $\mathcal{P}$ is applied to test case t. An *execution path*, $\sigma_t^{i,j}$, corresponds to $s_i \xrightarrow{\alpha} s_j$ in σ_t. A statement at a location *loc* executes in $\sigma_t^{i,j}$ when *loc* is reached at step k, where $i \leq k < j$.

An *execution occurrence*, $\mathcal{L}^{(x,y)}$, is the execution of statements at location $\mathcal{L}$ that maps input state s_x to output state s_y. If more than one statement executes in this mapping, $\mathcal{L}$ represents procedure names. If only one statement executes in this mapping, $\mathcal{L}$ represents a line number. An execution occurrence of one statement is called a *statement occurrence*. An occurrence $\mathcal{L}^{(x,y)}$ is in $\sigma_t^{i,j}$, when $i \leq x < y \leq j$.

We use Lamport's notation of state function [Lam89, Lam83] to treat program control flow as if it is another variable. A *state function* is a function that maps a state $(\pi, v_1, v_2, \ldots, v_n)$ to a value.

A *program variable* is an expression in a program that is associated with a memory location. Each variable can be treated as a state function that takes a state s as input and returns the variable value v_i in a state s. When a variable is out-of-scope in state s, its state function is not defined. A variable *var* at step i refers to the variable *var* at the statement reached by step i.

The *program control* indicates the point in the program that is reached by the flow of control. The program control can be treated as a state function *pc* that takes a state s as input and returns the the control point π in a state s.

2.1.2 Program specification

A *program specification* is a document that prescribes in a complete, precise, and verifiable manner the requirements, design, behavior, or other characteristics of a program or a program component [IEE83]. A *program behavior specification* describes properties that the program execution must satisfy. These properties either specify what the program is allowed to do or what the program must do. An execution ocurrence *violates a program behavioral specification* when it represents a disallowed state transition or an omitted state transition.

2.1.3 Faults

Software *errors* are inappropriate actions during software development that ultimately may cause software to fail [IEE83]. A software *fault* is the physical manifestation of an error in the program [IEE83]. A *faulty location* means the code at the location contains a fault or omits one or more statement.

A fault *manifests* itself when the execution of code at a faulty location yields an error-revealing state. A value in a state is *error-revealing* if it deviates from the program specification. An *erroneous variable* is a variable whose value is error-revealing. An *erroneous control flow* occurs when the value of *pc* is error-revealing. For example, if the specification specified $(i < j)$, but $(i > j)$ is used in the program, then *pc* can becomes error-revealing after the predicate $(i > j)$ is executed.

An *error-revealing state* is a state with at least one error-revealing value. A value in a state is *non-error-revealing* when it does not deviate from the program specification. A *non-error-revealing state* is a state with no error-revealing value. In the absence of a formal specification, the error-revealing or non-error-revealing status is determined by the programmer's interpretation of the available specification.

Two *classes of faults* are faults of commission and faults of omission.

A *fault of commission* is a fault in an existing statement whose manifestation causes a value in a program state to change to an error-revealing value.

A *fault of omission* is omitted code that inhibits a change of values in program states when it manifests itself. Omitted code that might inhibit the change of variable values includes (1) the omission of an assignment to a variable, (2) the omission of an input variable in an input statement, and (3) the omission of an argument in a procedure call. Omitted code that inhibits the change of control flow to a certain location includes (1) the omission of a predicate in a predicate statement, (2) the omission of a procedure call statement, and (3) the omission of a transfer statement (e.g., return, goto statements). Omitted code that inhibits the production of an output includes the omission of output statement.

There are circumstances when one error manifests itself as both a fault of omission and a fault of commission. First circumstance is the case of *incomplete predicate expression.* A predicate expression consists of a set of predicates, each of which represents a condition, that allow the program to perform certain actions. A predicate expression is incomplete when it does not specify all conditions (as per the specification) to control whether the program can perform a certain action. A predicate statement with an incomplete predicate expression contains a fault of commission because its execution changes the *pc* value in an incorrect value. The procedure enclosing this predicate statement also contains a fault of omission because the omitted predicate prevents the flow from reaching some statements. For example, when a predicate expression in an *if*-statement enclosing $x = y + z$ is incomplete, a new predicate can be added to an existing predicate expression to repair a fault of commission. However, a new *if*-statement with a new predicate can also be added to enclose another $x = y + z$ to repair a fault of omission.

A second circumstance is the case of a wrong variable assignment. This is the case when an assignment statement assigns the value of a wrong variable or an input statement reads a value into a wrong variable. Let *loc* be a location of such statement. If an erroneous variable depends on the statement at *loc*, we call the statement at *loc* an *extra dependency statement* and consider that this fault is manifested as a fault of commission. If no erroneous variable depends on the statement at *loc*, we call the statement *loc* a *missing dependency statement* and consider that this fault is manifested as a fault of omission.

2.1.4 Failure

A *program failure* is a departure of the program operation from program specification [IEE83]. A program *fails* when it maps a non-error-revealing state onto an error-revealing state. When the program that fails is expected to terminate according to specification, it may not terminate, may terminate abnormally, or may terminate with erroneous output.

Failure symptoms are visible evidence that a fault has been manifested in the execution of the given test case. If the detailed and formal specification of a program are available, failure symptoms can be generated. If a programmer only has access to a high-level natural language specification, failure symptoms are described according to his interpretation of such specification.

2.1.5 Program slicing

A *program slice* is a set of program statements that directly or indirectly contributes to the values assumed by a set of variables at some program point [Wei82]. Different types of program slices are characterized by the type of dependency analysis and the type of statements in the slice. Two main types of slice analysis, static and dynamic, are presented below. These descriptions are adapted from Agrawal [Agr91].

Static analysis identifies statements that, if executed, may affect the variable at the given location. A static slice is computed with respect to the program $\mathcal{P}$, a variable *var*, and a location *loc*.

Dynamic analysis identifies executed statements that actually affect the current value of the variable at the given location. A dynamic slice is computed with respect to the the program $\mathcal{P}$, a variable *var*, a location *loc*, and a test case t.

Types of statements in a slice are assignment statements and predicate statements. *Assignment statements* refer to any statement that assigns a value to a variable. An input statement and procedure call statement are also considered assignment statements. A *simple assignment statement* is a statement that can assign value to at most one variable (e.g., $x = y + z$). *Predicates* are in conditional statements such as *if*, *for*-loops, and *while*-loops.

The variation of static and dynamic slices, defined by Agrawal [Agr91], are as follows.

A *reaching definition* is an assignment statement that can define the variable *var* at a given location. The *static reaching definitions* are all reaching definitions of a variable *var* for all possible execution histories. The *dynamic reaching definition* is the reaching definition that defines the current value of *var* in a particular execution history.

A *data slice* includes assignment statements whose computation can propagate into the value of *var* at a given location. The *static data slice* is defined as transitive closure of static reaching definitions of *var*. The *dynamic data slice* is defined as transitive closure of dynamic reaching definitions of *var*.

A *control slice* includes predicates that control the flow to the given location (within one procedure). Agrawal does not distinguish between dynamic and static control slices.

A *program slice* includes both assignment and predicate statements. A *static program slice* is the transitive closure of static data slices and control slices. A *dynamic program slice* is the transitive closure of dynamic data slices and control slices.

Current slicing methods do not analyze *weak control dependency*, inter-statement control dependency [PC90]. If program slicing was enhanced to consider weak control dependency, it would be possible to determine the *transfer statements* (e.g., return, break, continue, goto's) that affect the flow of control to a given location.

2.2 Related Work in Debugging

2.2.1 Evaluation of hypotheses on program behavior

Conventional debuggers help a programmer verify his hypothesis about how the program behaves. They allow him either to *observe* or *query* the program and its changes in flow of control and values of variables. The programmer recognizes that the program fails when he observes discrepancies between the hypothesized behavior and the actual behavior. Techniques to explore program behavior are as follows.

Forward Stepping

In forward stepping, a programmer steps through program execution to observe the flow of control. Among debuggers that support this feature are Dbx [Dun86], Sdb [Kat79], and CodeCenter [Cen92].

Backward Stepping

Backward stepping allows the programmer to observe the flow of control in reverse order. Some systems, such as EXDAMS [Bal69], save all states in the execution history so that they can be backtracked by restoring the appropriate state. To backtrack without having to save the whole execution history, Agrawal, DeMillo, and Spafford [ADS91a] introduced a structured backtracking approach. This approach saves only the latest value of each variable changed in a statement. Backtracking over a simple or a composite statement is permitted, but backtracking to the inside of a composite statement is not.

Break-and-Examine

The execution of a program suspends at breakpoints to let the programmer examine the program state. Debugging tools from the 1960's, such as DDT [SW65], allow the programmer to set breakpoints in assembler programs. Conventional debuggers today, such as Dbx [Dun86], Sdb [Kat79], VAX Debug [Bea83] and CodeCenter [Cen92] support break-and-examine techniques. These tools leave it to the programmer to decide where to break and which variables to examine.

Conditional breakpoints

Conditional breakpoints cause the execution to suspend only when the condition holds. A programmer can use the condition to represent his hypothesis about program behavior. He can then reexecute the program to check if and when the conditions are true, and thus find out when anomalous conditions arise [Hua79, CC87a].

Retrospective observation

A programmer observes program behavior retrospectively if he observes the execution trace after program execution. A programmer can generate a trace by inserting print statements in a program. These statements either indicate that the control reaches certain points or they reveal the values of variables. Some systems save the execution history to be replayed [Bal69] or redisplayed in an order that is different from the actual execution (e.g. breadth-first order as in [Duc87, Llo86]).

Query about program behavior

In the design of the OMEGA programming system, Powell and Linton [PL83] introduced a debugging model that uses a database interface to access both static and dynamic information. OMEGA supports a rich set of queries on the values and interconnections of the data, and on where and when certain conditions (*events*) occur. OMEGA translates the query into machine-level breakpoints instead of storing run-time information in the database. The initial experience with OMEGA shows that it is too slow to be useful [LeD85].

Sniffer [Sha81] is a knowledge base interactive debugger for Lisp programs. Its *time rover* subsystem supports queries regarding the history of program states. It is time-consuming to write the query, however, because the programmer must describe the bug in the query [LeD85].

LeDoux's YODA [LeD85] is a debugger for Ada tasking programs. It supports time-related queries on a single-trace database as well as queries on a symbol table. A trace database collects time-dependent facts (events) and their time stamps to answer queries on relationships among events and abstractions of events. The queries allow a programmer to test assertions about program properties, including the ordering of states, the sequencing of events, and the simultaneity of a given set of conditions.

2.2.2 Formulation of hypotheses on fault identity

Formal specification can be used in methods to formulate hypotheses on fault identity. In Lukey's PUDSY [Luk80], the specification is compared with the abstract representation of code to find the faults. In Adam and Laurent's LAURA [AL80], the knowledge of the correct algorithms or implementations are used to identify discrepancies with the actual implementation. The discrepancies become hypothesized faults. In Jackson's ASPECT [Jac93], a static analysis technique uses abstract forms of specification to detect faults. Given a declarative, data abstraction specification, ASPECT can detect faults that are not detectable by other static means, such as missing data or missing dependency relations among data.

A knowledge base of faults can also be used in methods to formulate hypotheses on fault identity. A knowledge of faults allows a debugger to try to find code that matches the faulty pattern directly. Lint [Dar90], relying on its knowledge of common errors, finds common portability problems and certain types of coding errors in C programs. Other debuggers, such as FALOSY [STJ83], PROUST [Joh90] and Sniffer [Sha81], also operate on common faulty code patterns. A few others, such as Kraut [BH83], operate on anomalous execution patterns.

2.2.3 Formulation of hypotheses on fault location

Three main categories of methods to formulate hypotheses about fault locations are based on dependency analysis, on a knowledge base of plans, and on fault localization algorithms. Hypotheses about fault locations derived by these methods are currently verified by a programmer, not by an automated debugging oracle.

2.2.3.1 Program slicing

Besides the type of program slices we used in this dissertation (as described in Section 2.1.5), there are several other forms of slicing defined:

- Static slice

  Weiser's static slice [Wei82, Wei84] is an executable subprogram for computing variables of interest for any test case. To compute a static slice, Weiser's algorithm decomposes a program by statically analyzing the data-flow and control-flow of the program. An alternative approach is to compute the slice based on graph reachability in the program dependence graph, as presented by Ottenstein and Ottenstein [OO84] and Horwitz, Reps, and Binkeley [HRB90].

- Dynamic slice

  Korel and Laski [KL90] define a dynamic (executable) slice as an executable subprogram that computes the values of variables of interest for the specific test case. Their algorithm is an extension of Weiser's algorithm. In order to preserve the behavior of the original program, the dynamic executable slice includes extra statements needed in the computation of earlier values of the output variables.

Agrawal [Agr91] defines a dynamic (closure) slice as a closure of all assignment and predicate statements that affect the values of variables of interest for a specific test case. He extends Ottenstein and Ottenstein's program dependence graph into a dynamic program dependence graph in order to use the graph reachability approach to compute the slice. By checking overlapping memory cells among variables, Agrawal's algorithm can also handle a program that uses pointers, records, and arrays [ADS91b]. The dynamic closure slice excludes any statement that does not affect the current values of the variables.

- Expanded Dynamic slice

  Pan [Pan93] expands Agrawal's dynamic slice to include statements in the transitive closures of executed predicates that enclose a statement in the static slice of a variable. This slice is a superset of Agrawal's dynamic slice and a subset of a static slice.

- Critical slice

  Pan [Pan93] defines a critical slice via mutation analysis. This slice includes statements whose presence in the program affects how the program fails under a given test case. If a debugging process is integrated with a mutation-based testing tool, a critical slice is obtained as a by-product. Without such integration, this slice is computed by (1) removing a statement executed under a given test case, (2) recompiling, and (3) reexecuting the modified program. This process repeats n times, where n is the number of all executable statements in the original program.

- Forward Slice

  A different notion of a program slice, referred to as *forward slicing*, computes the set of statements affected by the variable of interest. Yau and Liu [YL88] define an algorithm for forward static slicing to support ripple-effect analysis. Their algorithm locates all statements that *may* be affected if the variable of interest is modified. Forward slicing can help programmers understand the propagation of a fault (once it has been located).

2.2.3.2 Program Dicing

Lyle and Weiser [LW87] propose the notion of *program dicing* which uses the static slices of both correct and incorrect variables to reduce the search space for faults. Their technique removes statements belonging to static slices of correct variables from the slices of incorrect variables. The system gains knowledge of the correctness of variables through the observation of variable values during the execution of the program with various test cases.

If the term "dicing" is taken literally as a process of cutting up a program to reduce the search space for faults, then slice operations suggested by Agrawal [Agr91] present other forms of program dicing. Operations such as union, subtraction, and intersection, can be used to combine the slices. Pan's heuristics [Pan93], as described on page 22, apply program dicing to help locate faults.

2.2.3.3 Heuristics that use test-based knowledge

Test-based knowledge encompasses the test data selection strategy and the set of test data generated. The test data selection strategy suggests the potential faults it tries to uncover [CR83]. The execution of a set of test data can be subjected to several forms of anomalous behavior analysis [Pan91]. It is more helpful, however, if we use an adequate test data set [DLS78] that differentiates a program being tested from incorrect programs.

Collofello and Cousins [CC87b] combine test-based knowledge with dependency analysis to support fault guessing at statement block levels. Using dependency analysis, the program is first partitioned into many decision-to-decision paths (DD paths), which are sections of straight line code existing between predicates in the program. During the testing session, execution frequency of DD paths is monitored. Based on these counts in error-revealing and non-error-revealing test cases, they propose several heuristics to predict which DD paths may contain the faults.

Pan [Pan93] defines families of heuristics to locate faults. These heuristics use dynamic dependency analysis to analyze the execution using error-revealing and non-error-revealing test data sets. Some heuristics work with mutation-based test knowledge. Execution frequency is used in some heuristics to identify a statement or a block of code that has high execution frequency in error-revealing test cases, but low in non-error-revealing test cases.

2.2.3.4 Near-miss recognition of program plans

Plans (also called *cliches* [RW88]) are the methods for achieving a *goal*, where a goal is a task performed in the program [Sol87]. Levels of plans range from common programming constructs and data structures to the algorithms of the whole program [HN90]. A plan may be represented in the same programming language as the code [JS85, Rut76, Luk80] or in some other abstract representation [AL80, Let87, KLN91, KN89, RW88, Sha81, Wil90, Har90, HN90].

Near-miss recognition of the plan suggests possible faulty locations in an almost correct section of code. The basic idea is to match plans with the code. The location where discrepancies arise between the best-matched plan and the code becomes the hypothesis about fault location.

2.2.3.5 Fault localization algorithms

- Shapiro's Divide and Query algorithm [Sha83] applies a binary search heuristic over a computation tree. A computation tree, which represents the legal computations of a program, is constructed from traces of the procedure calls in the program. In the tree, the parent node is the caller of its children nodes.

This approach weighs the number of procedure calls each subtree makes, then *divides* a computation tree rooted at p into two subtrees of roughly equal weight. The upper half of the original tree has p as its root, the lower half has another node q as its root. The algorithm then *queries* the programmer to verify input-output values of the procedure call at node q. If the programmer decides that the output values at q are correct, then the algorithm will continue the search on the upper half subtree. Otherwise, the search continues in the lower half subtree.

This diagnostic system operates under the assumptions that if a program is correct, then all of its subprograms must be correct, and if a program is incorrect, then one of its subprograms must be incorrect. The binary search algorithm works well for a logic programming language, such as Prolog, because it has no side effects. An execution of each procedure does not use values other than those that pass to it and does not define global values that it does not return. The presence of side-effects would disable the "halve the search space" scheme.

- Shahmehri, Kamkar, and Fritzon [SKF91] adapt Shapiro's algorithm to work with Pascal at the procedure-call level. However, it works under the assumption that no procedure call introduces side-effects.

- Korel and Laski's STAD [KL88] also uses a binary search heuristic, but the system posts a request for the programmer to verify the correctness of the flow of control instead of the correctness of the output values. Their technique works with a subset of Pascal at the intra-procedural level.

- Kuper's DEBUSSI [Kup89] also uses a binary search heuristic, but its break-and-examine point is the procedure call that lies nearest to the middle of the partial order determined by the program's data flow. If the procedure is called correctly, then everything that precedes it by data flow can be exonerated. One of DEBUSSI's limitations is the assumption that the program contains one bug only.

- Korel's PELAS [Kor88] uses immediate reaching definitions of variables as its guess on fault location. If a programmer judges that a variable has a correct value, PELAS would not consider the statements on which correct variables depend as possible fault locations.

2.2.4 Shortcomings in previous work in debugging

The first shortcoming is inadequate support to evaluate hypotheses about fault location. The assistance that allows the programmer to observe program behavior does not confirm or reject a fault location. To check whether faults lie in a suspicious program part, programmers can fix and rerun the program until they obtain correct output [Gou75, Ves85, ADS91a]. This can lead to the problem of *"fixation on the wrong location"* and can introduce more faults into the program.

The second shortcoming is that of inadequate support to formulate hypotheses about omitted statements and predicates. Program slicing [Agr91] and heuristics based on a combination of program slices [Pan93] can be used to identify possible faulty statements. It is up to the programmer to recognize that a slice omits some statements [Agr91]. An assignment statement that assigns a value to the wrong variable might not appear in the slice, because of the absence of dependency relations with the erroneous variables [Pan93].

A fault localization algorithm is not guaranteed to find the location of an omitted statement. As the algorithm uses correctness information to reduce the search space, the algorithm becomes inaccurate in the presence of coincidental correctness. An example of coincidental correctness is shown below:

```
Subroutine  F( X, Remainder)
begin
Remainder   = mod( X, 10)
end
```

Suppose both X and *Remainder* have non-error-revealing values before and after $F()$ is called, the binary search algorithm would rule out $F()$. However, if $F()$ is supposed to also compute *Quotient*, the algorithm would have discarded the faulty routine. Even for a fault of commission, coincidental correctness can also cause a fault localization algorithm to be inaccurate. Suppose X is error-revealing when $F()$ is called, but *Remainder* is coincentally correct (e.g., set to zero) after $F()$ returns. Korel's PELAS [Kor88] uses a data flow analysis to eliminate the statements preceding the correct variables from the list of possible fault locations. This means the statement that defines X incorrectly would have been ruled out.

It is possible to locate omitted statements when the code can be compared against a specification. Jackson's ASPECT [Jac93] uses a specification that depicts dependency among data to detect missing static dependency among variables in the program. One shortcoming is that the required specification may not be available. Another shortcoming is in the limitation of static analysis. ASPECT is not guaranteed to detect the absence of (1) a statement to establish dynamic dependency among data when a statement to establish static dependency is present, and (2) a statement to establish control dependency.

The third shortcoming is inadequate support to prevent the problem of *"fixation on the wrong location."* Section 1.2 describes this inadequacy in detail. There is no experimental evidence about other debugging assistants to indicate that any assistant can overcome this problem.

The fourth shortcoming is inadequate use of programmers' knowledge about the failure symptoms and about the program. Debugging assistants do not dynamically capture the programmers' expertise to enhance their capability. Although fault localization algorithms use programmers' knowledge about correctness of input and output values of a procedural call, that knowledge is not maintained for further analysis.

2.3 Related Work in Critic Systems

Our empirical studies (see Chapter 3) identify that a critic system can serve as an alternative assistant to a debugging oracle. A *critic system* takes the user's proposed solution and its problem as input, then produces comments on the solution as output. The comments may suggest improvements, draw attention to the possible risks, and indicate other alternative solutions. The purpose of the critic system is to support the user's own decision making rather than independently suggesting a solution to the given problem [Häg93].

A critic system provides a cooperative problem-solving environment. This environment combines the user's knowledge with the system's analytical power and knowledge to solve a problem. Unlike an expert system, the critic system does not derive the solution autonomously. In medicine, an expert system may take symptoms of the illness as input and produce a recommended treatment as output. A critic system would take the symptoms and the physician's prescribed treatment as input. It would then provide comments on the physician's prescribed treatment. It may also suggest an alternative treatment that is less risky or identify a lab test that can rule out diseases with similar symptoms.

Traditional critic systems are passive (user-invoked) and after-task [Sil92]. Such critic systems become operational after the user arrives at a tentative solution or decision. Some of the passive critic systems include: Miller's medical critic system *ATTENDING* [Mil83], Langlotz and Shortliffe's medical critic system *Oncocin* [LS83], Fischer's *LispCritic* [Fis87], Spickelmier and Newton's circuit designs critic [SN88], Fickas and Nagarajan's *Specification critic* [FN88], Zhou, Simkol, and Silverman's critic for antenna placement in ship design, *CLEER*, and [ZSS89], Löwgren and Nordquist's user interface critic *Kri/AG* [LN92].

Researchers [Sil92, FM91, Mil88, Rag91] found that to improve a critic system, it is desirable for the system to be active during the decision-making process and to offer unsolicited help before-, during-, and after-task. An active critic system helps prevent biases before they occur, helps correct the biases after they occur, and helps promote the use of a tool. In [Sil92], Silverman presents the results of his empirical study that compares passive and active critic systems for a statistical problem. This study involves over fifty statisticians and graduate students in statistics. The result shows that, without a critic system, 82% of the participants failed to solve a bias-prone statistical problem. With a passive and after-task critic system, 31% failed. With an active critic system, 0% failed.

Some of the active critic systems include: Fischer's kitchen design critic *KID* [FNO93], Raghavan's active decision support prototype *JANUS* [Rag91], Gertner's diagnosis/therapy plan critic *TraumaTIQ* [Ger93], and Silverman's *TIME* [Sil91]. *TIME* helps US Army personnel to write decision papers for each new piece of equipment the Army buys.

