Flexible Debugging with Controllable Overhead

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Abstract of the Dissertation

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This thesis is concerned with the problem of discovering bugs in a program. This crucial part of debugging is becoming ever more relevant as the complexity of software systems increases. Symbolic debuggers retain their relevance for bug diagnosis once a bug has been isolated in a development environment; however, *instrumentation* continues to grow in relevance because it allows the programmer to specify execution points of interest in advance and let the program run normally. Instrumentation's has a strong appeal if the nature of the bug is uncertain: the programmer can add checks or logging for a variety of interesting events and let the program run, automating what would otherwise be a painstaking manual process.

Instrumentation is widely-used in development environments; nearly every large software project has benefited from verbose logging or some kind of execution profiling. In fact, recently DTrace has brought instrumentation to system administrators as well, allowing them to diagnose performance problems and errors on production servers. However, particularly with the proliferation of consumer devices running full Unix software stacks, it is becoming more and more useful to be able to apply the same techniques that were available in development and system-administration environments remotely, in end-user environments with minimal user impact.

In this thesis, we present a body of work that addresses this desire. We have developed a GCC-based instrumentation system called `adb` that leverages the compiler's intermediate representation, which includes type, control-flow, and dominator information, to enable instrumentation at a variety of locations, called *probes*, in a program. A developer can ship a program with deactivated probes, and later develop small *consumers* that use the data at these probes and insert them into deployed copies of the program dynamically, with no end-user intervention required. We have also developed a novel overhead-management policy called SMCO that ensures that instrumentation incurs fixed overhead.

In addition to presenting `adb` and evaluating its performance guarantees, we also discuss a GCC plug-in system that we developed and that is being adopted by the GCC community for inclusion in release 4.5. Finally, we also describe overhead-control approaches we developed before SMCO, which put the design decisions made for `adb` in context.

To the builders of the Golden Gate Bridge

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Justin is my comrade-in-arms. He was always there for me, in every way. I am m honored to be in the same group with him.

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Rick is like a second brother for me. We can argue and call each other names, but no matter what, he's my best friend.

En taro Adun, Chris.

Trusting Jon feels implicit, like a law of nature. Talking to him is like talking to another part of me. How did I manage beforehand?

Dave stood by me from middle school, and being his best man was one of the greatest honors of my life. If the sky falls, I have him on speed dial.

Azumi sticks with me and supports me unquestioningly, cares about everything I do, and talks like *she*'s the lucky one.

My parents showed me that I could do anything with my life, and then convinced me that it mattered. Well, this is what I wanted.

Chapter 1

Introduction

Instrumentation is a powerful alternative to traditional interactive debugging techniques, and offers several major advantages. First, it offers considerably better throughput, allowing the programmer to process and filter hundreds of thousands of events in the time it would take to inspect a single one in a traditional debugger. Second, it is much more reliable: whereas manual fault diagnosis is fraught with mistakes, instrumentation can perform the same task again and again. Third, it can collect data that manual inspection cannot: the behavior of a live system under load, not artificially held in stasis as the debugger is used like a forceps. Instrumentation has been used to collect a wide variety of information, from application memory usage [47] to network accesses [69].

Instrumentation is characterized by the modification of an existing program—either by changing its code or interposing a new layer on one of its interfaces—to provide additional information about the program's execution. One of the most pervasive forms of instrumentation is the Linux and Solaris `proc` file system, in which the kernel merely makes available internal statistics about a process to other processes through an interface based on simple character devices [63]. Other tools, like `DTrace` and `Atom`, try to expose a more generic instrumentation interface to their users [11, 58]. It is this last tradition that we form part of. Tools like this typically modify the target binary, which abstracts their interface somewhat from the code level. They can add instrumentation at specific assembly locations into a binary, but it is much more challenging to find which assembly locations correspond to which lines of a program's source code, and which data locations in the program correspond to which variables.