According to Hägglund [Häg93], existing critic systems use either an analytical critiquing method or differential critiquing method. In *analytical critiquing*, the system may not be capable of solving the problem, but it can analyze the proposed solution by looking for flaws. Guidelines or other standard criteria can be used to evaluate the user's proposed solution [Häg93, Ran93].

Fischer's *LispCritic* [Fis87] and Fickas and Nagarajan's *Specification critic* [FN88] are examples of critic systems that use the analytical critiquing. *LispCritic* cannot write, but it can evaluate, a Lisp program. LispCritic analyzes a Lisp program and suggests ways to rewrite the code to promote clarity and efficiency. Fickas and Nagarajan's *Specification critic* cannot write a formal specification, yet it analyzes a petri-net-like formal specification and generates sample scenarios to argue for or against the user intention to add certain components into the specification.

In *differential critiquing*, the system compares the user's proposed solution with the solution it derives. This is useful in well-structured domains where solutions can be evaluated according to objective principles. For example, the critic system may compare cost and resource consumption between the two solutions [Ran93].

Gertner's diagnosis/therapy plan critic *TraumaTIQ* [Ger93] is an example of a critic system that uses the differential critiquing approach. *TraumaTIQ* is designed to be used in connection with TraumAID, a consultation system for multiple trauma management. *TraumTIQ* comments on a physician's plan to handle multiple severe injuries. It addresses errors in scheduling treatments, conflicting procedures with TraumAID, unidentified goals (according to TraumAID) for the action ordered by the physician, and repetition of ordered action. *TraumTIQ* works with incomplete knowledge of the situation. Some diagnostic results may not have been reported yet. Thus, its comments on the physician's current plan may change as it learns more about the symptoms of the injuries.

Critic systems have been used in several domains in the past ten years, but not in the debugging. This dissertation presents an active critic system for debugging that also serve as an alternative to a debugging oracle.

2.4 Summary

This chapter presented terms used in the dissertation. Previous work in debugging was presented. Current debugging assistants provide inadequate support to evaluate hypothesis about fault location, inadequate support to formulate hypothesis on omitted statements, inadequate support to prevent the problem of "fixation on the wrong location," and inadequate use of programmers' knowledge of failure symptoms and of the program. Previous work in critic systems was also presented.

3. EMPIRICAL STUDIES OF DEBUGGING ASSISTANTS

Pure logical thinking cannot yield us any knowledge of the empirical world; all knowledge of reality starts from experience and ends in it. Propositions arrived at by purely logical means are completely empty of reality.

– Albert Einstein

A debugging oracle can verify hypotheses about fault identities, locations, and repairs. Our goal was to design an alternative to a debugging oracle that improved debugging performance. The objective of this study was to identify the types of oracle-provided assistance that could improve debugging performance. We could not test how an automated oracle provides assistance because an automated oracle does not yet exist. To resolve this problem, we treated the person who wrote and maintained the program under test as an oracle. This approach allowed us to study oracle-provided assistance without having to predefine different types of assistance. We could observe what help the programmers needed, what debugging problems the programmers experienced, and what oracle-provided assistance could satisfy the needs and overcome the problems.

Our first hypothesis was that the presence of appropriate information can help programmers judge the correctness of hypothesized fault locations significantly faster or more accurately [SV92]. Information we anticipated to be helpful included program slices and *beacons*, defined in Brooks [Bro83] as information that suggests the presence of a particular data structure or operation in the program.

These studies did not support our first hypothesis. However, their results led us to the types of oracle-provided assistance that could improve debugging performance.

3.1 Overview of the Studies

Three studies were conducted. They involved a total of 14 expert programmers who debugged a C program containing over 4300 executable lines of code that included faults of omission. In these studies, we used common experimental materials, experimental procedures, and performance measurements. The difference was in the type of assistance provided to the programmers.

3.1.1 Program

The program under test was *Nu*, a locally-developed Unix system administrator program for maintaining a user database. Nu was a screen-oriented program for adding new users, deleting old users and modifying information about existing users on departmental hosts. Nu's C source code consisted of one header file and 16 source files. Nu consisted of 167 routines. The total number of lines was approximately 6700. The total number of executable lines was 4320. Nu maintained five database files that amounted to approximately 1600 lines of data.

3.1.2 Faults

Two faults under study were faults of omission that were found and fixed during the maintenance phase of the program *Nu*.[1] Fault #1 was a missing initialization statement. This fault left a pointer uninitialized, causing the program to terminate abnormally. Fault #2 was a missing data handling task. This fault left a pointer pointing to a copy of a database entry rather than to the original entry. When the program freed the copy and later re-allocated the same space, that space was written over. Ultimately, the program failed by producing wrong output.

[1]See Appendix A.1 (page 133) for more details.

3.1.3 Participants

Expert programmers in our study satisfied six requirements. First, they had at least six years of programming experience. Second, they had used C for at least five years. Third, they had spent at least three years as graduate students in the Department of Computer Sciences at Purdue University. Fourth, they had taken at least three classes that required them to use the C language. Fifth, they had previously coded C programs larger than one thousand lines. Sixth, they knew how to use a debugger, dbx, which offered assistance to set break points and to trace the program execution.

3.1.4 Procedures

Programmers were divided into groups of two. Although the types of assistance for each group varied, the experimental procedures for all groups were the same. At the beginning of the session, programmers received the source code listing of Nu, its data files, the failure description, and one error-revealing test case. Programmers ran Nu under SunOS version 4 in the X window environment. Only one debugger, dbx, was allowed. They were required to use *tcsh*, a C shell that monitors the time of day that each commands was issued.

At the end of each hour, each programmer electronically submitted a script of the debugging session, along with his hypotheses about fault location, identity, and repair. The debugging session ended when a programmer fixed the fault or when he exceeded the five-hour time limit. We interviewed each programmer after the debugging session.

3.1.5 Measurements

The debugging performance measurements we used were (1) actual debugging time, (2) estimated time taken to find and to fix the fault, (3) debugging speed, (4) accuracy, and (5) average accuracy of the hypothesized fault location at the end of each hour. Appendix A.2 lists the definitions of these measurements.

3.2 Pilot Study #1

3.2.1 The assistant

The assistant was an oracle: the Unix system administrator who maintained the program Nu. He could answer any questions from the programmers except "What is the fault?", "Where is the fault?", and "How can it be fixed?". We nevertheless refer to this feature as the *all-you-can-ask* feature.

3.2.2 The study

We studied the programmers' abilities to find and fix the fault. This study compared groups of programmers with and without oracle access. Eight programmers who participated were called S_1 to S_8. We randomly assigned two programmers to each fault-assistant combination. S_1, S_2, S_3, and S_4 worked with fault #1; S_5, S_6, S_7, and S_8 worked with fault #2. Only S_3, S_4, S_7, and S_8 had oracle access.

To prevent any eavesdropping, the oracle was in the room next to the programmers' room. Programmers with oracle access worked in different rooms from those without access. We observed them to make sure they did not interact.

3.2.3 The results

The performance comparison is shown in Appendix A.3. Programmers who debugged fault #1 debugged faster and more accurately than those who debugged fault #2. The statistical analysis result indicates with at least 95.5% confidence that the fault was the source of variation in our five measurements.

The analysis result did not indicate that the oracle helped improve debugging performance. The result was insufficient to determine whether information that the oracle provided helped the programmers because the programmers asked very few questions. S_3 and S_4 each asked only 2-3 questions. S_7 and S_8 only asked 19 and 11 questions, respectively. One problem was that the oracle in this study was passive most of the time. He provided information only after the programmer requested help. To find evidence to support our original hypothesis, we decided to conduct a follow-up study with an active oracle.

3.3 Pilot Study #2

3.3.1 The assistant

We extended the role of the oracle for Nu to allow him to take the initiative. He could observe, question, warn, and give information without the programmers' requests. We refer to this oracle as an *active oracle*. We refer to the oracle in the previous study as a *passive oracle*. The oracle was still the same person, however.

3.3.2 The study

We only studied fault #2 in this study because students who debugged Nu with fault #1 easily found and fixed it with no assistance other than *dbx*. We studied two more programmers, S_9 and S_{10}. The active oracle worked with S_9 and S_{10} on a one-on-one basis.

To stimulate the programmer to ask more questions, the oracle sat next to the programmer and gave a program overview and a failure overview at the beginning. His location not only permitted him to observe the programmer's progress and take the initiative, it also made the oracle easier to access. His overview established a context for the programmer to ask questions. The program overview described the general functions of Nu, the input and output, the global data variables, and the data files. The failure overview described an error-revealing test case, the nature of the failure, and the description of other failing conditions. The oracle also went through a sample run of an error-revealing test case.

After the oracle's overview, the session was open for questions and answers both ways. The performance of S_9 and S_{10} was compared with that of S_5 and S_6 who received no assistance and that of S_7 and S_8 who received assistance from the passive oracle.

3.3.3 The results

The active oracle succeeded in helping programmers debug twice as fast as those with the passive oracle. The comparison of the performances of all programmers who debugged fault #2 is shown in Appendix A.3. We used Analysis of Variance (ANOVA) to statistically analyze these on debugging performance measurements. ANOVA indicated with at least 96.7% confidence that the source of difference in accuracy measurements between the group with Nu's active oracle and the group with no assistant was the use of the active oracle. The result also indicated with at least 97.3% confidence that the source of difference in speed between the group with Nu's active oracle and the group with no assistant was the use of the active oracle.

The active oracle also increased the number of programmers' questions seven-fold. Based on our observation, we identified features of the active oracle that may have been responsible for the improved debugging performance.

1. The confirmation feature

   To respond to a confirmation request, the oracle indicated "yes" with reasons why, or "no" with criticisms. To indirectly criticize, the oracle asked a programmer to justify the programmer's decision. When a programmer gave his reasons, the oracle argued why they were wrong. In many cases, a programmer found his own flaws as he tried to explain. To directly criticize a programmer's decision, the oracle explained why he was against it. Note that the oracle's reason was not a proof of correctness. Rather, it gave the programmers reasonable doubt.

2. The explanation feature

   Although answers to the explanation requests varied, the answers to requests concerning program behavior deserved attention. Because such requests were often phrased as a "What-If" question (e.g., "What happens when (specified condition) occurs?"), the answers were both actual and hypothetical. The behavior was often explained in terms of the consequence of the specified conditions. One sample question was "What would the program do if it received the abort command at the top-level?".

3. The observation-and-action feature

   This feature helped to remedy or prevent potential problems that could affect debugging performance. Observation enabled the oracle to recognize events that called for his initiative. The action combined the use of questions and the use of hints. We categorized the event-and-action pairs, or *rules* into three classes: remedial rules, preventive rules, and promotional rules.

   (a) *Remedial rules*

      When the oracle recognized events suggesting potential problems, he took remedial action. The events may have suggested that a programmer suspected a wrong location, focused on irrelevant code, settled on a repair with faulty side-effects, or misunderstood the program.

      The remedy often began with a question, followed by a hint. The oracle asked questions to confirm his suspicion of the problem, to determine the programmer's assumptions and justifications, and to enforce schemes to overcome his fixations. The information was provided later, as the oracle argued with his justifications, answered his questions to resolve misunderstandings, and suggested alternatives.

(b) *Preventive rules*

The oracle recognized an opportunity to prevent commonly occurring problems. His preventive action was to ask a programmer to consider certain hints.

The oracle helped prevent a programmer from reviewing part of the program that was irrelevant to the fault and the failure. He gave an overview of the program before a programmer began to debug it. The oracle also helped prevent a programmer from reimplementing an existing routine. He asked a programmer to look at a source file file that contained a procedure that could perform the missing task. Both programmers immediately recognized the procedure they could reuse to repair fault #2.

(c) *Promotional rules*

The oracle recognized the opportunity for a programmer to use certain tools or features to improve his debugging time or accuracy. His action was to stimulate him to use the features.

For example, when a programmer did not make any fault-related decisions for a while, the oracle asked questions to stimulate a programmer to make hypothetical decisions. This gave the oracle more opportunities to describe the consequence of such decisions. Sample questions included: "What are the possible causes of failure?", "What is the correct value of this variable?", "How could the problem be fixed?".

The findings from this study did not support our first hypothesis. In our hypothesis, we assumed that information alone provides the necessary assistance. If this assumption were true, then the explanation and hints from the oracle would be sufficient. Perhaps S_9 and S_{10} performed better than $S_5 - S_8$ because they asked more and knew more. Perhaps the location of the active oracle alone, not the oracle's questions, was the factor that encouraged the programmers to ask more questions. To resolve this uncertainty, we devised two alternatives for an active oracle and tested them in our follow-up study.

3.4 Pilot Study #3

3.4.1 The assistants

In place of the all-you-can-ask feature, we summarized debugging information from previous studies into a set of hints. These hints were intended to help the programmers understand the program, formulate better fault-related decisions, and self-criticize their decisions.

We acted as the assistant. For one group, we provided *Information-only (I-only) assistance* by giving all hints simultaneously. The hints included a program overview, a failure overview, a test data set, output statements, data abstractions of erroneous data, a routine-level trace, a calling path, and dynamic slices of output variables.[2]

For another group, we provide *Observation-Information-Question (OIQ) assistance* by giving away both hints and questions when one of the four events below was observed. We looked for these events from the reports the programmers submitted electronically at the end of each hour. The hints provided after each event were the same as the hints in I-only assistance.

Event 1: A programmer entered the fault-finding phase.

> First, we gave the overview verbally. Afterward, we asked "What are the erroneous output variables (if any)?" and gave the statement that printed the erroneous output. Once the programmer identified the erroneous variable(s), he received the calling paths, the dynamic slices, and the routine-level trace of that variable(s).

[2]Our paper [SV93] describes these hints in more detail.

Event 2: A programmer suspected a wrong location.

If this event occurred after the programmer already had time to review the hints, this event would trigger us to suggest a strategic inspection of the trace. We made the programmer inspect the routine-level trace while we repeatedly asked "Is this program state correct?".

Event 3: A programmer claimed that he fixed the fault.

This event would trigger us to ask "Does your fix work with other test cases?" and to give the test data description. This question was repeated for each combination in the description.

Event 4: A programmer identified the missing task.

This event would trigger us to ask "Do you know of any existing code to fix the problem?" and to introduce the data abstraction of the erroneous global data that contained the reusable routine.

3.4.2 The study

We studied four more programmers: S_{11}, S_{12}, S_{13}, and S_{14}. S_{11} and S_{12} received the OIQ assistant. S_{13} and S_{14} received the I-only assistant. All four programmers worked with the second faulty version of Nu.

For both groups, we gave a 15-minute verbal overview first. For S_{13} and S_{14}, we gave all hints at once and allowed them to work on their own. For S_{11} and S_{12}, we gave the hints and asked questions about the hints gradually as we observed the trigger events. Afterward, we surveyed the programmers on the helpfulness of the assistance.

3.4.3 The results

The group that received the OIQ-assistance debugged almost as fast as the group that received the assistance from the active oracle. The group which received the I-only assistance performed worse than the group with no assistance.

The statistical analysis indicated with at least 96.7% confidence that the group with the OIQ assistance found and fixed the fault more accurately than the group with no assistance. The analysis result also indicated with at least 96% confidence that the group with the OIQ assistance debugged Nu faster and located the fault more accurately than the group with the I-only assistance.

The group with the OIQ assistance performed almost as well as the group with the active oracle. With the OIQ assistance, the programmers took about $2\frac{3}{4}$ to $3\frac{1}{4}$ hours to arrive at the right solution – about 15 - 45 minutes longer than the group with the active oracle. Their performance differences were not statistically significant.[3]

The group with the I-only assistance took longer to derive wrong solutions than the group with no assistance. Programmers in both groups settled for solutions which repaired the failure symptoms rather than the cause of the program failure. As a result, the repair introduced new faulty side-effects. However, with the I-only assistance, the programmers took about $3\frac{1}{2}$ to 4 hours – about twice as long as the group with no assistance.

3.5 Debugging Pitfalls

We observed two major pitfalls. One was the "fixation on the wrong location" problem; the other was the "underuse" problem. The first hindered the debugging process. The second hindered the effectiveness of debugging assistance. This study provided some insight as to why the problems occured.

[3]The term *significant* in statistics means the p-value (produced by statistical analysis such as ANOVA, contrast analysis, etc.) was less than .05. The p-value indicated the chance that a given outcome was a function of the technique employed rather than a result of chance. The p-value $\leq .05$ means there is no more than 5% chance that the outcome might have occurred by chance alone [WL79].

3.5.1 The "Fixation on the wrong location" problem

Eight out of fourteen programmers experienced this problem. A review of the debugging process and follow-up interviews revealed three causes of this problem.

The first cause was that the programmers with the passive oracle assistant did not make their requests to confirm a fault location until they spent time investigating the code at that location. According to our follow-up interview, we asked the programmers why they delayed making a request confirmation on fault location. The common response was that they were sure they already found the fault, therefore they found it unnecessary to request confirmation.

The second cause was that the programmers chose a poor starting point. Programmers who did not start to debug by identifying erroneous output variables were more likely to develop a fixation on a wrong location than programmers who did.

The third cause was that the programmers mistook the location with the failure symptoms for the fault location and ended the search for the fault prematurely. When the repair was made at the location that exhibited failure symptoms instead of at the fault location, the repair was prone to create other faulty side-effects.

In the case of fault #2 (see Appendix A.1), the absence of the code to reset the pointer before freeing it caused another pointer to become dangling. That dangling pointer caused the same memory location to be reallocated and overwritten. Four programmers found the routine that wrote over the old memory location, and concluded that the routine was faulty. Their repairs masked the old failure symptoms, but created new ones.

3.5.2 The "Underuse" problem

Programmers did not benefit from our passive assistants – the passive oracle and the I-only assistant – because of underuse problems. One underuse problem occurred when programmers underused the assistants that could have help them debug. The programmers did not really know how to use an intelligent, but passive, assistant such as an oracle. They admitted they did not always know what to ask for, or when to ask for it even when they needed help (e.g., when they were stuck at a wrong location). Programmers with the I-only assistant did not always know how to assimilate debugging hints. One of the programmers used only one hint and ignored the rest.

Another underuse problem occurred when the assistant underused the knowledge of the programmers that could have helped the assistant customize the assistance for each programmer. The passive oracle underused the knowledge of the programmers because he could not observe them. He would not know that the programmers misunderstood something until they asked for help. Thus, he was unable to resolve their misunderstandings early enough to prevent them from wasting their time.

We underused the programmer's knowledge when we provided I-only assistance. Programmers who received the OIQ assistance had to identify erroneous output variables. In turn, we only provided hints related to the erroneous variables they identified. Because we did not ask the programmers who received the I-only assistance to identify erroneous output variables, we gave hints related to all output variables.

3.6 Programmers' Needs

Programmers needed and asked for help to confirm their hypotheses. They needed, but did not frequently ask for, help to formulate their fault-related hypotheses.

1. Need for confirmation

   Confirmation requests constituted 86% of the total requests that programmers who debugged fault #2 made to the oracle (see Figure 3.1). Each confirmation request was either a hypothesis statement or a yes-or-no question. Explanation requests (e.g., the "what," "when," "where," "why," and "how" questions) made up the other 14%.

   One of the first two questions programmers asked the passive oracle was for confirmation of the fault location. Other questions followed after the oracle rejected the location. The request to confirm the fault-related hypotheses constituted two out of three requests from programmers who debugged fault #1; and one out of every seven requests from programmers who debugged fault #2.

We noticed that expert programmers preferred to arrive at a tentative decision or understanding before they asked for help. This coincided with psychological research by Lange and Harandi [LH85] which suggests that expert users prefer to solve the problem on their own first before they consult an expert system.

2. Need for help to formulate fault-related hypotheses

   Programmers needed help to formulate fault-related hypotheses. The percentage of rejected fault-related hypotheses was 40%. In comparison, the percentage of rejected program understanding-related hypotheses was only 23%. None of the hypotheses about correctness of program behavior and data values were rejected.

3.7 Desirable Debugging Assistance

3.7.1 Self-assistance

As we anticipated, we observed that programmers in our studies looked for beacons to gain understanding about the program. This result agreed with Brook's observation [Bro83]. However, the programmers did not request that information from our assistants. Instead they used a pattern matching command in Unix, *grep*, to locate the beacons. The *grep* command finds the text lines in the specified files that match the given name or expression [Pla86]. Next to *dbx*, *grep* was the most frequently used command. This phenomenon suggested that instead of providing beacons as assistance, a debugger could provide a pattern matching tool to look for beacons.

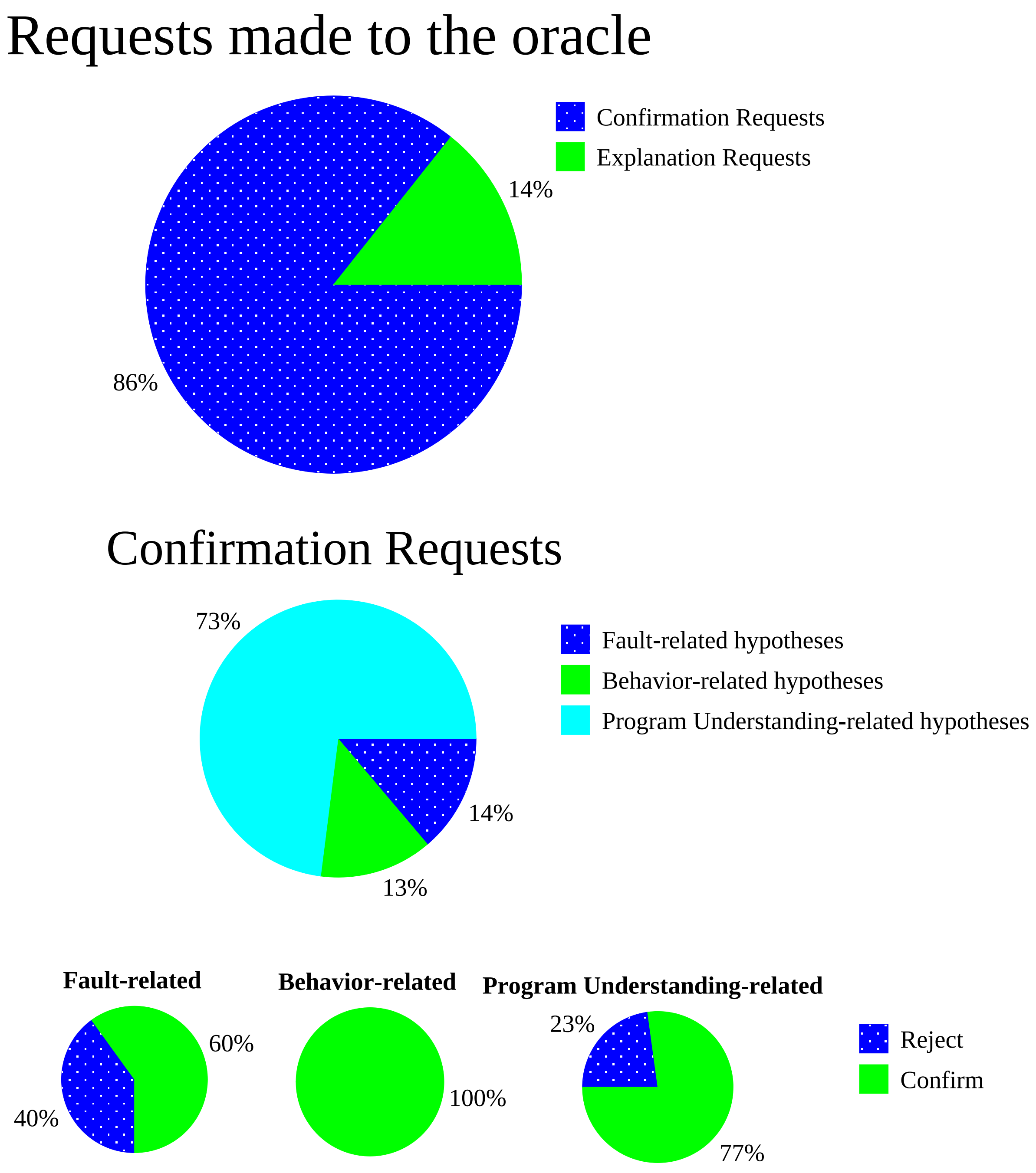


Figure 3.1 The requests made to the active and passive oracle in pilot study #1 and #2

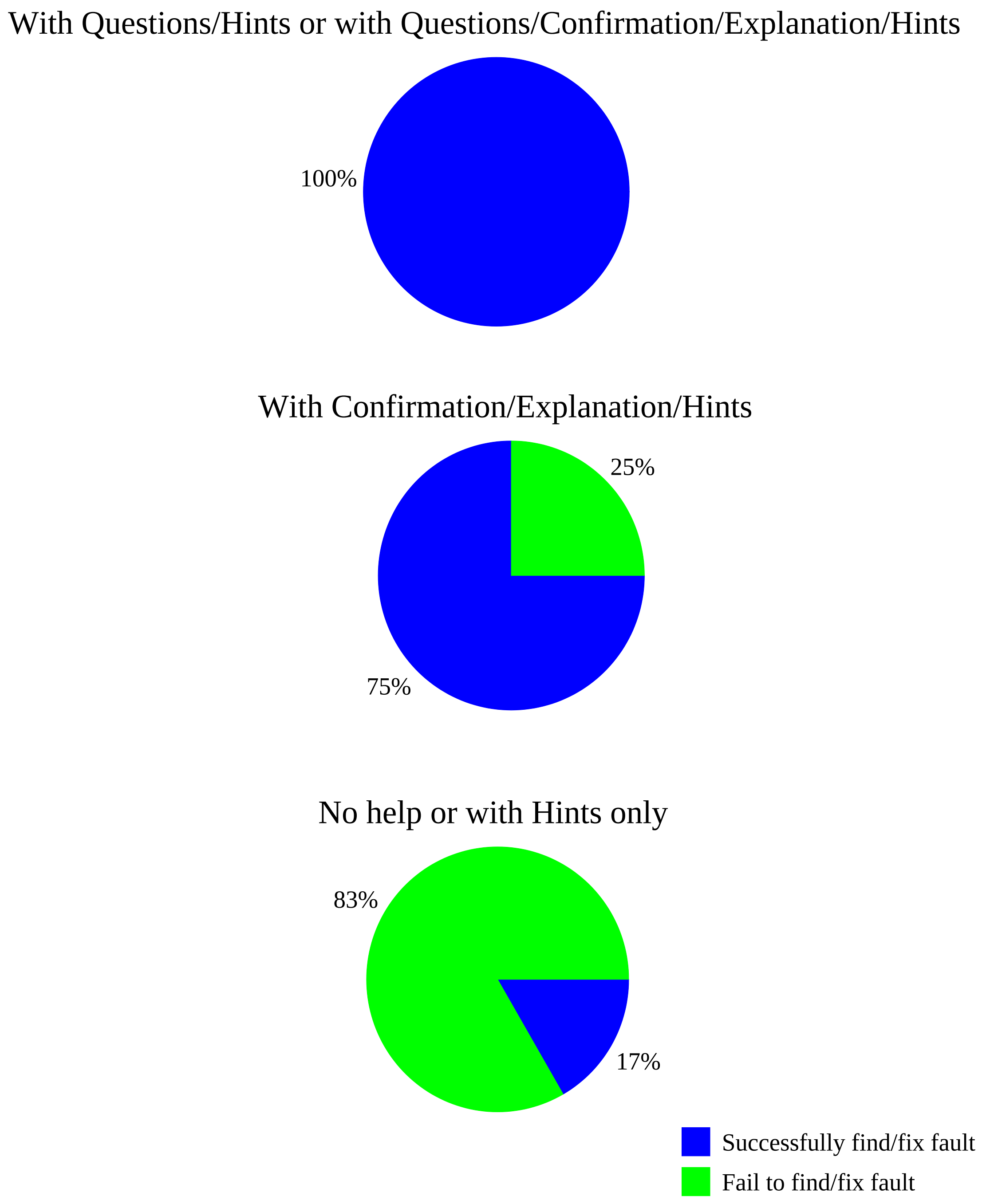


Figure 3.2 Percentage of programmers who found/fixed the fault

3.7.2 Assistance from assistants under test

The two active assistants that worked were the active oracle and the OIQ assistant. Both helped overcome the fixation and the underuse problems. When compared with the passive oracle, the active oracle increased the number of programmers' questions sevenfold. When compared with I-only assistance, the OIQ quadrupled the number of hints programmers used.

3.7.2.1 Confirmation

This feature helped confirm or reject hypotheses. The purpose was not to prove a hypothesis, but to present a convincing argument as to why a hypothesis was true. To reject a hypothesis about a fault location, the oracle often used dependency information. The common argument was that the failure did not depend on the code at the specified locations. To reject a hypothesis about a fault identity, the oracle often explained why the failure was not the consequence of such a fault. To reject a hypothesis about a fault repair, the oracle identified the undesirable consequence and the test conditions under which the program would fail.

3.7.2.2 Explanation

This feature accompanied the confirmation feature, as the explanation was embedded in the argument for or against the hypothesis. The explanations which the programmers frequently requested were about the consequence of a specified condition on the program behavior.

3.7.2.3 Hints

This feature helped the programmer formulate hypotheses. According to our survey, the following hints helped to formulate fault-related hypotheses.

For formulating hypotheses about fault location, the programmers indicated that slice-related hints helped programmers most. In order of preference, these hints were the routine-level trace, the calling path, and a dynamic slice of an erroneous output variable. A routine-level trace could be considered as a slice through an execution path of the program. A calling path could be considered as a routine-view of a dynamic slice. These hints helped them narrow the search for the fault.

For formulating hypotheses about fault identity, the programmers identified the three hints that helped them most as the failure overview, the routine-level trace, and the statement that printed the output. These hints helped enhance their understanding of the failure symptoms, which subsequently helped them hypothesize about possible causes of the symptoms.

For formulating hypotheses about fault repair, three hints that helped were the test data description, the data abstraction of erroneous data, and the routine-level trace. Test data and the routine-level trace helped them recognize the impact of a repair. The data abstraction of erroneous data helped them identify reusable code.

All programmers who received the hints indicated that they could not have debugged as fast (if at all) without them. But while hints worked well when we posed questions to help assimilate them, hints alone did not guarantee debugging improvement, as evidenced by the performance of the I-only group.

3.7.2.4 Questions

Questions played three major roles: preventing problems, remedying problems, and promoting the use of the assistant. They helped overcome both the "underuse" problems and "fixation on a wrong location" problem. They also promoted the use of an oracle (by stimulating the programmers to ask more) and the use of the hints in the OIQ assistant. As shown in Figure 3.2, in the groups where the assistant could take the initiative by questioning the programmers during the debugging process, 100% of the programmers correctly identified the fault location. In comparison, in the group that received no help in evaluating hypothesized fault locations, only 17% of the programmers succeeded. In the groups of programmers provided with confirmation, explanation, and hints from a passive oracle, 75% of the programmers succeeded. This result is strikingly similar to Silverman's results [Sil92] which support the need for an active assistant (see Chapter 2).

The roles of questions varied according to the event that triggered the assistant to pose the questions. Three types of questions that helped overcome debugging problems were as follows.

1. *Remedial questions*

   We observed two types of questions that remedied the "fixation on a wrong location" problem. One was the request for the programmer to justify why he hypothesized at a location that did not affect the program failure. Another was the request for the programmer to evaluate the value of erroneous variables in the execution trace prior to the execution of the code at his hypothesized location.

   These questions helped remedy the fixation problem in the following ways. First, when the programmer could not justify why he examined a particular location, the oracle had an opportunity to explain why the location he suspected could not affect the program failure. Second, when the programmer realized that a variable value was erroneous before the execution of the routine he suspected, he overcame his fixation and looked elsewhere.

2. *Preventive questions*

   We observed that questions pertaining to the variables or routines that exhibited failure symptoms helped prevent the "fixation on the wrong location" problem. When programmers asked a series of irrelevant questions, the oracle asked a programmer to explain a routine or a variable relevant to the failure. Sample questions included: "What is the role of the (specified variable)?", "What happens when the (specified condition) occurs?", and "What does this routine do?". Unable to reply, the programmer requested an explanation. In most cases, the oracle's questions were sufficient to shift the programmer's attention. To end a series of irrelevant questions in one case, the oracle also gave as a hint a calling path to the procedure that used an erroneous variable.

In the OIQ assistant, we prevented the problem by asking programmers to identify erroneous output variables before they started to debug. We gave overview hints and the output statement to help them answer. Based on the erroneous variable identified, we gave the appropriate routine-level trace, a calling path, and a dynamic slice.

3. *Promotional questions*

We observed that questions which promoted the formulation of fault-related hypotheses and the use of hints helped overcome the "underuse" problems. When programmers did not ask for help, the oracle asked them to propose fault-related hypotheses with questions such as: "What could possibly cause this failure?", "What is the correct value of the variable?", and "How could the problem be fixed?". This gave the oracle the chance to evaluate the programmer's hypothesis and eliminate some misunderstanding. In the OIQ assistant, questions promoted the use of hints. They promoted the use of the data abstraction hint and the test data set. Although both hints were used by the oracle to help programmers find the right repair, they were ignored by programmers with the I-only assistance. We successfully promoted use of the data abstraction hint by asking whether a programmer knew of existing code that would repair the missing task he identified. We successfully promoted use of the test data set by asking whether their repair worked with other test cases.

3.7.3 Assistance for debugging fault of omission

Programmers in our study suggested that the fault location for omitted statements was the location where they added the statements. However, there could be more than one place in a procedure where statements could be added to repair the same fault. Neither the location nor the repair for a fault of omission were unique.

For fault #1, the use of dbx and grep commands were sufficient to locate the routine that was missing an initialization statement. Dbx's *where* command identified routines and source files in the calling path leading to the point when the program abnormally terminated. Dbx's *print* command revealed an undefined value of pointer *pde*. The grep command on *pde* and other keywords in files specified by the *where* command assisted in locating the routine that should have initialized pde. As programmers traced through this routine, they realized that none of the existing initialization statements for *pde* were executed. Hence, they knew they found the fault location.

Numerous repairs for fault #1 included adding the initialization statement for *pde* at the beginning of the routine, adding code to check for null pointer before passing *pde* to a routine, etc. The code could also be restructured to allow the flow to reach an existing initialization statement for *pde*.

For fault #2, the assistants helped programmers to locate fault #2 by repeatedly asking them to verify the correctness of the erroneous global variable *pde* in a structure *home_dir_list* in the routine-level trace. The question led to the location below where the value of the variable *pde* was first found erroneous.

```
568:   delete_home_dir( start_pde, NULL);
569:   free_pde(pde);
```

The memory location being freed at line 569 was also pointed to by global *pde* in a structure *home_dir_list*. Before the execution of the statement at line 569, *pde* in *home_dir_list* was correctly pointed to a memory location. After the statement at line 569 executed, *pde* in *home_dir_list* became a dangling pointer. Once the programmer recognized that the same pointer changed its status from correct to erroneous because its value was not reset, he realized that code to reset *pde* in *home_dir_list* was missing in between line 568 and line 569. In short, he recognized a symptom of omitted code, which was *the value of the variable was not changed, but its status changed from a correct value to an erroneous value.*

Numerous repairs for fault #2 included adding code to reset the pointer, or adding a calling statement to *change_home_dir()* which handles this task. The data abstraction hint, which encapsulated the routines that operated on the record to which *pde* points, helped a programmer find the right repair. However, this hint alone was not sufficient. It only worked when the assistant also asked whether the programmer knew about existing code to handle the task.

3.8 Summary

The results suggested a more direct approach to provide alternative support for a debugging oracle. The oracle in this study rejected a hypothesis about a fault location by arguing that the failure did not depend on the code at the specified location. Thus, knowledge of program failure and dependency analysis could be used to confirm/reject a hypothesis about fault location.

Our results did not support our first hypothesis which stated that the presence of appropriate information can help programmers judge the correctness status of hypothesized fault locations significantly faster or more accurately. Providing more information alone was inadequate to increase the speed of the debugging process. Available information was useless when the programmers did not ask for it, did not know what to ask for, or did not know how to assimilate it.

Instead, our results indicated that an active debugging assistant is effective. Four types of desirable assistance are confirmation, explanation, hints, and questions. Questions play three roles: (1) remedy problems, (2) prevent problems, and (3) promote the use of the debugging assistant. To support these roles, the assistant has to know which questions to pose and when to pose them.

We observed two major problems to remedy and to prevent. They were the "fixation on a wrong location" and the "underuse" problems. To overcome these problems, both the assistant and the programmer could take the initiative. The assistant could improve its effectiveness by learning what the programmer knows and customizing its assistance to augment that knowledge.

The next chapter describes the types of systems that match the desirable characteristics of a debugging assistant. We design a new debugging assistant, a debugging critic, on the basis of these results.

4. DEBUGGING CRITIC

critic n. [One who makes adverse comments] faultfinder

– Webster's New World Thesaurus

An alternative to a debugging oracle is an assistant that answers the question "Is it conclusive that the statement at location $\mathcal{L}$ contains the fault that was manifested under the given test case t?" One approach to answer this question is to check all statement occurrences against a specification. Because a line-by-line specification is usually unavailable, this approach is infeasible.

Our empirical studies suggest an alternative approach. Given knowledge about how the program fails and a hypothesis about fault location, the assistant determines whether the statement at the given location causes the failure. The system that takes a problem and its tentative solution as input and produces comments on the solution as output is classified as a *critic system.*[1]

This chapter presents an overview of our debugging critic, its underlying supports, and its approaches to evaluate and formulate hypotheses about fault locations. A sample session with a debugging critic is also presented as an illustration. The implementation of a prototype of a debugging critic is presented in Chapter 5.

4.1 Overview of the Debugging Critic

A *debugging critic* is a system that takes knowledge about how the program fails and a fault-related hypothesis as input, then produces a confirmation, a rejection,

[1]See Chapter 2 for more details.

or an argument why the hypothesis may or may not hold as output. A fault-related hypothesis is a hypothesis about fault location, fault identity, or a fault repair.

4.1.1 Functions of a debugging critic

Our debugging critic works with hypotheses about fault location. It uses the differential critiquing approach,[2] which means our critic derives its own hypotheses from the given failure symptoms, compares the programmers' hypotheses with its own, and comments on the differences. Therefore, our debugging critic has two primary functions:

1. To evaluate a hypothesis about a fault location, and

2. To formulate hypotheses about fault location.

As a debugging assistant, our debugging critic should help improve debugging speed. Thus, its secondary function is to help avoid the "fixation on the wrong location" and "underuse" problems.

Our debugging critic can function with an incomplete knowledge of failure symptoms. It does not require knowledge of all the erroneous variables and all the erroneous control flow to support its functions. As it acquires more knowledge about failure symptoms, it can formulate more accurate hypotheses about fault locations.

4.1.2 Design of a debugging critic

A debugging critic can be designed as a passive assistant or as an active assistant. If a debugging critic is passive, then it may take as input an error-revealing test case t, failure symptoms, and a hypothesized fault location $\mathcal{L}$. It may (1) confirm $\mathcal{L}$ as a fault location, (2) reject $\mathcal{L}$, or (3) explain the conditions under which $\mathcal{L}$ may or may not contain a statement with a manifested fault. If the debugging critic cannot

[2]See Chapter 2 for definition.

confirm *loc*, it formulates an alternative hypothesis about a fault location and hints that location to the programmer.

If a debugging critic is active, it can also take the initiative. The use of questions is the key to making a debugging critic active. The critic's questions can be designed to prevent biases before they occur, help correct the biases after they occur, and promote tool use. Bias in debugging occurs when the programmer develops a fixation on a wrong location. Thus an active debugging assistant may help avoid both the "fixation on the wrong location" and "underuse" problems. Because our studies (see Section 3.7) showed that an active assistant improved debugging performance, but a passive assistant did not, we chose an active critic.

Our active debugging critic is designed to provide a cooperative problem-solving environment. This environment features confirmation, explanation, hints, questions, and a pattern matching tool.

Confirmation

In order to confirm a hypothesis about a fault location, our debugging critic evaluates an execution occurrence of code at $\mathcal{L}$ to determine whether the occurrence reveals a manifestation of a fault. Characteristics of such an occurrence are defined in Section 4.2.3.1 and Section 4.2.3.2.

To reduce the number of occurrences to evaluate, our debugging critic analyzes failure symptoms to define and to maintain search spaces for possible occurrences that could have caused the failure symptoms. These search spaces are defined in Section 4.3.3.

Hints

When our debugging critic cannot confirm that a manifested fault is at the hypothesized location, it can identify the code whose occurrences likely cause one of the known failure symptoms. To identify on which statement occurrence a symptom depends, our critic uses the dependency analysis (defined in Section 4.2.2) to analyze the failure symptoms (defined in Section 4.2.1).

Explanation

When our debugging critic cannot confirm that the fault is manifested in the evaluated occurrence, it explains whether unevaluated occurrences of the code at $\mathcal{L}$ can possibly cause the known failure symptoms.

Questions

Our debugging critic poses questions that can help evaluate a hypothesis as well as avoid the "fixation on the wrong location" and "underuse" problems. Questions include:

Acquire knowledge about failure symptoms

Instead of requiring the programmer to learn a special format to describe failure symptoms, our debugging critic uses questions to incrementally acquire knowledge about specific failure symptoms. The internal representation for failure symptoms can be derived from the programmer's answers.

Evaluate a statement at a hypothesized fault location

Questions to evaluate a statement and its occurrences are referred to as *evaluation questions*. The replies to evaluation questions determine whether a statement occurrence is fault-manifesting, new failure symptoms are found, or old symptoms should be updated.

Prevent the "fixation on the wrong location" problem

To encourage the programmer to inspect failure symptoms in the output first, the critic asks the programmer to evaluate the output statements at the beginning of a debugging session.

Remedy the "fixation on the wrong location" problem

If a programmer suspects a statement that does not execute in the search space, our debugging critic uses questions and explanations to remedy the problem. For example, suppose the hypothesis is about a location $\mathcal{L}$ that contains an unexecuted assignment statement in a static slice of an erroneous variable *var*. Our debugging critic poses the question *"The statement at $\mathcal{L}$ is not executed by this test case. Should it be? If so, it could have affected the value of an erroneous variable var,"* before it rejects $\mathcal{L}$ and recommends an alternative location.

Prevent the "Underuse" problem

To prevent the assistant from underusing the programmer's knowledge, our debugging critic acquires failure symptoms via evaluation questions. To prevent the programmer from underusing our debugging critic, our debugging critic promotes its usage with questions. These questions are asked when (1) our debugging critic's evaluation result does not yet identify the fault location or (2) when the programmer does not formulate a hypothesis for our debugging critic to evaluate within a prespecified time period. Examples of promotional questions are: *"Would you like to guess again?"*, *"Do you wish to continue evaluating line 10?"*, *"Would you like me to make another suggestion?"*, *"Would you like to examine my suggested location? I can automatically set break points for you."*

To communicate with a programmer, our debugging critic has access to a *dialogue-base* which contains our debugging critic's comment templates, question templates, and actions to be taken for each answer. Customized comments and questions can be generated from the template.

A pattern matching tool

This tool is offered to promote the use of the programmer's expertise in fault localization. The programmer can use this tool to look for patterns or beacons that, according to his expertise, may be associated with the fault location.

The conceptual model of our debugging critic, with components discussed in this section, is shown in Figure 4.1.

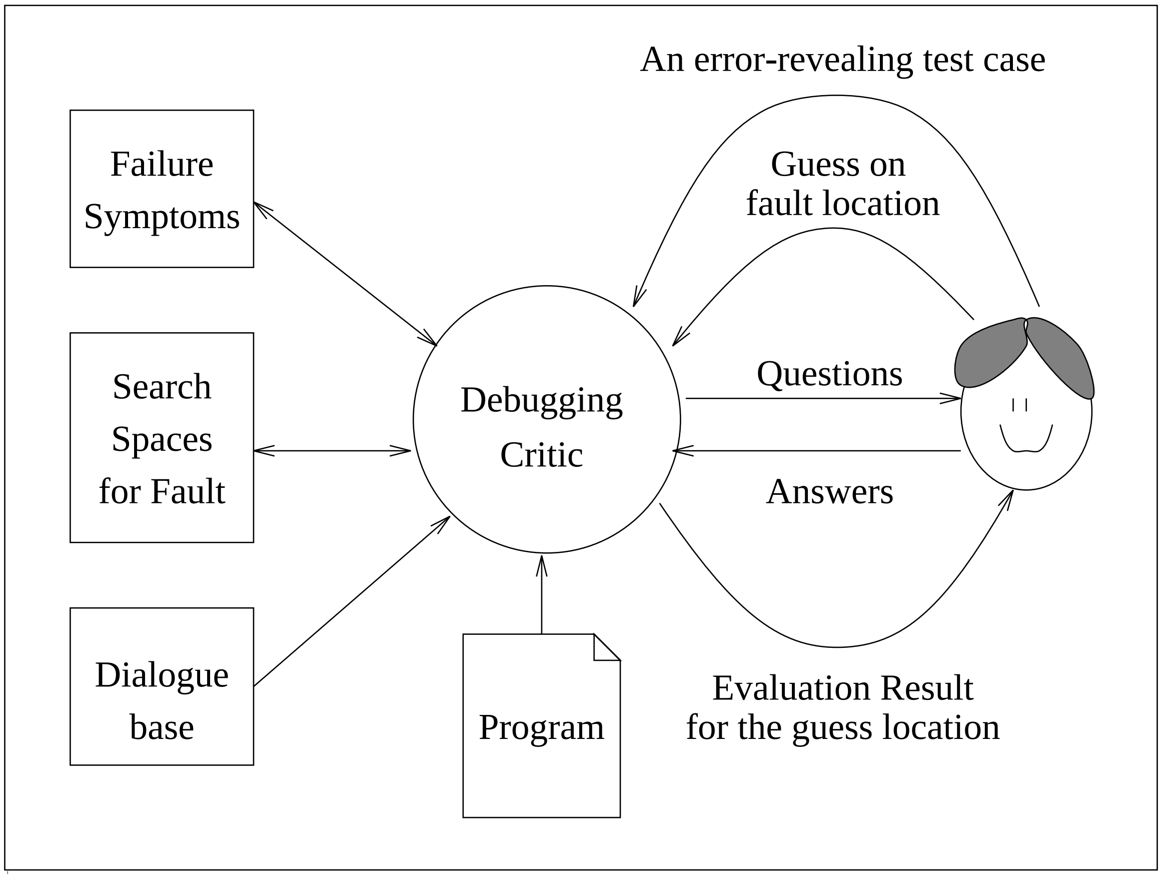


Figure 4.1 A concept model for a debugging critic

4.1.3 Scope

Our debugging critic evaluates five types of statements: (1) simple assignment, (2) procedure call, (3) predicate, (4) input, and (5) output. The line number is used to denote a statement location. A procedure name is used to denote a location with omitted statements. We assume a statement does not have a function call "nested" in its expression that can cause side-effects.

Our debugging critic operates under the assumption that only one fault is manifested with respect to a given test case. The program itself can contain multiple faults. An omission of multiple statements is treated as one fault if the missing statements are supposed to handle the single task of defining one variable.

Our debugging critic can recognize a statement with either a fault of commission or a fault of omission (e.g., missing dependency statement). Depending on the programmer's replies to our debugging critic's questions, an incomplete predicate may be recognized as either a fault of commission or a fault of omission. Our debugging critic recognizes the statements that are placed in the incorrect sequence as either faulty or extraneous statements.

Our debugging critic formulates an alternative fault location hypothesis to help locate a manifested fault of omission, if any. The critic can sometimes identify whether the missing statements should (1) define a value (e.g., simple assignment, procedure call, and output statements), (2) allow the control flow to reach a location (e.g., procedure call and predicate statements), (3) block the control flow to a location (e.g., predicate statements), and (4) produce the output.

4.2 The Concept Underlying a Debugging Critic

The key to a debugging critic's operation is its capability to recognize when an execution occurrence of the code at $\mathcal{L}$ reveals the manifestation of a fault at $\mathcal{L}$. We refer to such an execution occurrence as the *fault-manifesting occurrence*. We identify two basic characteristics of a fault-manifesting occurrence. First, the execution occurrence represents a violation of a program behavior specification. It may carry out a disallowed state transition or omit a state transition. Second, such a violation is not a consequence of a previous error-revealing state.

In general, the problem of evaluating a statement at a hypothesized fault location $\mathcal{L}$ is the problem of finding an occurrence of a statement at $\mathcal{L}$ whose output state is error-revealing, but not as a consequence of an error-revealing input state (according to the programmer). If such an occurrence is found, the hypothesis that $\mathcal{L}$ is the fault location is confirmed.

If a fault-manifesting occurrence is not found because an input state is error-revealing, the debugging critic records the characteristics of the violation of a program behavior specification. The violation is described as either erroneous variables or evidence of erroneous flow of control. Both are referred to collectively as *failure symptoms*. To formulate a hypothesis about a fault location, we define an *execution path slicing* method to find statement occurrences that can cause a given failure symptom. The absence of these occurrences indicates the presence of a manifested fault of omission.

This section presents knowledge representation for failure symptoms and the execution path slicing method. The notations for both are used in describing specific characteristics of fault-manifesting occurrence when either the fault of commission or fault of omission manifests itself.

4.2.1 Knowledge representation for failure symptoms

We define failure symptoms, $Symptoms(\mathcal{P}, t)$, as a collection of erroneous variables and erroneous flow of control[3] in a program $\mathcal{P}$ when it executes an error-revealing

[3]This is *not* a claim that the symptoms only appear on erroneous variables and flow of control.

test case t.[4] Each symptom is represented as a triple: $(g, {\sigma_t}^{c,e}, errcond)$, where g is a state function,[5] ${\sigma_t}^{c,e}$ is a path to search for an erroneous transition on g, and $errcond$ describes the erroneous condition associated with transition on g in $\sigma_t^{c,e}$.

Lamport's state function allows us to use g to identify either a variable or a program control point (pc). Thus, we can uniformly represent both the erroneous variable and the erroneous control flow.

The *erroneous path* ${\sigma_t}^{c,e}$ limits the path to search for an immediate cause of the failure symptom. If g is a variable, the value of g is non-error-revealing at step c but is error-revealing at step e. If g is pc, then the flow of control reaches a location at step c properly, but the flow of control in $\sigma_t^{c,e}$ is erroneous. A special case $c = e$ can identify the exact location of an omitted statement. This case occurs when g is defined with a non-error-revealing value in the transition prior to state s_c, but when the value of g from state s_c is used by the subsequent transition, the value is considered to be error-revealing. In this case, a fault of omission is located between the statement whose output state is s_c and the statement whose input state is s_c.

Note that the inclusion of an erroneous path ${\sigma_t}^{c,e}$ does not imply that the critic system must store the execution sequence from step c to e for each symptom. It can uniquely identify this erroneous path by step c, step e, and test case t.

The *erroneous condition* for $\sigma_t^{c,e}$ is defined by a predicate state transition function. We define a *predicate state transition function* as a function that maps a state transition to a boolean value. It may indicate whether a transition on g in $\sigma_t^{c,e}$ is disallowed or is omitted.

The failure symptoms used by our debugging critic are listed below. This set is sufficient to support our debugging critic. We do not claim that this set is complete. If a detailed specification is available, more detailed and application-specific failure symptoms can always be defined.

[4]Note that we define failure symptoms according to a program $\mathcal{P}$ and test case t. This is possible under the assumption that an execution sequence σ_t is finite and deterministic. If the execution is non-deterministic, σ_t should be used instead.

[5]See Chapter 2 for definition.

$(var, {\sigma_t}^{c,e}, erroneous(var))$

This symptom describes an erroneous variable var that is non-error-revealing at step c, but the value of var changes and becomes error-revealing at step e. The change of value of var means the dynamic reaching definition of var executes in $\sigma_t^{c,e}$.

$(var, {\sigma_t}^{c,e}, unchange(var))$

This symptom describes an erroneous variable var that is non-error-revealing at step c, but the unchanged value of var becomes error-revealing at step e. The value of var does not change when the dynamic reaching definition of var does not execute in $\sigma_t^{c,e}$.

$(var, {\sigma_t}^{c,e}, undefine(var))$

This symptom describes an erroneous variable var that is error-revealing because its value is undefined at the time var is used at step e. The value of var is undefined when var at step e has no dynamic reaching definition.

$(pc, {\sigma_t}^{c,e}, reach(loc))$

This symptom describes the flow of control that reaches a location loc by mistake at step e. It also indicates that the flow properly reaches a location at step c.

$(pc, {\sigma_t}^{c,e}, unreach(loc))$

This symptom describes the flow of control that does not reach a location loc in $\sigma_t^{c,e}$. It also indicates that the flow properly reaches a location at step c.

$(pc, {\sigma_t}^{c,e}, missAction(pattern))$

This symptom describes the flow of control in $\sigma_t^{c,e}$ that does not reach a statement that matches $pattern$. The $pattern$ is a regular expression pattern. It also indicates that the flow properly reaches a location at step c.

The unreached location symptom cannot be used to describe this symptom because it is possible that the statement that matches *pattern* is missing from the program.

Our debugging critic derives failure symptoms from the programmer's answers to its questions about program states. The only *pattern* defined by our debugging critic is a regular expression pattern to match an output statement in a specific programming language. A variety of patterns can be specified if an implementation of a debugging critic allows a programmer to define failure symptoms directly.

4.2.2 Execution path slicing

We define *execution path slicing* to identify which statement occurrences may have caused one (or all) of the known failure symptoms. Unlike program slicing that identifies statements on which a variable or a statement depends, execution path slicing identifies statement occurrences on which a given variable or control point at the given program state depend.

This section describes two classes of execution path slices: *dynamic path slices* and *static path slices*. Dynamic path slices are used in producing hints and recognizing omission-fault-manifesting occurrences. Static path slices are used in defining search spaces for a fault-manifesting occurrence.

4.2.2.1 Dynamic analysis for path slicing

Dynamic path slices are composed of statement occurrences that actually affect the value of a variable or a control point at a given program state. A failure symptom, $(g, {\sigma_t}^{i,j}, errcond) \in Symptoms(\mathcal{P}, t)$, contains the necessary input to compute dynamic path slices. For an erroneous variable, they are computed with respect to a program $\mathcal{P}$, a test case t, execution step j, and a variable g. For an erroneous control point pc, they are computed with respect to a program $\mathcal{P}$, a test case t, an erroneous path ${\sigma_t}^{i,j}$, and a location loc (embedded in $errcond$).

We adapt Agrawal's dynamic slicing methods [Agr91] to compute dynamic path slicing instead of defining algorithms for dynamic path slicing from scratch. Agrawal's dynamic slice is computed by traversing a history graph backwards from the current execution step. A history graph is created and updated as the program executes. Nodes in the history graph are occurrences of nodes in the program dependency graph, each of which is associated with either an assignment statement or a predicate expression. Under the assumption that the program terminates, the history graph has a finite number of nodes, though its size is unbounded.

To compute an execution path slice based on a given failure symptom, our critic has to reconstruct the history graph up to the state s_j when the failure symptom is observed. As the history graph is constructed, our critic records an execution step with each history node. Thus, when Agrawal's algorithms are used to traverse the graph, the resulting slice contains the statement occurrences.

With the exception of dynamic control path slice, Agrawal's algorithm can be used in defining dynamic path slices. A *dynamic program path slice* includes occurrences of statements in the dynamic slice of variable g when the program execution reaches step j. A *dynamic reaching definition occurrence* is the occurrence of a dynamic reaching definition of *var* at the location reached by step j. A *dynamic data path slice* includes occurrences of statements in the dynamic slice of variable g when the program execution reaches step j.

To define *dynamic control path slices*, extensions to the computation and semantics of Agrawal's control slice are required. Agrawal's control slice includes predicates enclosing a location in one procedure. Agrawal argues that a static and dynamic control slice are the same because

> ... *unlike reaching definitions, a statement always has at most one predicate immediately enclosing it. No narrowing of enclosing predicates can occur at run time. Thus the control slice with respect to a given location remains the same in both static and dynamic cases. If control incorrectly*

reaches a statement during program execution, we must examine all predicates enclosing the statement; if on the other hand, a desired statement is not reached during program execution, we must still examine the same set of predicates [Agr91].

We dispute this reasoning. First, fewer predicates need to be examined if the control flow does not reach a location. When a failure symptom indicates that a location is reached in error, predicates that allow the flow to a given location should be examined. When a failure symptom indicates that a location *loc* is not reached in error, the predicate that blocks the control flow to *loc* should be examined. The unexecuted predicates nested under the blocking predicate cannot contain a manifested fault, so they do not need to be examined. Suppose a procedure $R()$ encloses a location *loc*. If the code at *loc* is not reached because $R()$ has not been called, predicates enclosing *loc* in $R()$ are not the ones that block the control flow to *loc*. Therefore, they do not need to be examined.

Second, if a control slice is an interprocedural slice, the calling statement, not only the predicate, can direct the flow of control. If *loc* is not enclosed by any predicate in $R()$, the statement that allows the flow to reach it is the calling statement to $R()$. As there can be more than one calling statement to $R()$, there can be more than one dynamic control slice to *loc*. Therefore, the static and dynamic control slices are not identical.

We extend Agrawal's control slice in two ways. First, we extend it into an interprocedural control slice. This extension includes procedure call statements and their enclosing predicates on the path to a given location. Second, we extend its semantics to distinguish between predicates and statements that direct control flow to reach a given location (*steerers*) and predicates that block the control flow to a given location (*blockers*). Dynamic control path slices for steerers and blockers are listed below.

Definition: A dynamic steerers slice, $DynSteerer(\mathcal{P}, t, loc, step)$, includes occurrences in $\sigma_t^{0,step}$ of (1) predicates enclosing *loc*, (2) procedure call statements in the dynamic calling path up to step *step*, and (3) predicates enclosing each calling statement in the calling path. A *dynamic calling path* to step *step* includes the transitive closure of procedure call statements to $R()$ that execute in $\sigma_t^{0,j}$, where $R()$ is a procedure that executes at step *step*. □

Definition: A dynamic blocker slice, $DynBlocker(\mathcal{P}, t, loc, i, j)$, includes occurrences of predicates that block the flow of control to a statement at *loc* on $\sigma_t^{i,j}$.

- If the statement at *loc* executes in $\sigma_t^{i,j}$, then the dynamic blocker slice is null.
- If the statement at *loc* does not execute, but the procedure $R()$ that enclosed *loc* executes in $\sigma_t^{i,j}$, then dynamic blocker slice includes at most one unique *blocking occurrence*, which is the occurrence of a predicate that blocks the flow to *loc*.

  Let $\mathcal{C}$ be a set of predicates in Agrawal's control slice[6] for *loc*. The execution of any predicate $\mathcal{C}$ can determine whether the flow will reach *loc*. When an occurrence of a predicate in $\mathcal{C}$ allows the flow to reach another predicate in $\mathcal{C}$ in $\sigma_t^{i,j}$, it still is possible that the newly reached predicate would allow the flow to reach *loc*. Thus, the *blocking occurrence* of *loc* in $\sigma_t^{i,j}$ is the occurrence of a predicate in $\mathcal{C}$ that executes last in $\sigma_t^{i,j}$.
- If the procedure $R()$ that encloses *loc* does not execute in $\sigma_t^{i,j}$, then the dynamic blocker slice contains predicate occurrences that block the procedure calls that could have lead the control flow to $R()$. These calling statements are in the static calling path to $R()$, and do not execute in $\sigma_t^{i,j}$. A *static calling path* to a procedure $R()$ is the transitive closure of calling statements to $R()$. □

Example: Suppose the program in Figure 4.2 executes test case #3: 1 2 3. The execution sequence is $4^{(1,2)}$, $5^{(2,3)}$, $6^{(3,4)}$, and $8^{(4,\$)}$. The statement to compute *Remainder*

[6]See definition in Chapter 2, Section 2.1.5.

at line 20 is not reached. In this case, the dynamic blocker of line 20 contains an execution occurrence $6^{(3,4)}$ of a statement $if\ (A > B)$ at line 6.

Example: Suppose the program in Figure 4.2 executes test case #2: 1 −1 0. The execution sequence is $4^{(1,2)}$, $5^{(2,3)}$, $6^{(3,4)}$, $7^{(4,5)}$, $13^{(5,6)}$, $14^{(6,7)}$, $15^{(7,8)}$, $20^{(8,9)}$, $16^{(9,10)}$, and $8^{(10,\$)}$. The dynamic steerers to the statement to compute *Remainder* at line 20 include the occurrences of the statements below.

6:	if $(A > B)$	occurrence: $6^{(3,4)}$
7:	G(X)	occurrence: $7^{(4,5)}$
15:	F(X,Remainder)	occurrence: $15^{(7,8)}$

In both examples, Agrawal's control slice for line 20 would be null.

4.2.2.2 Static analysis for path slicing

Static path slices are composed of statement occurrences that may affect the value of a variable at a given location. They are computed with respect to a program $\mathcal{P}$, a test case t, an execution step $step$, a variable var, and a location loc.

A *static program path slice* includes occurrences of statements in Agrawal's static program slice in $\sigma_t^{0,step}$. *Static reaching definition occurrences* are occurrences of static reaching definitions of var at loc that execute in $\sigma_t^{0,step}$. A *static data path slice* includes occurrences of statements in a static data slice of var at loc that execute in $\sigma_t^{0,step}$.

A *static control path slice* is computed the same way as the dynamic steerers slice, except the calling statements are from a static calling path instead of a dynamic calling path. A *static blockers slice* is a static control path slice minus the occurrences of the calling statements.

4.2.3 Characteristics of fault-manifesting occurrences

4.2.3.1 Commission-fault-manifesting occurrence

If an occurrence $\mathcal{L}^{(in,out)}$ is a commission-fault-manifesting occurrence of the code at $\mathcal{L}$, then the transition from s_{in} to s_{out} is disallowed and this transition does not take place as a consequence of a previous error-revealing state.

Case C1: The code at $\mathcal{L}$ contains a manifested fault of commission.

$\mathcal{L}^{(in,out)}$ represents a disallowed transition because it produces as output an error-revealing value. The output values at s_{out} are error-revealing if (1) they cause the control flow to reach some other location in error, (2) variable values defined during the execution of code at $\mathcal{L}$ are error-revealing at step out, or (3) program output is erroneous.

This disallowed transition is not a consequence of a previous error-revealing state when the code at $\mathcal{L}$ takes as input non-error-revealing values in s_{in}. The input values at s_{in} are non-error-revealing if (1) the control flow properly reaches loc at step in and (2) the variable values used during the execution of code at $\mathcal{L}$ are non-error-revealing at step in.

Commission-error-revealing occurrence $\mathcal{L}^{(in,out)}$ for types of statements our debugging critic evaluated are described as follows.

- A simple assignment statement

  There is a symptom $(var, {\sigma_t}^{in,out}, erroneous(var))$ where var is the variable to which the statement assigned value. Values in state s_{in} that are used in defining var in state s_{out} are non-error-revealing. The control flow also properly reached the statement at step in.

- An input statement

  There is a symptom $(var, {\sigma_t}^{in,out}, erroneous(var))$ where var is an input variable. The control flow properly reached the statement at step in.

- A procedure call

  There is a symptom $(var, {\sigma_t}^{in,out}, erroneous(var))$ where var is the formal parameter of the procedure being called. The corresponding actual parameter used non-error-revealing values in its expression. The control flow also properly reached the statement at step in.

- A predicate statement

  If the predicate evaluates to *true* instead of *false*, then there is a symptom $(pc, {\sigma_t}^{in,out}, reach(loc))$ where loc is the location of the statement to be executed next. If the predicate evaluates to *false* instead of *true*, then there is a symptom $(pc, {\sigma_t}^{in,out}, unreach(loc))$ where loc is the location that would be reached had the predicate evaluates to true.

  In both cases, values in state s_{in} that are used in the predicate are non-error-revealing. The control flow also properly reached the statement at step in.

- An output statement

  The output at step *out* is erroneous.[7] Values in state s_{in} that are used in the output statement are non-error-revealing. The control flow also properly reached the statement at step in.

Case C2: The code at $\mathcal{L}$ is extraneous.

When a statement is extraneous, its execution always causes a disallowed transition. This disallowed transition is not a consequence of a previous error-revealing state when (1) no statement directs the flow of control to $\mathcal{L}$ by mistake, and (2) the omission of the predicate to block control flow to $\mathcal{L}$ is proper.

More precisely, an execution occurrence $\mathcal{L}^{(in,out)}$ of an extraneous statement is commission-fault-manifesting when

[7]We did not define a failure symptom for erroneous output because the output value is not a value in a program state (in our definition). If the output statement contains the manifested fault, the fault location can be confirmed without having to store the failure symptom. If the output statement produces erroneous output because it uses an error-revealing output variable, then the failure symptom for an output variable is added instead.

- $(pc, {\sigma_t}^{0,in}, reach(\mathcal{L}))$ is in $Symptoms(\mathcal{P}, t)$,
- $DynSteerer(\mathcal{P}, t, \mathcal{L}, in)$ is null or the programmer decides that steerers to $\mathcal{L}$ do not cause any erroneous flow of control, and
- the programmer decides that $\mathcal{L}$ is not supposed to be enclosed by any predicate.

Note that if the programmer decides that an extraneous statement is properly reached, then the fault manifests itself the same way as described in Case C1.

Example: Suppose in the program in figure 4.2 the read statement at line 4: $read(A, B, X)$ should not have read in the value for X. When the program executes test case #1: 10 5 30, the execution occurrence $4^{(1,2)}$ (reads: an occurrence of a statement at line 4 which is reached at step 1 and exits at step 2) maps undefined values for A, B, X to 10, 5, 30. This occurrence is commission-fault-manifesting if the programmer decides that (1) the control flow reached line 4 properly at step 1, (2) no error-revealing value is used at step 1, and (3) the value of X is error-revealing at step 2.

Example: Suppose in the program in figure 4.2 the read statement is correct, but the statement at line 5: $X = A * B$ is extraneous. The execution occurrence $5^{(2,3)}$ is commission-fault-manifesting if the programmer decides that (1) the control flow reached $X = A * B$ at step 2 by mistake and (2) $X = A * B$ is not supposed to be enclosed by a predicate.

4.2.3.2 Omission-fault-manifesting occurrence

If an occurrence $\mathcal{L}^{(in,out)}$ is an omission-fault-manifesting occurrence of the code at $\mathcal{L}$, then the execution from s_{in} to s_{out} omits a state transition, but not as a consequence of a previous error-revealing state. An omitted transition is a consequence of a previous error-revealing state when (1) the flow reached a location at step in improperly, or (2) the code to carry out the transition exists, but an execution of some statements blocks the control flow to the code.

		execution steps		
		test case #1	test case #2	test case #3
line	**statements**	10 5 30	1 -1 0	1 2 3
1:	main()			
2:	begin			
3:	Integer A, B, X			
4:	read(A, B, X)	1	1	1
5:	X = A * B	2	2	2
6:	if (A > B)	3	3	3
7:	G(X)	4	4	
8:	end	10	10	4
9:				
10:	Subroutine G(X)			
11:	begin			
12:	Integer Remainder, Quotient			
13:	Remainder = 0	5	5	
14:	Quotient = 0	6	6	
15:	F(X, Remainder)	7	7	
16:	print(Remainder, Quotient)	9	9	
17:	end			
18:	Subroutine F(X)			
19:	begin			
20:	Remainder = MOD(X, 10)	8	8	
21:	end			

Figure 4.2 A sample faulty program (in a psuedo-language)

Conversely, an omitted transition is *not* a consequence of a previous error-revealing state when the flow reaches a location at step in properly, and either (a) the code to carry out the transition does not exist, or (b) the code to carry out the transition exists, but none of the statements that execute between step in and step out block the control flow to that code. Note that if none of the statements that execute between step in and step out block the control flow to such code, then either condition (a) or (b) would be true (a missing statement has no blocker). Thus, the absence of blocking statement occurrences can indicate the presence of an omission-fault-manifesting occurrence.

We define four cases of omission-fault-manifesting occurrences, $\mathcal{L}^{(in,out)}$, as follows.

Case O1: Omitted a statement to assign value to variable var

$\mathcal{L}$ is the location of the code that omits an input statement, a simple assignment statement, a variable var in an input statement, or an argument in a procedure call to define a formal parameter var. $\mathcal{L}^{(in,out)}$ omits a transition to change a value of var, but not as a consequence of a previous error-revealing state when a static reaching definition of var at s_{out} (a) does not exist, or (b) exists but the statement that can block the flow to it does not execute in $\sigma_t^{in,out}$.

More precisely, $\mathcal{L}^{(in,out)}$ is omission-fault-manifesting when

- $(var, {\sigma_t}^{in,out}, undefine(var))$ or $(var, {\sigma_t}^{in,out}, unchange(var))$ is in $Symptoms(\mathcal{P}, t)$, and
- $\bigcup_{loc_j \in L'} DynBlocker(\mathcal{P}, t, loc_j, in, out)$ is null, where L' consists of locations of static reaching definitions of var at loc and loc is the location reached at step out.

Case O2: Omitted a procedure call

$\mathcal{L}$ is the location of the code that omits a procedure call. $\mathcal{L}^{(in,out)}$ omits a transition to change the value of pc to loc. This means the control flow does not reach the procedure $R()$ enclosing location loc between step in and step out.

This omitted transition is not a consequence of a previous error-revealing state when the control flow properly reached a location at step in, and procedure call statements that allow the flow to reach $R()$ (a) do not exist, or (b) exist, but a statement that can block the flow to it does not execute in $\sigma_t^{in,out}$.

More precisely, $\mathcal{L}^{(in,out)}$ is omission-fault-manifesting when

- $(pc, {\sigma_t}^{in,out}, unreach(loc))$ is in $Symptoms(\mathcal{P}, t)$, and $DynBlocker(\mathcal{P}, t, loc, in, out)$ is null, or
- $(pc, {\sigma_t}^{in,out}, missAction(pattern))$ is in $Symptoms(\mathcal{P}, t)$, $\bigcup_{loc_j \in L'} DynBlocker(\ \mathcal{P}, t, loc_j, in, out)$ is null, where L' consists of locations of code that match $pattern$.

Case O3: Omitted a predicate

$\mathcal{L}$ is the location of the code that omits a predicate statement or omits a predicate within a predicate expression (incomplete predicate). An execution of this incomplete predicate causes an erroneous flow of control that skips some location loc_i, reaches some locations loc_j, or both. If a location loc is unreached by mistake, then the characteristic of the omission-fault-manifesting occurrence for L is the same as in Case O2.

If a non-extraneous location loc is reached by mistake, $\mathcal{L}^{(in,out)}$ omits a transition that can block a control flow from reaching loc at step out. This omitted transition is not a consequence of a previous error-revealing state when the control flow reaches the location at step in properly, and predicates that a flow of control to reach a location loc (a) does not exist, or (b) exists, but does not execute in $\sigma_t^{in,out}$.

In this case $\mathcal{L}^{(in,out)}$ is an omission-fault-manifesting when

- $(pc, {\sigma_t}^{in,out}, reach(loc))$ is in $Symptoms(\mathcal{P}, t)$,
- $DynSteerer(\mathcal{P}, t, loc, out)$ is null, and

- the programmer decides that the code at loc is not extraneous.

Case 4: Omitted an output statement

$\mathcal{L}^{(in,out)}$ omits a transition that can produce the expected output. This omitted transition is not a consequence of a previous error-revealing state when the output statement to print expected output (a) does not exist, or (b) exists, but a statement to block its execution does not execute in $\sigma_t^{in,out}$.

More precisely, an execution occurrence $\mathcal{L}^{(in,out)}$ is omission-fault-manifesting when

- $(pc, {\sigma_t}^{in,out}, missAction(print.*(.*))$ is in $Symptoms(\mathcal{P}, t)$, and
- $\bigcup_{loc_j \in L'} DynBlocker(\ \mathcal{P}, t, loc_j, in, out)$ is null, where L' consists of locations of print statements.

With an omission-fault-manifesting occurrence $\mathcal{L}^{in,out}$, our debugging critic's hypothesized location for a fault of omission includes all procedures that enclosed a statement that executed in $\sigma_t^{in,out}$.

Example: Suppose in the program in Figure 4.2, the fault is the omission of a statement to compute $Quotient$. Given test case #1: 10 5 30, the execution sequence is $4^{(1,2)}$, $5^{(2,3)}$, $6^{(3,4)}$, $7^{(4,5)}$, $13^{(5,6)}$, $14^{(6,7)}$, $15^{(7,8)}$, $20^{(8,9)}$, $16^{(9,10)}$, and $8^{(10,\$)}$.

$\mathcal{L}^{(7,9)}$ is omission-fault-manifesting if a programmer decides that (1) after the statement that initializes $Quotient$ at line 14, the zero value for $Quotient$ at step 7 is non-error-revealing, (2) the zero value of $Quotient$ in the print statement reached at step 9 is error-revealing, and (3) none of the statements which execute from steps 7 to 9 block the execution of the static reaching definition of $Quotient$ at line 14.

With this omission-fault-manifesting occurrence, our critic hypothesizes that procedures $F()$ and $G()$ may omit one or more statements. The missing statement may either be (1) a static reaching definition of $Quotient$, or (2) a statement to redirect the flow of control to an existing static reaching definition of $Quotient$ at line 14.

Example: Suppose in the program in Figure 4.2, the fault is the omission of a predicate statement to block flow of control to subroutine $F()$ when X is less than zero. Given test case #2: 1 -1 0, $X = -1$ when the control flow reaches line 7: $G(x)$ at step 4.

$\mathcal{L}^{(5,7)}$ is an omission-fault-manifesting occurrence if a programmer decides that (1) the flow of control properly reaches line 13: $Remainder = 0$ in $G()$ at step 5, (2) the flow reaches the calling statement at line 15: $F(X, Remainder)$ by mistake at step 7, (3) none of the statements which execute from steps 5 to 7 direct the flow of control to line 15 by mistake, and (4) the call to $F()$ is not extraneous. With this omission-fault-manifesting occurrence, our critic would hypothesize that procedure $G()$ omits a predicate that should have blocked the flow of control to line 15.

Note that the difficulty in locating a fault of omission is in acquiring the symptoms of omitted transition, rather than in analyzing the symptoms. Our debugging critic is designed to acquire these symptoms as it evaluates hypotheses about fault location.

4.3 Debugging Critic Operations

4.3.1 Overview

Our debugging critic operates in two phases. The first phase is when it takes the initiative at the beginning of a debugging session. The second phase is when it responds to the programmer's requests to evaluate a hypothesized fault location.

In phase 1, our debugging critic takes the initiative when $Symptoms(\mathcal{P}, t)$ is empty for the newly selected error-revealing test case t. The critic poses questions about output statements. If the fault is not found in an output statement, our debugging critic acquires an initial set of failure symptoms. It then defines search spaces for a manifested fault from failure symptoms. Our debugging critic formulates a hypothesis about a fault location, and recommends that location as a starting point for the programmer.

In phase 2, our debugging critic takes the following steps in response to the programmer's request to evaluate a hypothesized fault location $\mathcal{L}$.

1. Identify types of statements at $\mathcal{L}$

   If the statement at $\mathcal{L}$ is an assignment, a predicate, a procedure call, or an input or output statement, our debugging critic proceeds to step 2. For any other type of executable statement, our debugging critic indicates that it does not yet evaluate that type of statement.

   If the statement at $\mathcal{L}$ is not executable, (e.g., blank line, comment), our debugging critic would reject $\mathcal{L}$.

2. Evaluate a statement at location $\mathcal{L}$

   Our debugging critic poses *evaluation questions* about the statement at $\mathcal{L}$. The allowed replies are "yes", "no", and "do not know."

   (a) Check execution status of the statement.

   If the statement at $\mathcal{L}$ does not execute in the search spaces for a manifested fault, our debugging critic poses a question to the programmer to determine whether location $\mathcal{L}$ is not reached by mistake. If so, the symptom of erroneous flow of control is added. Otherwise the evaluation continues to step 2b.

   (b) Determine if it can cause an omitted transition.

   The statement itself, not its execution occurrence, is evaluated. Our debugging critic poses a question to the programmer to determine whether the statement can cause an omitted transition. If so, our debugging critic proceeds to step 5. Otherwise, the evaluation continues to step 2c.

   (c) Select an execution occurrence to evaluate.

   An occurrence of a statement at $\mathcal{L}$ is selected from the search spaces for the manifested fault. Note that at this point, our debugging critic does not loop to evaluate every execution occurrence. If this was done, our critic might cause the problem of "fixation on the wrong location." Instead, our critic gives the programmer an option to further evaluate the same location, or examine another location that it recommends, after one selected occurrence is evaluated.

(d) Evaluate an occurrence.

An occurrence is evaluated for a possible fault-manifesting occurrence. Even if an occurrence is not in the search space for a manifested fault, it can exhibit a failure symptom (e.g., uses erroneous variables) that can reduce the search space further.

If a fault-manifesting occurrence has been identified, the critic proceeds to step 5. Otherwise, the critic derives or updates failure symptoms from the evaluation. As a result, our debugging critic may be able to identify the omission-fault-manifesting occurrence for the code at a location other than $\mathcal{L}$.

If an omission-fault-manifesting occurrence also is not found, our debugging critic proceeds to step 3.

3. Reduce search spaces for fault

   Search spaces for a manifested fault are reduced as each new failure symptom is added. If the search space for the manifested fault of commission becomes null, a fault of omission is identified and our debugging critic proceeds to step 5. Otherwise, it proceeds to step 4.

4. Formulate an alternative hypothesis about fault location

   Our debugging critic formulates an alternative hypothesis about fault location. If a new symptom is added, the hypothesis includes locations of code that may have caused this new symptom. Otherwise, its hypothesis is based on the earliest occuring symptom.

5. Draw Conclusion

   The evaluation result of a hypothesized location $\mathcal{L}$ may take one of the following forms:

Case 1: a fault-manifesting occurrence is found at $\mathcal{L}$.

Our debugging critic confirms that $\mathcal{L}$ is the fault location.

Case 2: a fault-manifesting occurrence is found, but not at $\mathcal{L}$.

Our debugging critic rejects $\mathcal{L}$, but identifies where the fault is.

Case 3: the evaluated occurrence of a statement at $\mathcal{L}$ has an error-revealing output state, but a programmer replies "do not know" to an evaluation question, Q, about the input state.

Our debugging critic indicates that the fault could be at $\mathcal{L}$ if the condition specified in Q holds.

Case 4: the statement at $\mathcal{L}$ does not execute in the reduced search spaces.

Our debugging critic rejects $\mathcal{L}$ with an explanation.

Case 5: the evaluated occurrence is not error-revealing, but the statement at $\mathcal{L}$ still executes in one of the search spaces.

Our debugging critic indicates that $\mathcal{L}$ needs to be evaluated further before a conclusion can be made.

Default:

Our debugging critic indicates that it does not have enough information to reach a conclusion.

If the fault is not yet found, our debugging critic recommends its alternative hypothesis about fault location. It also recommends the next possible step, such as examining the statements it recommends or selecting one of the statements it recommends for evaluation.

4.3.2 Evaluation of output statements

For each output statement occurrence, $\mathcal{L}^{(i,j)}$, our debugging critic poses the following series of questions (in the sequence shown). The loop terminates when a reply is "yes" for one of the question or when there are no more output statement occurrences.

Table 4.1 Output statement evaluation and derived failure symptoms

Yes to	Add symptoms
$Q_{omitOutput}$	$(pc, {\sigma_t}^{okstep,j}, missAction(\text{“}print. * (.*)\text{”}))$ where *okstep* is a step that properly reached the last output statement. The default *okstep* is zero.
$Q_{erReach}$	$(pc, {\sigma_t}^{0,i}, reach(loc))$.
Q_{errUse}	$(var, {\sigma_t}^{0,j}, erroneous(var))$ or $(var, {\sigma_t}^{0,j}, undefine(var))$ for each erroneous variable *var* the programmer identifies.

$Q_{omitOutput}$:	*“Is there any output statement that should have executed before the control flow reaches $\mathcal{L}$ at step i [and after the most recent output statement]?”*
$Q_{erReach}$:	*“At step i, does the control flow reach $\mathcal{L}$ by mistake?”*
Q_{erUse} :	*“At step i, does $\mathcal{L}$ use any erroneous variable values?”*
$Q_{erOutput}$:	*“At step j, does $\mathcal{L}$ print an incorrect value?”*

If the loop exits when all output statements have been evaluated, our debugging critic poses the question $Q_{omitOutput}$ one last time. The occurrence $\mathcal{L}^{(i,j)}$ for this question is the occurrence where j is the last execution step for σ_t.

Our debugging critic's reaction for all programmer's replies are as follows.

Case 1: there is a “yes” reply to $Q_{omitOutput}$, $Q_{erReach}$, or Q_{erUse}

Our debugging critic adds the corresponding symptom shown in Table 4.1. If there are more executed output statements, our debugging critic repeats only Q_{errUse}. The knowledge of more erroneous variables can reduce the search space for fault of commission. The search space for fault of omission cannot be reduced further, as the earliest symptom for output statements has already been identified.

Case 2: there is a "yes" reply to $Q_{erOutput}$

Our debugging critic confirms or conditionally confirms a fault location. It confirms that $\mathcal{L}$ is a fault location if the replies for $Q_{omitout}$, $Q_{erReach}$, or Q_{erUse} with respect to $\mathcal{L}^{(i,j)}$, are all "no." Because an erroneous output state is not a consequence of a previous error-revealing state, a fault-manifesting occurrence is found. Our debugging critic confirms that $\mathcal{L}$ is the fault location.

If one of the replies is "do not know," our debugging critic conditionally confirms $\mathcal{L}$ as a fault location. The condition is identified from the question with a "do not know" reply. An example is the conclusion which states that *"if $\mathcal{L}$ is properly reached, $\mathcal{L}$ is the fault location."*

Default:

In this case, all replies are mixtures of "no" and/or "do not know". Our debugging critic offers the programmer a chance to reevaluate the output again. If he chooses not to, our debugging critic exits with an explanation that it cannot operate without knowledge of failure symptoms. If he chooses to, our debugging critic repeats the output evaluation process, starting from the first output statement.

4.3.3 Initialization of search spaces for a manifested fault

Our debugging critic first defines search spaces for a manifested fault that includes possible occurrences that could have caused the failure symptoms. These search spaces are updated as our debugging critic acquires new failure symptoms through its evaluation of hypotheses about a fault location.

4.3.3.1 Search path

The search path for fault, $SearchPath(\mathcal{P}, t)$, is a path $\sigma_t^{top,bottom}$ to search for a fault-manifesting occurrence. The step *top* identifies the latest non-error-revealing state, s_{top} according to $Symptoms(\mathcal{P}, t)$. The step *bottom* identifies the earliest error-revealing state, s_{bottom} according to $Symptoms(\mathcal{P}, t)$. $SearchPath(\mathcal{P}, t)$ is null if $Symptoms(\mathcal{P}, t)$ is null.

A state s_i is the *latest error-revealing state* according to $Symptoms(\mathcal{P}, t)$ if (1) $i = 0$ and a fault-manifesting occurrence has not yet been found, or (2) a fault-manifesting occurrence $\mathcal{L}^{(i,j)}$ has been found. A state s_j is an *earliest error-revealing state* according to $Symptoms(\mathcal{P}, t)$ when among all erroneous paths ${\sigma_t}^{c,e}$, the minimum value for e is j.

4.3.3.2 Search space for a manifested fault of commission

The search space for a manifested fault of commission, $SSC(\mathcal{P}, t)$, consists of the possible commission-fault-manifesting occurrences of statements and predicates in σ_t that can cause the symptoms in $Symptoms(P, t)$, with the exception of some missing dependency statements.

Case 1: $Symptoms(\mathcal{P}, t)$ contains an erroneous variable.

$SSC(\mathcal{P}, t)$ includes statement occurrences in the intersection of static path slices of all erroneous variables in $Symptoms(\mathcal{P}, t)$.

Case 2: $Symptoms(\mathcal{P}, t)$ contains only erroneous flow.

$SSC(\mathcal{P}, t)$ includes all execution occurrences in $SearchPath(\mathcal{P}, t)$.

Default:

$SSC(\mathcal{P}, t)$ is null.

A statement *executes in* $SSC(P, t)$ if its occurrence that has not yet been evaluated as non-fault-manifesting is in $SSC(P, t)$.

If a fault of commission is the only fault exposed by test case t, then $SSC(\mathcal{P}, t)$ always includes a commission-fault-manifesting occurrence. The proof of this is presented in Appendix B.2.

4.3.3.3 Search space for a manifested fault of omission

The search space for a manifested fault of omission, $SSO(\mathcal{P},t)$, specifies a path to search for an omission-fault-manifesting occurrence. $SSO(\mathcal{P},t)$ is the same path as $SearchPath(\mathcal{P},t)$. A statement occurrence that executes in in the search path $SearchPath(\mathcal{P},t)$ also executes in $SSO(\mathcal{P},t)$, unless that occurrence has already been evaluated as a non-fault-manifesting occurrence.

If a fault of omission is the only fault exposed by test case t, then $SSO(\mathcal{P},t)$ always encloses an omission-fault-manifesting occurrence. The proof of this is presented in Appendix B.1.

4.3.4 Formulation of hypotheses about fault location

Our debugging critic identifies a *prime suspect*, which consists of a hypothesis about fault location and optionally, a hypothesis about fault identity. A prime suspect can be prime suspect statements (for fault of commission) or prime suspect procedures (for fault of omission).

$PrimeSuspect(symp)$ is the prime suspect of $symp = (g,\ {\sigma_t}^{i,j},\ errcond)$ that executes in the search path $\sigma_t^{top,bottom}$ and in the erroneous path $\sigma_t^{i,j}$. The first choice for $symp$ is the newly added symptom. If the erroneous path $\sigma_t^{i,j}$ in $symp$ does not overlap with the search path $\sigma_t^{top,bottom}$ then the next choice is the symptom at the earliest error-revealing state, s_{bottom}.

4.3.4.1 Formulation of a hypothesis for a location of fault of commission

Our debugging critic first identifies *prime suspect statements*, statements executed in $\sigma_t^{i,j}$ that could have caused $errcond$ in the symptom $(g, {\sigma_t}^{i,j},\ errcond)$. The occurrence of the *prime suspect statement* is derived through dynamic path slicing, with respect to g, $\sigma_t^{i,j}$, and a location loc identified in an $errcond$. Table 4.2 matches the symptoms and the dynamic path slices.

Table 4.2 Occurrences of prime suspect statements for each failure symptom

$(var, {\sigma_t}^{i,j}, erroneous(var))$	Dynamic reaching definition occurrence of var at step j.
$(var, {\sigma_t}^{i,j}, undefine(var))$ $(var, {\sigma_t}^{i,j}, unchange(var))$	Dynamic blockers for unexecuted static reaching definitions of var at location reached by step j.
$(pc, {\sigma_t}^{i,j}, reach(loc))$	Dynamic steerers to the statement at location loc at step j.
$(pc, {\sigma_t}^{i,j}, unreach(loc))$	Dynamic blockers that prevent the statement at location loc from executing in $\sigma_t^{i,j}$.
$(pc, {\sigma_t}^{i,j}, missAction(pattern))$	Dynamic blockers that prevent the statement that matches $pattern$ from executing in $\sigma_t^{i,j}$.

The type of the prime suspect depends on the types of g and *errcond*. If g represents an erroneous variable, the prime suspect can be its dynamic reaching definitions, the predicate that blocks the execution of some of its static reaching definitions, or the extraneous reaching definitions. If g represents erroneous flow *pc*, the prime suspect can be statements that can steer the flow of control to locations reached in error, or predicates that can block the flow of control to locations not reached in error.

If there are no prime suspect statement occurrences, then our debugging critic formulates a hypothesis on a location for a fault of omission. Otherwise, statements whose occurrences are prime suspect occurrences and also are executed in the search path $\sigma_t^{top,bottom}$ form our debugging critic's hypothesis for fault of commission.

If the existing prime suspect occurrences do not execute in the search path, the hypothesis consists of statements executed in both the search space for fault of commission and the erroneous path $\sigma_t^{i,j}$.

4.3.4.2 Formulation of a hypothesis for a location of fault of omission

The absence of statements that can cause a failure symptom *symp* in an erroneous path $\sigma_t^{i,j}$ indicates the presence of an omission-fault-manifesting occurrence. The procedures that execute in $\sigma_t^{(i,j)}$ are referred to as *prime suspect procedures.* Our debugging critic's hypotheses about the type of the missing statement are listed in Table 4.3. When *symp* is not a symptom of a statement reached in error, our debugging critic would confirm that a fault of omission is in one of the prime suspect procedures.

When *symp* is the symptom of a statement reached in error, our debugging critic formulates a hypothesis that if the statement at *loc* is not extraneous, a statement is missing from one of the the prime suspect procedures.

Table 4.3 Hypotheses about missing statements for each failure symptom when the prime suspect statements are absent

$(var, {\sigma_t}^{i,j}, erroneous(var))$	N/A
$(var, {\sigma_t}^{i,j}, undefine(var))$	Missing code to initialize var.
$(var, {\sigma_t}^{i,j}, unchange(var))$	Missing code to update var.
$(pc, {\sigma_t}^{i,j}, reach(loc))$	Missing code to block the flow of control to loc.
$(pc, {\sigma_t}^{i,j}, unreach(loc))$	Missing code that allows the flow of control to reach loc.
$(pc, {\sigma_t}^{i,j}, missAction(pattern))$	Missing code that allows the flow of control to reach loc, where loc contains a statement that matches $pattern$.

4.3.5 Evaluation of statements outside search spaces

A hypothesized location $\mathcal{L}$ is outside the search path for test case t, $\sigma_t^{top,bottom}$ when it contains a statement that (1) has already been rejected as a fault location, (2) does not execute in σ_t, (3) executes after step *bottom*, or (4) executes before step *top*.

Our debugging critic rejects $\mathcal{L}$ in all four cases. In case 1, it rejects $\mathcal{L}$ on the grounds that $\mathcal{L}$ has been rejected earlier. In case 4, it rejects $\mathcal{L}$ because the fault location has already been found. Recall that our debugging critic sets step *top* to value greater than zero only when an error-revealing occurrence has been identified. In cases 2 and 3, our debugging critic poses the following question before it rejects $\mathcal{L}$.

$Q_{outsideSS}$: *"The statement at $\mathcal{L}$ is not executed by this test case [$beforesymptom$] Should it be? [$consequence$]"*

In this question, our debugging critic specifies $beforesymptom$ if the statement at $\mathcal{L}$ executes. This term is a description of the symptom observed at the state s_{bottom} in the search path. Our debugging critic specifies a general *consequence* of an erroneous variable or erroneous flow had the statement at $\mathcal{L}$ executed. If the statement at $\mathcal{L}$ is in a static program slice of a known erroneous variable *var*, the *consequence* is "the statement could have changed the erroneous value of *var*." If the statement at $\mathcal{L}$ is a calling statement that could have led the flow of control to an unreached location *loc* in an unreached procedure R(), the *consequence* is "the statement at *loc* might be reached."

A "yes" reply for $Q_{outsideSS}$ leads our debugging critic to add an unreached location symptom. The added symptom is $(pc, {\sigma_t}^{0,\$}, unreach(\mathcal{L}))$ if the statement does not execute. The added symptom is $(pc, {\sigma_t}^{top,bottom}, unreach(\mathcal{L}))$ if the statement does not execute in search path $\sigma_t^{top,bottom}$. Our debugging critic adds no symptom when the reply is "no" or "do not know". Despite this reply, our debugging critic would reject $\mathcal{L}$ and recommend an alternative location.

4.3.6 Evaluate statements inside search spaces

4.3.6.1 Evaluate a statement

Our debugging critic evaluates whether the statement at $\mathcal{L}$ can cause an omitted transition by posing one of the following questions.

$Q_{omitAssign}$:	*"Does the statement at $\mathcal{L}$ assign a value to a wrong variable?"*
$Q_{omitCall}$:	*"Does a procedure call at $\mathcal{L}$ pass too few parameters?"*
$Q_{omitInput}$:	*"Does an input statement at $\mathcal{L}$ read too few values?"*
$Q_{omitOutput2}$:	*"Does an output statement at $\mathcal{L}$ print too few values?"*
$Q_{omitPred}$:	*"Is a predicate at $\mathcal{L}$ incomplete?"*

A "yes" reply implicates $\mathcal{L}$ as a location of a fault of omission. A "no" or "do not know" reply leads our debugging critic to select an occurrence of the statement to evaluate.

4.3.6.2 Select an execution occurrence

Our debugging critic selects an occurrence of a statement at $\mathcal{L}$, $\mathcal{L}^{(i,j)}$ to evaluate. The order of preference is listed below. The first choice that is not null is selected.

1. Prime suspect occurrence of statement at $\mathcal{L}$ in $SSC(\mathcal{L}, t)$

2. Prime suspect occurrence of statement at $\mathcal{L}$ in $SSO(\mathcal{L}, t)$

3. Last occurrence of statement at $\mathcal{L}$ in $SSC(\mathcal{L}, t)$

4. Last occurrence of statement at $\mathcal{L}$ in $SSO(\mathcal{L}, t)$

A prime suspect occurrence is chosen because it has a cause-effect relationship with a known failure symptom. Therefore, it is likely to be faulty. If it is not faulty, it should exhibit failure symptoms (e.g., uses an erroneous variable value). The last occurrence is also likely to exhibit a failure symptom, even if $\mathcal{L}$ is not faulty. A common *off-by-one* fault in a loop predicate, for example, would manifest itself in the last execution occurrence of the loop body.

4.3.6.3 Evaluate a statement occurrence

Our debugging critic poses questions about $\mathcal{L}^{(i,j)}$ to determine whether it is a commission-fault-manifesting occurrence. The first two questions determine if the values used from the input state s_i are non-error-revealing.

$Q_{erReach}$:	*"At step i, does the control flow reach $\mathcal{L}$ by mistake?"*
Q_{erUse} :	*"At step i, does $\mathcal{L}$ use any erroneous variable values?"*

If the reply is "yes" for $Q_{erReach}$ or Q_{erUse}, the corresponding symptom shown in Table 4.1 is added. Our debugging critic proceeds to draw a conclusion about $\mathcal{L}$ (see Section 4.3.1).

If the reply is "no" or "do not know" for $Q_{erReach}$ or Q_{erUse}, our debugging critic poses the question, Q_{erDef}, to determine if $\mathcal{L}$ defines an error-revealing value. This question is phrased according to the type of statement at $\mathcal{L}$.

$Q_{erAssign}$:	*"At step j, does $\mathcal{L}$ define an incorrect value?"*
Q_{erCall} :	*"At step j, is there any parameter that gets assigned to an incorrect value?"*
Q_{erPred} :	*"At step j, does the predicate evaluate to an erroneous boolean value?"*
$Q_{erInput}$:	*"At step j, does $\mathcal{L}$ read in an incorrect value?"*
$Q_{erOutput}$:	*"At step j, does $\mathcal{L}$ print an incorrect value?"*

Table 4.4 Update for a failure symptom

No to Q_{erDef}	Define	Update erroneous path for
$Q_{erAssign}$ $Q_{erInput}$ Q_{erCall}	var	$(var, {\sigma_t}^{c,e}, errcond)$
Q_{erPred}	pc	$(pc, {\sigma_t}^{c,e}, errcond)$
$Q_{erOutput}$	output	$(pc, {\sigma_t}^{c,e}, missAction(\text{``}print.*(.*)\text{''}))$

If the reply is "yes" for Q_{erDef}, our debugging critic confirms or conditionally confirms a fault location. If the replies for $Q_{erReach}$ or Q_{erUse} are both "no", then a commission error-revealing occurrence is found. Our debugging critic confirms that $\mathcal{L}$ is the fault location. If one of the replies for $Q_{erReach}$ or Q_{erUse} is "do not know", our debugging critic conditionally confirms $\mathcal{L}$. The condition is identified from the question with the "do not know" reply.

If the reply is "no" for Q_{erDef}, our debugging critic may be able to reduce an erroneous path of some failure symptoms. Recall that the erroneous path ${\sigma_t}^{c,e}$ in a symptom $(g, {\sigma_t}^{c,e}, errcond)$ indicates that at step c, g is non-error-revealing and at step e, g is error-revealing. If the statement under evaluation assigns a non-error-revealing value to g at step j, then the erroneous path ${\sigma_t}^{c,e}$ can be reduced to ${\sigma_t}^{j,e}$, if $j > c$. Table 4.4 shows which symptoms can be reduced according to a "no" reply to each type of Q_{erDef}.

If $\mathcal{L}^{(i,j)}$ is a prime suspect occurrence, a "no" reply to Q_{erDef} may change a symptom of an erroneous transition to a symptom of an omitted transition.

1. $\mathcal{L}^{(i,j)}$ is a reaching definition occurrence of var in $(var, {\sigma_t}^{c,e}, erroneous(var))$.

   The symptom changes to $(var, {\sigma_t}^{j,e}, unchange(var))$.

2. The erroneous path in a symptom $(g, {\sigma_t}^{c,j}, errcond)$ is reduced to ${\sigma_t}^{j,j}$.

   When g is non-error-revealing after it is defined by a statement at $\mathcal{L}$ but error-revealing when it is used in the next statement at $\mathcal{L}'$, then a statement or a predicate is missing in between.

When our debugging critic formulates a hypothesis based on the newly added symptom, it may recognize an omission-fault-manifesting occurrence.

Example: Let $(balance, {\sigma_t}^{0,4}, erroneous(balance))$ be a symptom for the code below. Suppose the execution sequence is $20^{(1,2)}$, $21^{(2,3)}$, $22^{(3,4)}$, $23^{(4,5)}$.

```
20:  read( deposit, balance)
21:  if (deposit < 0)
22:    balance = balance + deposit
23:  print(balance)
```

When the prime suspect occurrence $20^{(1,2)}$ is evaluated, both $balance = 100$ and $deposit = 20$ are found to be non-error-revealing at step 2. The symptom $(balance, {\sigma_t}^{0,4}, erroneous(balance))$ is updated to $(balance, {\sigma_t}^{2,4}, unchange(balance))$.

Example: Let $(balance, {\sigma_t}^{0,2}, erroneous(balance))$ be a symptom for the code below. Suppose the execution sequence is $5^{(1,2)}$, $6^{(2,3)}$.

```
5:  read( deposit, balance)
6:  print(balance)
```

When the prime suspect occurrence $5^{(1,2)}$ is evaluated, $balance = 100$ is found to be non-error-revealing at step 2. The symptom $(balance, {\sigma_t}^{0,2}, erroneous(balance))$ is updated to $(balance, {\sigma_t}^{2,2}, unchange(balance))$. This implies that a statement to update $balance$ is missing between line 20 and 21.

Example: Let $(pc, {\sigma_t}^{0,\$}, unreach(8))$ be a symptom for the code below.

```
7:  if   (match == 4)
8:       print( "invalid triangle")
```

Suppose *"invalid triangle"* should be printed when *match* is 0 or 4, and *match* is 0 when control flow reached line 7 at step 15. When the prime suspect occurrence $7^{(15,16)}$ is evaluated, the programer finds $(match == 4) = false$ non-error-revealing. The symptom $(pc, {\sigma_t}^{0,\$}, unreach(8))$ is updated to $(pc, {\sigma_t}^{16,\$}, unreach(8))$.

4.4 A Sample Session with a Debugging Critic

This section presents a sample debugging session for the program *trityp.c* (see Figure 4.3) which is similar to one used in the paper by Ramamoorthy [RHC76]. Given three sides of a triangle as input, this program determines the type of a triangle: scalene, isosceles, equilateral, or not a triangle.

An error-revealing test case: 2 2 4 causes a fault at line 48 to be exposed. The fault is that the >= operation is used instead of the > operation. The program produces the erroneous output: "Return match = 2, the triangle is isosceles."

In phase 1, our debugging critic poses questions about output statements. It executes the program and breaks at step 13 when it reaches the first print statement at line 57. It then poses the question:

> *"Is there any output statement that should have executed before control reaches line 57 at step 13?"*

When our debugging critic receives a "no" reply, it poses the next question:

> *"At step 13, does the control flow reach line 57 by mistake?"*

When our debugging critic receives a "no" reply, our debugging critic prints the values of the variables used before the statement executes, then poses the next question:

```
/*
* trityp -
*
*    MATCH is output from the routine
*          = 1 if triangle is scalene
*          = 2 if triangle is isosceles
*          = 3 if triangle is equilateral
*          = 4 if not a triangle
*/

#include <stdio.h>

main()
{
     int i, j, k, match;

     printf("Please enter 3 sides:");
     scanf("%d %d %d", &i, &j, &k);
     match_sides( i, j, k, &match);
    print_output( match);

}

match_sides( i, j, k, match)
     int    i, j, k, *match;
{

*match = 0;
if (i  == j)
    *match = *match + 1;
if (i == k)
    *match = *match + 2;
if (j == k)
    *match = *match + 3;

/* scalene? */

if (*match == 0) {
     if (i+j <= k || j+k <= i || i+k <= j)
          *match = 4;
     }

/* Confirm it's a legal triangle before declaring it
    to be isosceles or equilateral */

else if (*match  > 3)
        *match = 3;
else if (*match == 1 &&  i+j >= k)
       *match  = 2;
else if (*match == 2 &&  i+k >= j)
       *match   = 2;
else if (*match == 3 &&  j+k >=i)
       *match  = 2;
else
       *match = 4;

printf("\nReturn match = %d, ", *match);
return;
}

print_output( match)
{
switch( match)
        {
        case 1:
                  printf("the triangle is scalene.\n");
                  break;
        case 2:
                   printf("the triangle is isosceles.\n");
                   break;
        case 3:
                   printf("the triangle is equilateral.\n");
                   break;
        default:
                   printf("it is not a triangle.\n");
                   break;
        }
}
```

Figure 4.3 A faulty program trityp.c

*"match is (int *)0xf7fffa94*

match is 2

At step 13, does line 57 use any erroneous variable values?"

When our debugging critic receives a "yes" reply, it stops evaluating output statements and poses a request for the programmer to identify the erroneous variable. After the programmer identifies $*match = 2$ at line 57, execution step 13 as erroneous, our debugging critic adds $(*match, \sigma_1^{0,13}, erroneous(*match))$.

Our debugging critic then uses this information to initialize its search space for fault of omission and fault of commission for test case 1. $SSO(trityp.c, 1)$ is defined as ${\sigma_t}^{0,13}$. $SSC(trityp.c, 1)$ includes occurrences: $18^{(2,3)}$, $19^{(3,4)}$, $28^{(4,5)}$, $29^{(5,6)}$, $30^{(6,7)}$, $31^{(7,8)}$, $33^{(8,9)}$, $38^{(9,10)}$, $46^{(10,11)}$, $48^{(11,12)}$, and $49^{(12,13)}$.

As there are no more executed print statements that used a variable, our debugging critic ends the output evaluation process. It identifies the prime suspect occurrence for $(*match, \sigma_1^{0,13}, erroneous(*match))$ to be the dynamic reaching definition of $*match$ at line 49. It then makes the following recommendation:

"Given what you told me, I would recommend the following statement as

*a possible fault location because it defines *match*

49: $*match = 2;$

Would you like to guess at a fault location?"

When our debugging critic receives a "yes" reply and line 49 as the programmer's hypothesis, our debugging critic enters phase 2.

In phase 2, our debugging critic begins to pose evaluation questions. The first question is:

"Does the statement at line 49 assign a value to the wrong variable?"

When our debugging critic receives a "no" reply, it selects a dynamic reaching definition occurrence, $49^{(12,13)}$, for the symptom $(*match, \sigma_1^{0,13}, erroneous(*match))$. It then poses the question:

"At step 12, does the control flow reach line 49 by mistake?"

When our debugging critic receives a "yes" reply, it adds $(pc, {\sigma_t}^{0,12}, reach(49))$. The search spaces are reduced. $SSO(trityp.c, 1)$ is reduced to (0,12). $SSC(trityp.c, 1)$ is reduced to: $18^{(2,3)}$, $19^{(3,4)}$, $28^{(4,5)}$, $29^{(5,6)}$, $30^{(6,7)}$, $31^{(7,8)}$, $33^{(8,9)}$, $38^{(9,10)}$, $46^{(10,11)}$, and $48^{(11,12)}$. As the statement at line 49 no longer executes in either search space, our debugging critic rejects line 49 and recommends dynamic steerers of line 49.

"Line 49 is not the fault location.
You may want to consider statements that allow the flow of control to reach line 49 by mistake.
19: match_sides(i, j, k,&match);
38: if $(*match == 0)$
46: else if $(*match > 3)$
48: else if $(*match == 1 \&\& i + j >= k)$
Would you like to guess again?"

When our debugging critic receives a "yes" reply and the programmer specifies line 48 as his next hypothesis, our debugging critic poses the question:

"Is a predicate at line 48 incomplete?"

When our debugging critic receives a "do not know" reply, it selects the occurrence $48^{(11,12)}$, a prime suspect occurrence of $(pc, {\sigma_t}^{0,12}, reach(49))$. It then continues with the question:

"At step 11, does the control flow reach line 48 by mistake?"

When our debugging critic receives a "no" reply, it displays the values used at line 48 and a question about them:

*"match is (int *) 0xf7fffa94*
$*match$ *is 1*

i is 2

j is 2

k is 4

At step 11, does line 48 use any erroneous variable values?"

When our debugging critic receives a "no" reply, it displays the boolean value of the predicate:

"$(*match == 1 \&\& i + j >= k)$ *is true*

At step 12, does the predicate evaluate to an erroneous boolean value?"

When our debugging critic receives a "yes" reply, it recognizes that $48^{(11,12)}$ is a commission-fault-manifesting occurrence. It then confirms line 48 as the location of a manifested fault.

"Congratulations, I believe you have discovered the fault location!"

4.5 Summary

This chapter presents an active debugging assistant, a debugging critic, that can evaluate as well as formulate a hypothesis about a fault location. Our debugging critic is designed with features identified to overcome debugging pitfalls: confirmation, explanation, hints, and questions. In support of our debugging critic's operations, we define a uniform representation for failure symptoms, an execution path slicing method, two new types of dynamic control slices, characteristics of fault-manifesting occurrences for both a manifested fault of commission and omission, and search spaces for them.

5. IMPLEMENTATION AND EVALUATION

Never utter these words: 'I do not know this, therefore it is false.'
One must study to know; know to understand; understand to judge.
– Apothegm of Narada

This chapter covers an implementation of a debugging critic prototype and a debugging experiment on this prototype. The experimental results support our hypothesis: programmers can debug faster when they have access to a critic system than when they only have access to fault localization and break-and-examine tools. A fault localization tool alone does not significantly improve debugging speed. According to a survey of our experimental subjects, the users of our debugging critic are in favor of adding a debugging critic and its supporting functions on to other conventional debuggers.

5.1 A Debugging Critic Prototype

A prototype of a debugging critic was built as an extension to a prototype debugger, Spyder. This section gives an overview of Spyder and discusses the critic system's extension to Spyder.

5.1.1 Spyder

Spyder is a prototype debugger originated by Agrawal [Agr91] for ANSI C programs. It was built on top of the GNU C compiler, *gcc* and the GNU source-level debugger *gdb*. The development environment of Spyder is a SUN SPARC workstation running SUN OS 4, a derivative of BSD Unix. Details about Spyder's implementation can be found in Agrawal's dissertation [Agr91] and Pan's dissertation [Pan93].

Original Spyder commands are grouped into three major sets: break-and-examine operations, slice-related operations, and heuristics.

Break-and-Examine operations:

> This set includes commands that monitor program execution and behavior. Break commands set and delete break points in the program. Trace commands allow programmers to step forward or backward through the program execution. Print commands print values of a marked expression in the program or the value of a selected variable in a menu. Agrawal's dissertation [Agr91] describes execution backtracking in more detail.

Slice-related operations:

> This set includes commands to compute static and dynamic slice commands to compute combinations of slices. The slice types are: program slice, reaching definitions, data slice, control slice, and control predicate. These slices can be added, subtracted, intersected, and saved via slice-operations commands. Agrawal's thesis [Agr91] covers the implementation of slice-related operations in more detail.

Heuristics:

> This set includes 16 heuristics which, under predefined criteria, combine dynamic slices of a selected variable from a set of error-revealing and non-error-revealing test cases. Pan's thesis [Pan93] covers the implementation of the heuristics in more detail.

5.1.2 Spyder's critic extension

To support the critic system's operations, we added to Spyder's control panel window (1) an *evaluate locations* button, (2) an *error information* button, (3) a *grep* button, and (4) buttons for *enhanced break and print operations*. The new Spyder main window is shown in Figure 5.1. This section presents the operations of these buttons.

5.1.2.1 Evaluate locations

The *evaluate locations* button opens the main window for the critic system to communicate with the programmer. As shown in Figure 5.2, this main window is divided into four panes.

1. Critic's Dialogue pane:

   This window displays the critic's questions, comments, and values associated with the statement under evaluation.

2. Critic's Label pane:

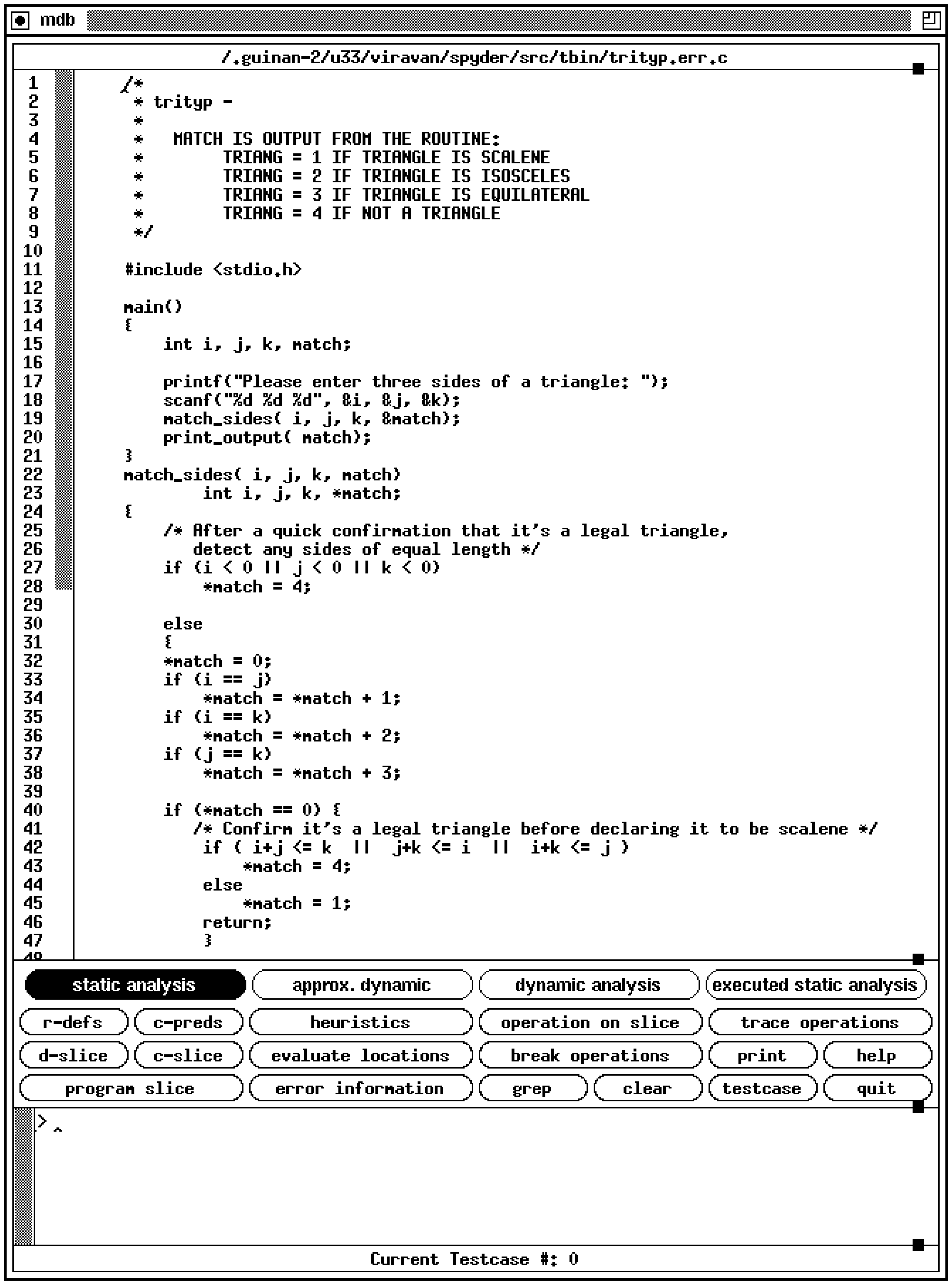
   This pane gives a one-line description of lines listed in the show-list pane.

3. Critic's Show-List pane:

   This window displays selected program statements or selected routine names (without parameters). The initial list includes the names of all routines in the program. When a programmer makes a hypothesis, this pane lists the statements at the hypothesized location. When the critic system suggests alternative locations, this pane lists the suggested lines. When the fault location is found, this pane lists the lines, routine name(s), or a code block that contains the fault.

4. Critic's Button pane:

   This pane consists of reply buttons and command buttons. The critic system selectively activates them during its conversation with the programmer.

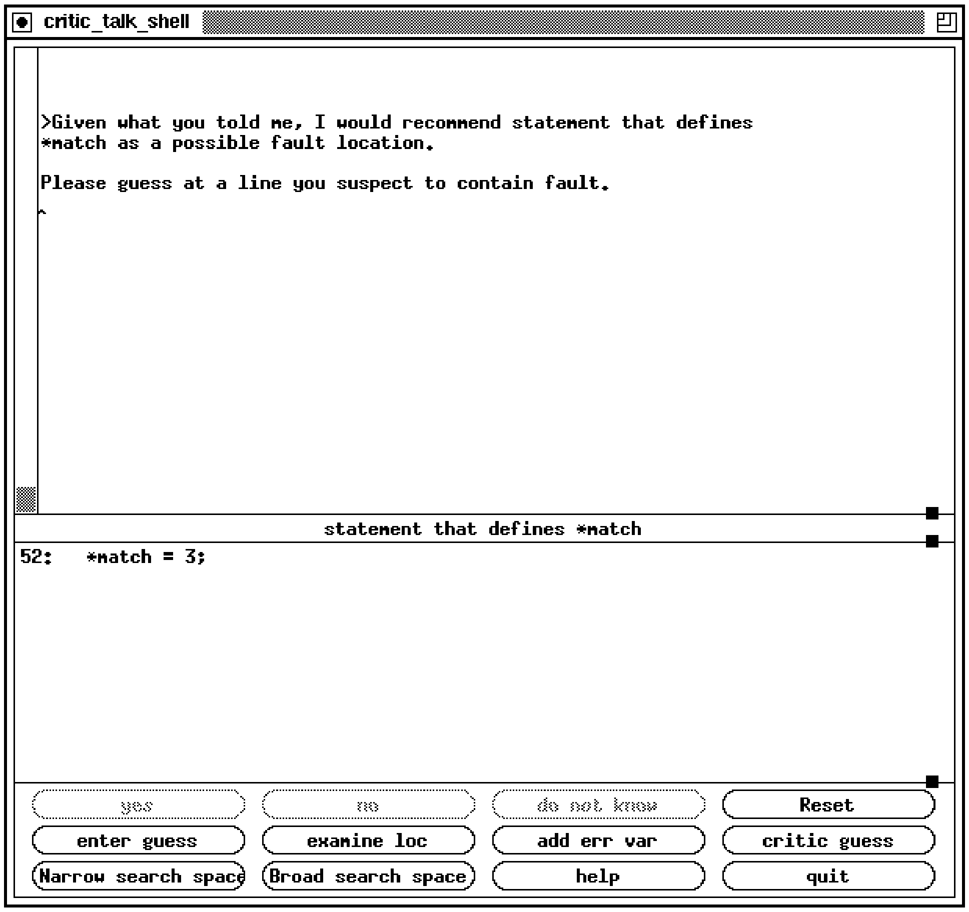


```
/*
 * trityp -
 *
 *   MATCH IS OUTPUT FROM THE ROUTINE:
 *        TRIANG = 1 IF TRIANGLE IS SCALENE
 *        TRIANG = 2 IF TRIANGLE IS ISOSCELES
 *        TRIANG = 3 IF TRIANGLE IS EQUILATERAL
 *        TRIANG = 4 IF NOT A TRIANGLE
 */

#include <stdio.h>

main()
{
    int i, j, k, match;

    printf("Please enter three sides of a triangle: ");
    scanf("%d %d %d", &i, &j, &k);
    match_sides( i, j, k, &match);
    print_output( match);
}
match_sides( i, j, k, match)
        int i, j, k, *match;
{
    /* After a quick confirmation that it's a legal triangle,
       detect any sides of equal length */
    if (i < 0 || j < 0 || k < 0)
        *match = 4;

    else
    {
    *match = 0;
    if (i == j)
        *match = *match + 1;
    if (i == k)
        *match = *match + 2;
    if (j == k)
        *match = *match + 3;

    if (*match == 0) {
       /* Confirm it's a legal triangle before declaring it to be scalene */
        if ( i+j <= k  ||  j+k <= i  ||  i+k <= j )
            *match = 4;
        else
            *match = 1;
        return;
        }
```

```
> ^
```

Current Testcase #: 0

Figure 5.1 New Spyder's Main Window



```
>Given what you told me, I would recommend statement that defines
*match as a possible fault location.

Please guess at a line you suspect to contain fault.
^
```

statement that defines *match

```
52:   *match = 3;
```

Figure 5.2 Critic's Window

```
KEY("Blank line or comment line");
COMMENT("Line $GUESS_LINE$ cannot execute.");
QUESTION("You may want to consider $SUGGEST_LOC$.  \
Would you like to guess again?");
ANSWERS( BID_YES,         cr_guess_again_callback);
ANSWERS( BID_NO,          cr_any_command_callback);
ACTIVE_BUTTON( BID_YES);
ACTIVE_BUTTON( BID_NO );
ACTIVE_BUTTON( BID_QUIT);
```

Figure 5.3 Sample dialogue entry

- Reply buttons

  Three buttons, YES, NO, DO NOT KNOW, are activated when the critic system poses a question. The functions corresponding to these buttons vary with respect to the question.

- Command buttons

  The command buttons and their corresponding functions are shown in Table 5.1.

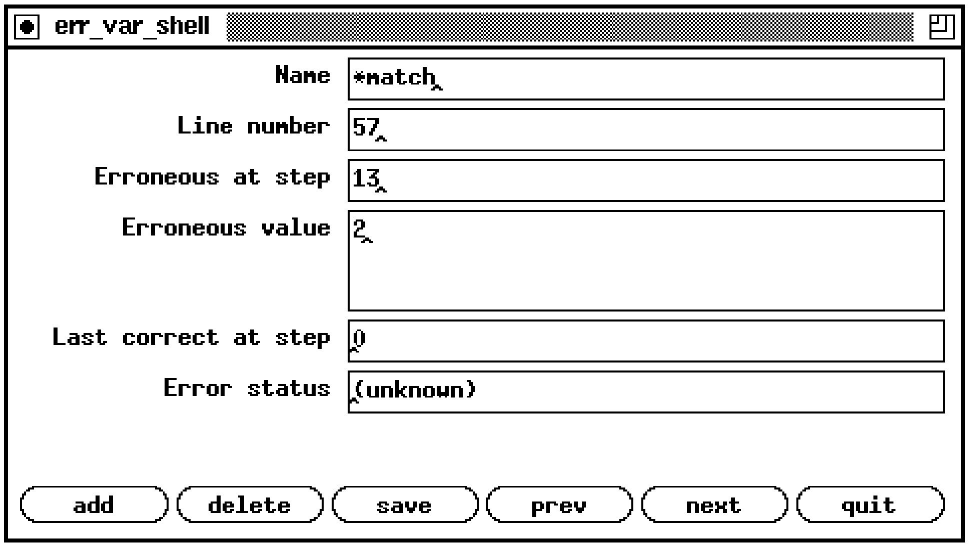
The critic system's questions-and-answers interface is controlled by its dialogue-base. Each dialogue entry includes the key, the critic's comment template and/or the critic's question template, the allowed responses with their corresponding functions, and the critic's keys to be activated. An example of a dialogue entry is shown in Figure 5.3. Keywords in each template are enclosed by $ signs. All dialogue entries are contained in one C routine. KEY, COMMENT, QUESTION, ANSWERS, and ACTIVE_BUTTON are also C routines.

5.1.2.2 Error information

The *error information* button opens a submenu. Three buttons on this submenu are: erroneous variables, erroneously reached lines, and erroneously unreached lines. Each button opens up a form to add, delete, save, or view records on error information.

Table 5.1 Critic's command buttons

Critic command keys	Functions
enter guess	Enters a line number for the critic to evaluate.
examine loc	Automatically sets break points on lines listed in the bottom window.
add err var	Opens a window to add erroneous variables.
critic guess	Critic hypothesizes at a possible fault location.
narrow search space	Lists statements in $SSC(\mathcal{P}, t)$.
broad search space	Lists routines on the search path.
reset	Erases all known error information and sets both search spaces to null.
help	Displays help message.
quit	Closes the critic's window.


err_var_shell

Name	*match
Line number	57
Erroneous at step	13
Erroneous value	2
Last correct at step	0
Error status	(unknown)

Figure 5.4 A window to enter erroneous variables

Figure 5.4 shows the entry screen for erroneous variables. Screens for erroneously reached or unreached lines are similar.

5.1.2.3 Grep

This key opens a dialog box. After the programmer enters the word on which to do the grep, the critic system highlights the lines that match the given word in the Spyder window. It also lists these lines in the Critic's dialog pane, if the critic system's window is opened.

5.1.2.4 Enhanced break and print operations

Some of the enhanced break and print operations that the critic system invokes internally are made directly available to the programmer.

1. *Print values before execution*

   This key prints the values of all expressions on the current line before the line is executed. The critic system invokes the function underlying this key implicitly before it asks a programmer whether he sees any variable with erroneous values.

2. *Print values after execution*

   This key executes a step command and print command. If an assignment statement is executed, a variable gets defined and its value is printed. If a predicate is executed, the predicate and its boolean value are printed. If a calling statement is executed, the formal parameter variables and their assigned values are printed. The critic system invokes the function underlying this key implicitly before it asks a programmer whether he sees any erroneously defined values.

3. *Stop in slice*

   This key automatically sets the break points on lines highlighted by slicing techniques, grep, or the critic system. The critic system invokes the function underlying this key to set break points in all lines listed within its show-list pane.

5.1.3 Implementation limitations

Our first prototype version of the debugging critic has a few implementation limitations. First, it operates under the assumption that each line of the program contains at most one statement. Second, because the program dependency graph underlying Spyder does not establish weak dependencies among statements, this prototype version does not yet evaluate any hypothesis about transfer statements (e.g., return, continue, break, goto's). Third, it cannot evaluate a statement that contains a function call in its expression. To handle this case, the critic system could treat both the values of the parameter and the return values from each function call as input values to the statement. If the return value is error-revealing, the critic can then compute the dynamic reaching definition from the expression of that function call to identify the statement that returns that erroneous value. Agrawal's dynamic slicing method can be extended to accomplish this.

Fourth, it has a limited capability in handling side-effects from variable aliasing (e.g., more than one variable name is associated with the same memory location).

If the side-effect symptom is identified first, the critic system can hypothesize about the statement that caused it (via Agrawal's dynamic slicing [Agr91]). However, if the critic system evaluates the statement that causes the side-effect before the side-effect symptom is identified, then the critic system may not always confirm that the statement is faulty.

For example, suppose variable var_1 is an alias of variable var_2 and a statement that defines var_1 at line 10 causes var_2 to become error-revealing. If the erroneous value of var_2 has been identified as a failure symptom, then the critic system can hypothesize that the dynamic reaching definition of var_2 at line 10 could have caused it. However, if the critic system has to evaluate line 10 before the symptom of var_2 has been identified, the critic system would recognize line 10 as a fault location only if the defined value of var_1 is also error-revealing.

5.2 Experimental Evaluation

This section presents our experiment to evaluate whether a debugging critic can improve programmers' debugging speed. We compared three groups of programmers who used Spyder to debug a program. The first group used only break-and-examine operations. The second group used both program slicing and break-and-examine operations. The third group used a debugging critic, program slicing, and break-and-examine operations. In this experiment, program-specific information was not available to our debugging critic.

A follow-up pilot study that tested a group of programmers who debugged a program using a modified version of our debugging critic is presented in Section 5.3. It is not presented here because not all program versions under test in this experiment were tested in the pilot study.

5.2.1 Experimental design

We used a factorial design for our experiment. Our experimental design and its mathematical model are shown in Figure 5.5. In the mathematical model,[1] Y_{ijkl} was a *dependent variable.* A_i, B_j, and P_k were *factors* or *independent variables.* The error, $\epsilon_{(ijk)l}$ was not synonymous with "mistakes," but included all types of extraneous variations that tended to mask the effect of the treatment [CC57].

A measurement to be compared is debugging speed instead of debugging time. We did not use debugging time directly because when the programmer cannot find the fault, time was infinity. The reciprocal of time, on the other hand, is zero. Thus, debugging speed, computed as a reciprocal of time as shown below, is also zero when the the programmer could not find the fault.

$$DSPEED = \frac{\text{total lines in a program with one fault}}{TIME}$$

$DSPEED$ is the total lines debugged per minute *(lpm).* TIME was measured in minutes and was automatically computed by Spyder when it recorded each debugging session. TIME excluded the compilation time, test case entering time, and time to run an error-revealing test case for the first time.

The factors in this experiments were as follows:

Spyder

Spyder level 1 only allowed access to the break-and-examine operations. Spyder level 2 allowed additional access to program slicing and slice operations. Spyder level 3 allowed additional access to Spyder with a debugging critic based on the model described in chapter 4. We disabled the heuristics and execution backtracking features in all three versions of Spyder.

[1]The interaction terms (e.g., the combined effects of the factors) are not in the model. As the effects of the interaction terms were found insignificant in our study, the terms can be pooled into the error term, $\epsilon_{(ijk)l}$ [Mon91].

Spyder	1				2				3			
Program	1		2		1		2		1		2	
Fault Class	1	2	1	2	1	2	1	2	1	2	1	2

$$Y_{ijkl} = \mu + A_i + B_j + C_k + \epsilon_{(ijk)l}$$

where

$$\begin{aligned} Y_{ijkl} &= \text{debugging speed} \\ \mu &= \text{average of Y} \\ A_i &= \text{Spyder, } i = 1, 2, 3 \\ B_k &= \text{Program, } k = 1, 2 \\ C_j &= \text{Fault class, } j = 1, 2 \\ \epsilon_{(ijk)l} &= \text{Error, } l = 1 \end{aligned}$$

Figure 5.5 Experimental design

Programs

Levels of programs represented two syntactically correct C programs. Neither program contained transfer statements. We wrote both programs.

1. *Payday program*

   This program computes the next three paydays after the given date. Every last Friday of the month is a payday unless: (1) the last Friday is Christmas or New Year's Eve, or (2) the month is June or July. In the first case, the following Monday is the payday. In the second case, no pay check is given, so the next payday would be in August.

   The Payday program contains a total of 274 lines, 189 of which are executable. It has 8 procedures with a maximum nesting level of five. This program contains an average of 19 characters per line. Comments constitute 13.1% of the program.

2. *Shipbook program*

   This program identifies the sizes of boxes in which to ship an order of books. A book order consists of the number of books, length, width, and total pages per book. Three box sizes are available. Each box is not allowed to weigh more than 30 pounds. The program prints out the box size, the total number of books in each box, and the box weight.

   The Shipbook program contains a total of 338 lines, 238 of which are executable. It has 9 procedures with a maximum nesting level of three. This program contains an average of 18.4 characters per line. Comments constitute 8.6% of the program.

Fault Class

Fault class level 1 corresponded to a fault of commission. Fault class level 2 corresponded to a fault of omission. All faults used in this experiment were real faults found during development of the programs.

In the Payday program, the fault of commission was in a loop predicate where an operation $<$ was used instead of $<=$. This fault was in $find\_last\_friday()$, nested at level 4. The fault of omission was a missing predicate and assignment to increment the year when the payday in December was already past. This fault was in $find\_next\_month\_pay\_day()$, nested at level 2.

In the Shipbook program, the fault of commission was in an assignment statement where two operands of the subtract operation were interchanged. This fault was in $compute\_max\_books\_in\_box()$, nested at level 3. The fault of omission was a missing assignment statement. This fault was in $find\_best\_fit\_box()$, nested at level 2.

5.2.2 Participants

Our experimental subjects were senior undergraduate students in the Department of Computer Sciences at Purdue University. All had at least three years of programming experience and knowledge of the programming language C. All had written at least one major project using C.

5.2.3 Procedures

One week before the experiment, the participants were given a Spyder homework assignment. This homework was designed to help them learn break-and-examine operations and program slicing operations. The debugging critic was not available at this time.

For the experiment, 39 students were randomly assigned to 12 subgroups. Each group contained 3 or 4 students. The experiment was carried out in lab sessions for a senior-level computer science class. Groups that debugged the same program were tested in the same lab session. Students had a maximum of three hours to find the fault location.

At the beginning of the session, programmers received a program listing, its one-page natural language specification, one error-revealing test case, one non-error-revealing test case, and a description of how the program failed externally (e.g., which output values were erroneous). They were instructed to run a script file that automatically retrieved the faulty program, compiled the program, entered the test cases, and started Spyder. During a debugging session, Spyder recorded debugging time, debugging commands used, and output produced by Spyder. When the programmer was convinced that he had found the fault, he were asked to complete a survey form (see Appendix C.1) to indicate the fault location. In the survey, each programmer was asked to rate the helpfulness of the Spyder features to which he had access. He also was asked to indicate whether he would like to see such features added to other conventional debuggers.

5.2.4 Analysis results

Comparison of average debugging speed is shown in Figure 5.6. Overall results showed that programmers debugged twice as fast with the critic system than without it. For the faults of omission, the programmers debugged four times faster with the critic system than with only break-and-examine operations. Overall, programmers who debugged with only the break-and-examine operation (group 1) had an average debugging speed of 2.1 lpm. Programmers who had additional access to slicing and slice operations (group 2) had an average speed of 2.3 lpm. Programmers who had additional access to a debugging critic (group 3) had an average speed of 4.4 lpm.

To analyze possible causes of debugging speed variation, we used the General linear model (GLM). The General Linear Model consists of several analysis methods, one of which is Analysis of Variance with unbalanced data.[2] The resulting p-value was used to determine the confidence level (1 − p-value)% in identifying the source of variation for debuging speed.

[2]The underlying statistical theory behind GLM is the same as Analysis of Variance (ANOVA), but ANOVA requires balanced data [Sea71].

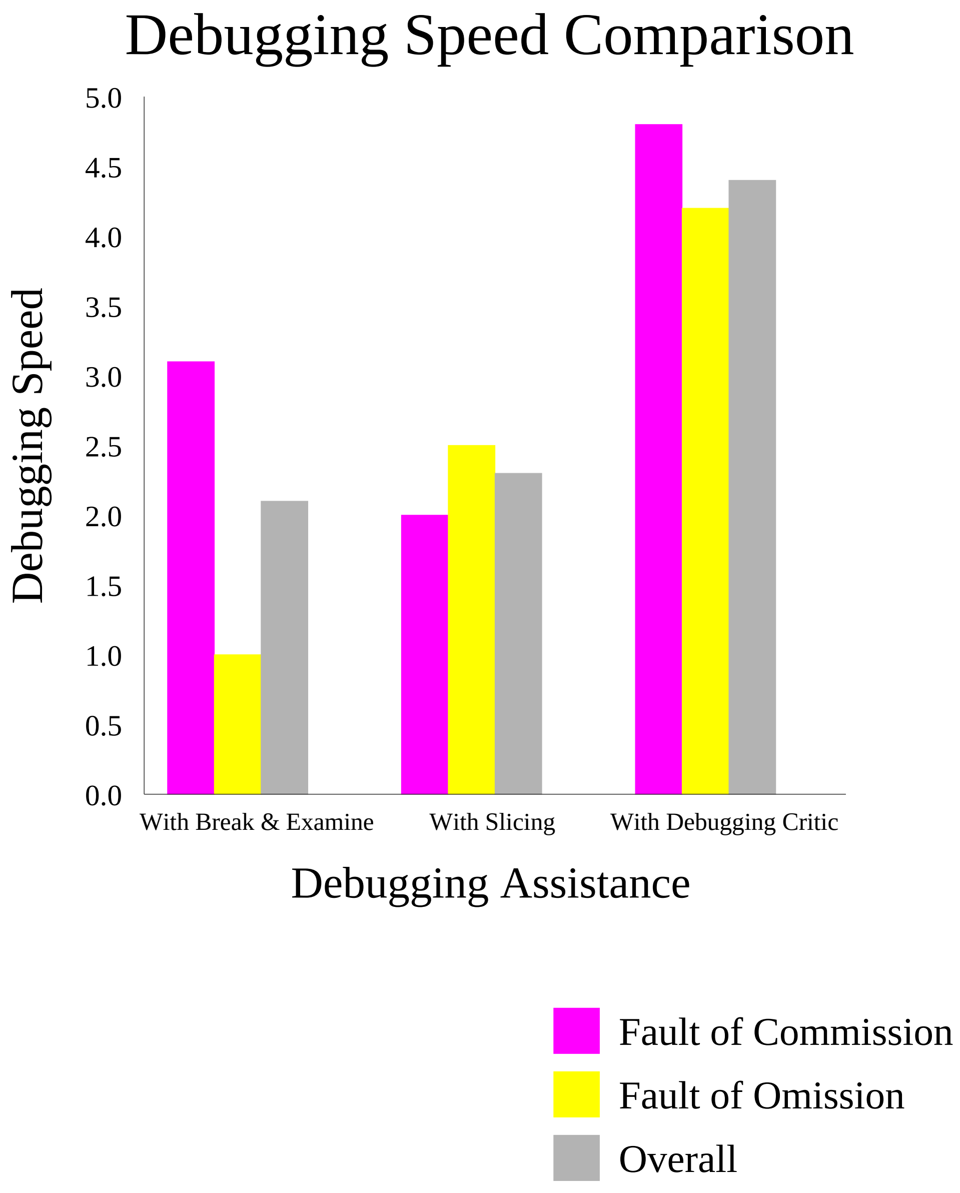


Figure 5.6 Debugging speed comparison

Table 5.2 Statistical result

Source of speed variation	Confidence Level	P-value
Spyder Version		
Version 1 vs. Version 3	99.09%	0.0091
Version 2 vs. Version 3	94.94%	0.0506
Version 1 vs. Version 2	22.49%	0.7751
Program		
Payday.c vs. Shipbook.c	95.40%	0.0460
Fault class		
Commission vs. Omission	40.58%	0.5942

The statistical results shown in Table 5.2 supports our statement of thesis that *programmers can debug faster when they also have access to a tool to help confirm hypotheses on fault locations than when they only have access to tools that help formulate the hypotheses.* Spyder versions and programs were the source of variation in debugging speed. Programmers who had access to the critic system (Spyder verion 3) debugged significantly faster than those who had access to the break-and-examine features only (Spyder version 1), and faster than programmers who had access to program slicing and break-and-examine features (Spyder version 2). Programmers debugged program Payday.c significantly faster than they debugged program Shipbook.c. However, they did not debug a fault of commission significantly faster than they debugged a fault of omission.

5.2.5 Qualitative results

Our survey results and our observation indicated that the critic system helped overcome the two previously identified debugging pitfalls: "fixation to the wrong location" and "underuse" problems. It helped the programmers to benefit from the fault localization technique (program slicing). It also worked in conjunction with a fault recognition tool (grep).

5.2.5.1 Overcoming the "Fixation on the wrong location" problem

A debugging critic helped overcome the "fixation on the wrong location" problem. We counted the number of programmers who identified a wrong fault location to determine how many programmers did not overcome this problem. Figure 5.2.5.1 shows that with break-and-examine operations alone, 33% of the programmers did not overcome the fixation problem. When the programmers had additional access to slicing operations, 43% of the programmers did not overcome the fixation problem. However, when the programmers had additional access to the critic system, only 8% did not overcome the fixation problem.

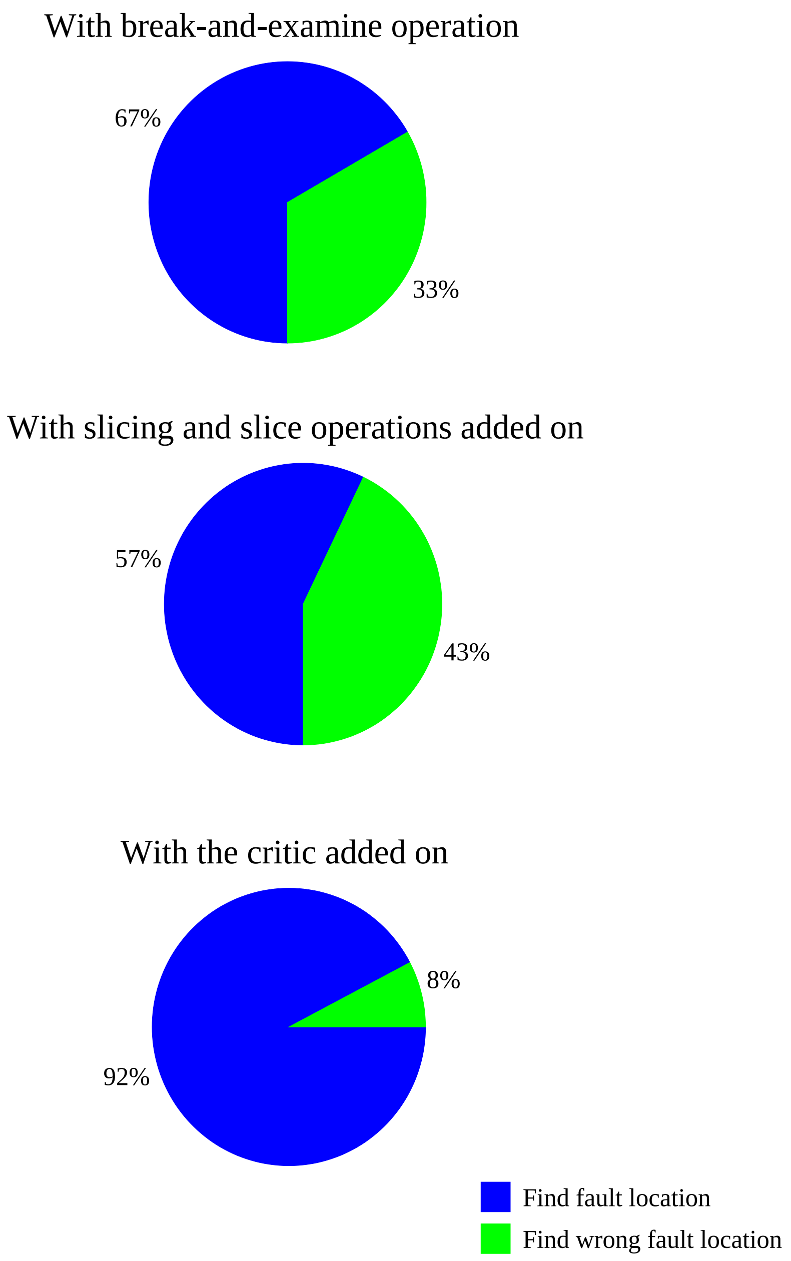


Figure 5.7 Percentage of programmers who identified wrong fault location

From our observation, programmers who had access to the critic system did experience the fixation problem, but the critic system helped them overcome it. Once the critic system rejected their hypothesized location and suggested an alternative location, the programmer investigated the program further. Afterward, some programmers hypothesized at the location that the critic system recommended. Some examined the program to find other possibilities.

5.2.5.2 Overcoming the "Underuse" problems

The critic system did not underuse a programmer's knowledge, as it incrementally acquired his knowledge of the failure symptoms. Further analysis on the symptoms allowed it to formulate and evaluate hypotheses about fault locations.

Programmers did not underuse the critic system. All programmers who had access to the critic system used it. In our survey, the programmers were asked to rate the helpfulness of all Spyder's features under test, as N/U (for unused), or as a number between 0 to 10, where 0 indicates no help and 10 indicates the most help. The rating for our debugging critic was 8.5385, the highest rating among all Spyder's features under test (see Table C.1) It was also the only feature with no N/U rating (see Table C.2). Also, 12 out of 13 programmers recommended that the critic system to be added on to conventional debuggers (see Table C.3).

5.2.5.3 Augmenting program slicing techniques

Programmers benefited more from program slicing when the critic system computed the relevant slices for them than when they had to compute the slices on their own. Without the critic system, program slicing and slice operations were underused. According to the survey, 8 out of 13 programmers did not use program slicing and 10 out of 13 programmers did not use slice operations (see Table C.2). The programmers indicated that program slicing would be more helpful to them if (1) they had more experience in using it, (2) on-line help with numerous examples were available, or

(3) a manual that thoroughly described different program slices was available. From our observation, it appeared that programmers did not know which slices to use and when to use them.

With the critic system, the programmers benefited from program slices without the overhead of training time. (Recall that the programmers did not have access to the critic system during the one week before the experiment.) The knowledge of program slices, when presented as the critic system's recommendation, did persuade programmers to look elsewhere. Without the critic system, we observed programmers develop a fixation on a wrong statement in a dynamic slice, such as the dynamic reaching definition of an erroneous variable.

The critic system also promoted the understanding of program slices. When the programmer used program slicing without the critic system, the programmers had to determine what types of statements they were searching for and what types of slices (or their combinations) would identify those statements. The critic system determined which slices might contain faulty statements, recommended them, and explained how they affected the known failure symptoms.

5.2.5.4 Augmenting fault recognition tool

A pattern matching tool, such as *grep*, can be considered a primitive fault recognition tool, as a programmer can use the tool to find code that matched a specified pattern. From our observation, programmers did use *grep* in conjunction with the critic system. Programmers used *grep* to locate code with a keyword that was related to the failure symptom. For example, the word "Friday" was used when the program *payday.c* failed to identify the last Friday of the month. A programmer then requested that the critic evaluate one of the statements from the matched statements or from the code block near the matched comments. In one case, the critic system confirmed a statement *before* the programmer knew what the fault was.

The use of the critic system with grep complimented the critic's analysis capabilities with the programmer's expertise in pattern recognition. The result was a cooperative problem-solving environment that significantly improved debugging speed.

5.3 Questions about Debugging Critic

1. *"Would any question and any hint also help overcome debugging pitfalls and improve debugging speed?"*

   According to our follow-up pilot study on a *"mock"* critic system, the answer is "no." A mock critic system was developed to pose questions about the program that did not pertain to output statements, did not acquire failure symptoms, and did not promote the use of the critic system. We studied three computer science students who used Spyder with the mock critic system, program slicing and break-and-examine assistance to debug the program Shipbook.c with the fault of omission.

   The results show that the programmers did not find the mock critic system useful. The average helpfulness rating was 2.3. In comparison, the rating of the real debugging critic from programmers who debugged the same version of Shipbook.c was 8. In this pilot study, the mock critic system did not overcome the fixation on the wrong location problem, as two out of three students identified the wrong fault location. Programmers who debugged the same version of Shipbook.c with only break-and-examine and slicing assistance debugged faster (the average speed was 2.5 lpm) than the programmers who had additional access to the mock critic system (the average speed was 1.5 lpm).

2. *"Can a debugging critic work as a standalone tool? If so, how?"*

   The answer is "yes." Two out of thirteen programmers used the critic system alone to find the fault. Both programmers used the critic system to indirectly evaluate hypotheses about program behavior as well as formulate hypotheses about a fault location.

To query about program states associated with a given location, the programmer can hypothesize the location. For example, if the programmer hypothesizes that a statement at line 100 does not execute, he can invoke the critic system to evaluate line 100. If the critic system poses the question *"The statement at line 100 does not execute, should it?"*, then the programmer receives his confirmation. If the programmer hypothesizes that a statement at line 100 used an erroneous value of variable *var*, he can invoke the critic system to evaluate line 100. To help the programmer evaluate the statement, the critic system would print values the statement used before its execution.

To trace to the cause of the newly acquire failure symptom, a programmer can invoke the critic system to evaluate an alternative location it recommended. The critic system would internally execute the hypothesized statement, display the values used before the statement executes, and the values defined after the statement executes. After the critic system evaluates the hypothesized statement, it may acquire another failure symptom and recommend another location. Thus, the tracing process can continue.

3. *"Can a debugging critic operate when multiple faults are manifested under the same test cases?"*

   The answer is "yes," although it is not predictable whether all faults that manifested under the given test case can be found. We tried using the critic system in the setting where we debugged our own program as we implemented it. In this case, the program did contain several faults that were exposed by the same test case. The critic system successfully helped us locate at least one fault for each error-revealing test case. To find another fault, however, we had to fix the one we found first, then use the critic system again.

5.4 Summary

This chapter described a debugging critic prototype added in to Spyder and an experimental study based on this prototype. The results showed that programmers can debug significantly faster with a critic system. In our survey, the debugging critic had the highest helpfulness rating among Spyder's features under test. The users of our debugging critic recommended it as an extension to conventional debuggers.

6. CONCLUSIONS

The only limit to our realization of tomorrow will be our doubts of today.
– Franklin D. Roosevelt

6.1 Support for Statement of Thesis

This dissertation presents a new debugging assistant, the *Debugging Critic*. A debugging critic is an alternative to a debugging oracle. It answers "Is it conclusive that the statement at location *loc* contains the fault that was manifested under the given test case *t*?" by recognizing a fault-manifesting occurrence of either a fault of commission or a fault of omission.

Given a hypothesized location of a statement and a test case, the critic system can evaluate whether the statement contains the fault that causes a program to fail under the given test case. The critic system does not rely on a formal specification or a knowledge base of a common fault pattern. Instead, it poses questions about the statement and its occurrence to determine whether the statement at the hypothesized location has a fault-manifesting occurrence, exhibits failure symptoms, or neither. Because we identified the characteristics of fault-manifesting occurrence for both fault of commission and fault of omission, we can design the critic system to recognize the location where either fault manifests.

To design an debugging assistant that can improve debugging speed, we conducted empirical studies involving expert programmers who debugged a large program. The results revealed debugging pitfalls and types of assistance to overcome them. The design of our debugging critic incorporates the four types of assistance identified:

confirmation, explanation, hints, and questions. The results also helped us design the proposed mechanisms to support the hypotheses evaluation process in ways that can improve debugging speed:

Maintain knowledge about the program.

The critic system maintains two types of knowledge about the program: failure symptoms and search spaces for a manifested fault. Failure symptoms are uniformly described for both erroneous variables and erroneous flow of control, as opposed to application-specific special cases. The search space for a manifested fault of commission is defined separately from the search space for a manifested fault of omission.

The critic system's ability is enhanced as it acquires more symptoms. When the evaluation process does not confirm a fault location, it may yield new failure symptoms that can define and reduce the search spaces. A subsequent hypothesis can be rejected without evaluating any of their execution occurrences when the statement at the hypothesized location does not execute in either search space.

Formulate an alternative hypothesis on fault location.

Based on a selected failure symptom, the critic system identifies either prime suspect statements as a possible fault of commission location or prime suspect procedures as a possible fault of omission location. We define *execution path slicing* as a means for the critic system to identify statements whose occurrences can cause the symptom and which appear in at least one of the search spaces. The absence of statements that can cause the symptom indicates a fault of omitted statements. The critic system can also hypothesize about the type of missing statement with respect to the failure symptom.

Augment existing fault localization or fault recognition tools.

> The critic system can augment an existing fault localization tool, program slicing. Our experimental study of a debugging critic prototype showed that the critic system can promote the programmer's use of knowledge from program slices to locate faults without a long training period.
>
> The critic system also augments an existing pattern-matching fault recognition tool, grep. In our experiment, the programmers used grep with keywords related to program failure to quickly locate relevant code and comments. They then selected one of the statements for the critic system to evaluate. This process forms a cooperative problem-solving environment, where the programmer's expertise in pattern recognition and the critic system's analysis capabilities are combined to find the fault.

Our experimental study of a debugging critic prototype showed that programmers who used it can overcome two debugging pitfalls: "fixation on the wrong location" and "underuse" problems. As a result, these programmers debugged faster than programmers who had access to break-and-examine tools or both break-and-examine tools and program slicing tools. Without our debugging critic, programmers underused program slicing and/or could not overcome their fixation on an incorrect location. The result of this experiment provides evidence to support our statement of thesis.

6.2 Contributions

The research in this dissertation contributes to debugging and critic systems. In debugging, our empirical studies of the debugging assistants and our experimental study of a debugging critic contribute to the knowledge that an active debugging assistant can effectively improve debugging performance. In addition to providing information about the program, an active debugging assistant would use questions to direct the programmers' focus, to help them develop fault-related hypotheses, and to evaluate these hypotheses.

Another contribution is our approach to evaluate and formulate hypotheses on fault location in the absence of formal specification and knowledge base of faults, especially our approach to locate and recognize locations with a manifested fault of omission location. Each key component in our approach can form a foundation for a future debugging assistant. First, characteristics of an omission-fault-manifesting occurrence make it possible to design other fault localization techniques to locate omitted statements. Second, our uniform representation of failure symptoms can be used to define failure symptoms in other failure modes, such as non-termination and abnormal termination. A uniform failure symptom representation provides support for a uniform failure analysis method. Third, execution path slicing methods can be applied to design a variety of fault localization algorithms other than the binary search algorithms.

In the critic system domain, one of the main concerns is how to present criticism without offending users. The solution offered by our debugging critic is to use questions. A question such as *"The statement at $\mathcal{L}$ is not executed by this test case. Should it be?"* offers an informative and non-insulting criticism.

6.3 Future Research Directions

Large scale experimental evaluation of an automated debugging critic

The goal is to conduct experiments where our debugging critic is used in debugging programs in natural settings. Several possibilities include testing the effectiveness of a debugging critic when:

- programmers debug their own programs.
- programmers debug other's programs ranging in size from hundreds to thousands of lines.

- programmers have access to the critic system during the program implementation phase.
- programmers have no access to any other debugging assistance except the critic system.

It is desirable to conduct these experiments with a debugger that also supports languages and features found in large software systems (such as preprocessor statements) and also build a program dependency graph that depicts weak dependency among statements [PC90]. It is also desirable to enhance our debugging critic to evaluate and formulate hypotheses about transfer statements and to become more active during the debugging process. The critic system may interrupt a programmer when he repeatedly inspects locations on which erroneous variables did not depend, and offer to evaluate such locations.

Evaluation of a procedure as a possible fault location

There are two subgoals. The first subgoal is to minimize the the number of program states and the number of values associated with the hypothesized procedure that the critic system would ask the programmers to evaluate. The second subgoal is to define methods to recognize when a procedure omits statements.

Debugging critic with knowledge base of faults

The goal is to investigate how a knowledge base of faults can enhance a debugging critic. Some possibilities include customizing questions to evaluate locations where the code matches a fault pattern, and formulating and evaluating hypotheses about fault identity. The enhanced critic system may be able to check whether an existing set of failure symptoms is the consequence of the hypothesized fault.

Debugging critic with test-based knowledge

The goal is to investigate how a test data set and other test-based knowledge can enhance a debugging critic. Some possibilities include the added capability to formulate and evaluate hypotheses about fault repair. The enhanced critic system may be able to determine whether existing failure symptoms would remain if the hypothesized repair is made. The enhanced debugging critic may also identify the test cases that reveals when the hypothesized repair leads to a new set of failure symptoms.

Fault localization algorithms for omitted statements

The goal is to extend our technique to locate omitted statements to also locate other types of statements beside assignment statements, procedure calls, predicate statements, initialized statements, and output statements. The technique can also be extended to locate faults of omission that lead to abnormal termination or non-termination.

6.4 Concluding Remarks

Our debugging critic dispels two myths about debugging. The first myth is that it is impossible to confirm a fault location because of the lack of detail and formal specification. Our research shows that failure symptoms and dependency analysis can be used to confirm the location of a statement with a fault, when only one fault is manifested under a given test case. The second myth is that it is impossible to define a method to locate faults of omission. Our research shows that it is possible to locate procedures that omit assignment statements, procedure calls, predicate statements, initialized statements, or output statements when the fault of omission is manifested under the given test case. This research establishes a foundation for debugging research in both areas.

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APPENDICES

Appendix A: Data from Empirical Studies on Debugging Assistants

A.1 The faults used in the empirical studies

Faults	**#1**	**#2**
Type	Missing data definition	Missing data handling task
Failure	Core dump	Wrong output
Error-revealing test data	Empty GECOS field in chfnadd file	Add home directories for multiple users
Chain of Causes of Failures	Reference bad pde pointers in mark_ml() ↑ Pass undefined pde to mark_ml() from get_chfn_info() ↑ Missing definition for pde when GECOS field is empty	Overwrite the same memory location in add_home_dir() ↑ Dangling pointers in home_dir_list in edit() ↑ Forget to reset pde in home_dir_list to point to the original entry before freeing the memory of copy of pde
Faulty routine	get_chfn_info()	edit()
Calling level	1	3
Correct fixes	- Initialize pde before calling mark_ml() - Do not call mark_ml() when pde is uninitialized	- Call change_home_dir() before freeing pde copy

A.2 The Measurements

1. *Accuracy in hypotheses on fault location (ACLOC):*

$$ACLOC = \frac{\text{total faulty routines}}{\text{total routines in search space}}$$

ACLOC is 0 if the search space omits the faulty routine. *A search space* is regarded as a collection of hypotheses on fault location.

2. Accuracy in hypotheses on fault identity (ACID):

$$ACID = \frac{\text{number of causes of failure identified}}{\text{total causes of failure}}$$

We describe the fault identity in a chain of causes of the program failure. Causes of fault 1 and 2 are shown in Appendix A.1.

3. *Accuracy in hypotheses on fault repair (ACFIX):*

$$ACFIX = \begin{cases} 1, & \text{if correct solution;} \\ .50, & \text{if solution with side effect;} \\ 0, & \text{Otherwise.} \end{cases}$$

A solution is a repair made on one of the causes of failures (see Appendix A.1). Thus, any repair that merely avoids the failures does not count. A print statement that echos the known correct output, for example, is not considered a solution.

4. *Overall accuracy (AC):*

$$AC = 33 * ACLOC + 33 * ACID + 34 * ACFIX$$

5. The average accuracy in locating faulty routine (AACLOC):

   AACLOC is the sum of ACLOC reported at end of each hour divided by the number of hours.

6. *The accuracy gained per hour (SPEED)*

$$SPEED = 60 * \frac{AC}{TIME}$$

7. *The actual time (TIME):*

   TIME is measured in minutes. This excludes (1) the time to copy over the tar file, expand it, compile and run Nu for the first time, (2) the time to write fault-related hypotheses and mail it with the script at the end of each hour, and (3) the break time. The consulting time with the oracle is included.

8. *The estimated time taken to fix the fault correctly (ETIME):*

$$ETIME = 100 * \frac{TIME}{AC}$$

Figure A.1 Debugging time comparison

Figure A.2 Debugging accuracy comparison

Appendix B: Proofs for Search Spaces on a Manifested Fault

This appendix presents proofs by contradiction that the search spaces defined for a manifested fault contains a fault-manifesting occurrence.

B.1 Proof for Search Space for a Manifested Fault of Omission

Theorem: If a fault of omission is the only fault exposed by test case t, then $SSO(\mathcal{P}, t)$ always includes a omission-fault-manifesting occurrence.$\Box$

Proof: Let $\mathcal{L}$ represent either a location of a procedure or a statement. Suppose $\mathcal{L}$ contains a fault that is manifested as a fault of omission under test case t, but the code at $\mathcal{L}$

To prove by contradiction, we have to consider the following cases when the code containing fault of omission is not executed in $SSO(\mathcal{P}, t)$. The code is either executed or not executed in σ_t. If it is not executed, then it is not executed in $SSO(\mathcal{P}, t)$. If it is executed in σ_t, σ_t may associate with no failure symptoms or at least one failure symptom. If there is no failure symptom, $SSO(\mathcal{P}, t)$ is null and no code can execute in it. If there is at least one failure symptom, $SSO(\mathcal{P}, t)$ is defined as ${\sigma_t}^{top,bottom}$ minus the execution occurrences that have already been evaluated to be non-fault-manifesting occurrences. In this case, the code is not executed in $SSO(\mathcal{P}, t)$ when it is executed before step *top*, is executed after step *bottom*, or all of its execution occurrences have already been evaluated to be non-fault-manifesting occurrences Thus, there are five cases to contradict:

Case 1: The code at $\mathcal{L}$ is not executed.

In this case, the fault at $\mathcal{L}$ cannot be manifested. This contradicts the assumption that a fault in $\mathcal{L}$ is manifested.

Case 2: $Symptoms(\mathcal{P}, t)$ is null.

In this case, the program $\mathcal{P}$ does not fail under test case t. This means no fault is manifested under test case t, which contradicts the fact that $\mathcal{L}$ contains a manifested fault.

Case 3: The code at $\mathcal{L}$ executes at step j where $j > bottom$

In this case, the failure symptom at step *bottom* can be observed before the fault at $\mathcal{L}$ is manifested. This contradicts the assumption that only one fault is manifested.

Case 4: The code at $\mathcal{L}$ executes at step j where $j < top$.

There are three cases.

1. $j < 0$: This is not possible, as zero is minimum step number.
2. $s_j \longrightarrow s_{top}$ maps an error-revealing state to a non-error revealing state.

   This happens when coincidental correctness occurs. This means the fault at $\mathcal{L}$ is not manifested into the output. Therefore, another fault is manifested after step *top*. This contradicts the assumption that only one fault is manifested.
3. $\mathcal{L}$ has an occurrence $\mathcal{L}^{(i,j)}$ that is a fault-manifesting occurrence. As the last state s_n of an error-revealing test case, the execution occurrence of *loc* from step *top* to n is fault-manifesting. This contradicts the assumption that only one fault is manifested.

Case 5: All occurrences of the code at $\mathcal{L}$ have already been evaluated as non-fault-manifesting occurrences.

This condition contradicts the assumption that an occurrence of the code at $\mathcal{L}$ is an omission-fault-manifesting occurrence.

B.2 Proof for Search Space for a Manifested Fault of Commission

Theorem: If a fault of commission is the only fault exposed by test case t, then $SSC(\mathcal{P}, t)$ always includes a commission-fault-manifesting occurrence.

Proof: Let $\mathcal{L}$ represent the location of a statement. Suppose $\mathcal{L}$ contains a fault that is manifested as a fault of commission under test case t, but it is not executed in $SSC(\mathcal{P}, t)$.

To prove by contradiction, we consider the following cases when the code containing the fault of commission is not executed in $SSC(\mathcal{P}, t)$. The statement is either executed or not executed in σ_t. If it is not executed, then it is not executed in $SSC(\mathcal{P}, t)$. If it is executed in σ_t, σ_t may associate with no failure symptoms or at least one failure symptom. If there is no failure symptom, $SSC(\mathcal{P}, t)$ is null and no statement can execute in it. If there is at least one failure symptom $Symptoms(\mathcal{P}, t)$ either includes or does not include a symptom of an erroneous variable.

If $Symptoms(\mathcal{P}, t)$ includes a symptom of an erroneous flow of control only, then $SSC(\mathcal{P}, t)$ is defined as statement occurrences in search path ${\sigma_t}^{top,bottom}$ minus statement occurrences that have been evaluated to be non-fault-manifesting occurrences. In this case, a statement is not executed in $SSC(\mathcal{P}, t)$ when it is executed before step *top*, is executed after step *bottom*, or all of its execution occurrences have already been evaluated to be non-fault-manifesting occurrences.

If $Symptoms(\mathcal{P}, t)$ includes one or more symptoms of erroneous variables, then $SSC(\mathcal{P}, t)$ is defined as statement occurrences in the intersection of static path slices of all erroneous variables, minus statement occurrences that have been evaluated to be non-fault-manifesting occurrences. In this case, a statement is not executed in $SSC(\mathcal{P}, t)$ when a statement does not executes in a static path slice of at least one erroneous variable or all of its execution occurrences have already been evaluated to be non-fault-manifesting occurrences.

Thus, there are six cases to contradict:

Case 1: The code at $\mathcal{L}$ is not executed.

In this case, the fault at $\mathcal{L}$ cannot manifest itself. This contradicts the assumption that $\mathcal{L}$ contains a manifested fault.

Case 2: $Symptoms(\mathcal{P}, t)$ is null.

In this case, the program $\mathcal{P}$ does not fail under test case t. This means no fault is manifested under test case t, which contradicts the fact that $\mathcal{L}$ contains a manifested fault.

Case 3: The code at $\mathcal{L}$ is not executed in the search path ${\sigma_t}^{top,bottom}$.

In this case, the proof by contradiction is the same as for Case 3 and 4 in Appendix B.1.

Case 4: The statements at $\mathcal{L}$ do not belong to the static slice of any erroneous variable in $Symptoms(\mathcal{P}, t)$.

In this case, the statements at $\mathcal{L}$ can affect erroneous variables only when $\mathcal{L}$ contains a missing dependency statement. Threfore, the fault at $\mathcal{L}$ is manifested as a fault of omission. This contradicts the assumption that the fault at $\mathcal{L}$ is manifested as a fault of commission.

Case 5: The statement at $\mathcal{L}$ is in a static slice of an erroneous variable var_1 but is not in a static slice of an erroneous variable var_2.

There are two cases.

- The statement at $\mathcal{L}$ causes only var_1, not var_2, to have an erroneous value. This means another fault is manifested to cause var_2 to be erroneous. This contradicts the assumption that only one fault is manifested.
- The statements at $\mathcal{L}$ causes both var_1 and var_2 to have erroneous values. This can happen when $\mathcal{L}$ contains a missing dependency statement with respect to var_2 and is an extra dependency statement with respect to var_1.

In our context, the fault at $\mathcal{L}$ is manifested as a fault of omission. This contradicts the assumption that it is manifested as a fault of commission.

Case 6: All occurrences of the code at $\mathcal{L}$ have already been evaluated as a non-fault-manifesting occurrence.

This condition contradicts the assumption that an occurrence of the code at $\mathcal{L}$ is a commission-fault-manifesting occurrence.

Appendix C: Survey from Experimental Study on Debugging Critic

C.1 Spyder Survey Form

Please let me know how each of Spyder's features help you debug faster. Put N/A if the feature was disabled. Put N/U if the feature was enabled, but you did not use it.

Features	Degree of helpfulness (range from 0 to 10, where 0 = no help and 10 = the most help)	Would you like to see this feature added on to conventional debuggers like dbx? (YES/NO)
1) Evaluate a location (Debugging critic)		
2) Program slicing: (r-defs, c-preds, d-slice, c-slice, program-slice)		
3) Operations on slices: (add, subtract, intersect, swap, save)		
4) Break operations: (stop in slice)		
5) Grep		
6) Print multiple values before or after executing a line without having to select a variable name		
7) Print from menu		
8) Maintain records on error information		

C.2 Survey Results

The survey results were calculated from 37 out of 39 programmers. One programmer did not fill out the survey; the other provided a descriptive answer instead of a numerical rating.

Table C.1 Average helpfulness rating of Spyder features

Features	Group 1	Group 2	Group 3
Critic	N/A	N/A	8.5385
Record error info	N/A	N/A	5.0000
Grep	N/A	N/A	6.6923
Slicing	N/A	1.4615	3.0000
Slice operations	N/A	0.6923	0.6154
Multiple breaks	7.2727	5.6154	4.4615
Print before/after	8.1818	6.8460	6.6154
Print from menu	2.8182	3.8461	2.6923

Table C.2 Percentage of programmers who did not use Spyder features

Features	Group 1	Group 2	Group 3
Critic	N/A	N/A	0%
Record error info	N/A	N/A	23.08%
Grep	N/A	N/A	15.38%
Slicing	N/A	61.54%	38.46%
Slice operations	N/A	76.92%	46.15%
Multiple breaks	9.09%	23.08%	30.77%
Print before/after	0%	15.38%	23.08%
Print from menu	36.36%	38.46%	38.46%

Table C.3 Number of programmers who recommended Spyder features as an extension of conventional debuggers

Features	Group 1	Group 2	Group 3
Critic	N/A	N/A	12/13
Record error info	N/A	N/A	6/13
Grep	N/A	N/A	9/13
Slicing	N/A	7/13	7/13
Slice operations	N/A	5/13	4/13
Multiple breaks	6/11	10/13	6/13
Print before/after	8/11	10/13	11/13
Print from menu	4/11	8/13	6/13

VITA

VITA

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