To solve this problem, we take advantage of the GNU Compiler Collection, which is equipped with compilers for a variety of languages. Using the intermediate representations provided by GCC, our system is capable of inserting instrumentation in a wide variety of locations, and, most importantly, getting full access to program data at these locations without worrying about the operation of the optimizer [68]. To achieve this, we use *providers* that select potentially interesting locations in advance and add *probes* at those locations. When a program thus instrumented runs normally, these probes do nothing, incurring a very modest overhead; if a so-called *consumer* requires the data provided by one or more probes, those

probes are enabled, and incur whatever overhead the consumer incurs in addition to the time they take to extract data. In exchange for this overhead, they provide read-write access to program data in a way that DTrace other binary instrumentation tools cannot. (DTrace provides so-called *static probes*, user-annotated locations that allow hooks. However, these rely on programmer annotation.) We introduce the concept of compiler-based instrumentation, tools we have built to support it, and applications in Section 2.1.

The overhead incurred by a large number of activated probes can potentially be very high. Particularly when instrumentation is taking place in parallel with critical computations, it is very useful to measure and control the overhead incurred by instrumentation. In the past, such overhead was controlled via *sampling*, effectively rolling an n-sided die whenever it was possible for a particular piece of instrumentation code to run, and allowing the probe to run if $n < m$ for some *sampling rate* m. This approach saw many variations: Liblit et al.'s Bernoulli sampling [37] (which in turn inherits some concepts from counter overflow sampling [75]), and Chilimbi and Hauswirth's bursty sampling [29]. These approaches, however are related in a non-linear way to overhead, because they only indirectly regulate overhead. In this work, we introduce two novel approaches to overhead regulation: first, overhead regulation based on accrual of *confidence* in the correctness of a particular part of the system (see Section 3.1), and then overhead regulation to compensate immediately for measured overhead. This system, which we call Software Monitoring with Controlled Overhead (SMCO), performs well experimentally, as seen in Section 3.2.

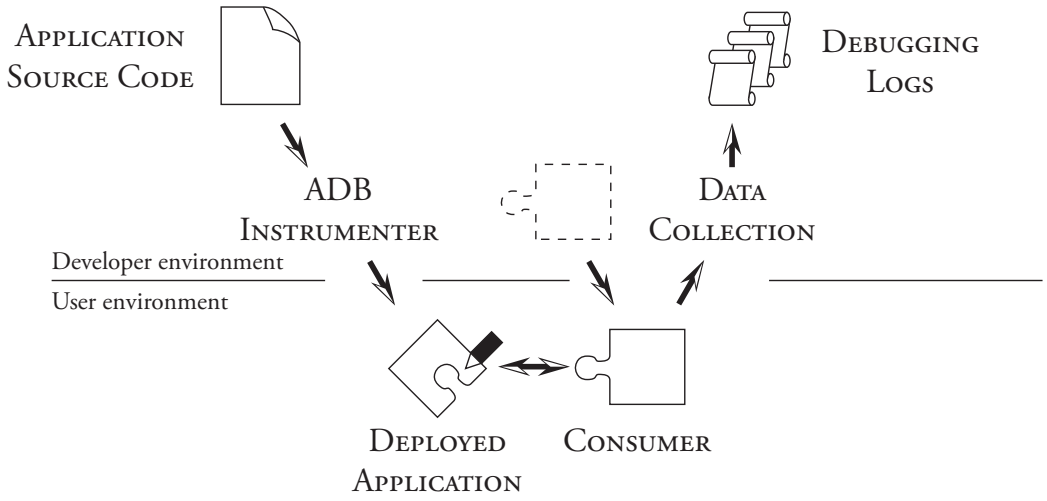


Figure 1.1: A high-level view of how `adb` *can be used.*

In this thesis, we present a unified and generic instrumentation architecture called `adb` that combines the benefits of both of these approaches, offering low-overhead, compiler-inserted probes that provide highly verbose, typed information through a convenient API when activated, and a robust overhead-control mechanism based on SMCO that regulates the probes so that consumers stay within

user-set overhead constraints. Figure 1.1 shows the way in which `adb` is meant to be used.

The `adb` system is meant for use in three stages.

- The programmer compiles source code with the `adb` instrumenter, a plug-in based on GCC. As described in Section 4.1, this typically only involves adding a new flag to `CFLAGS` and the `adb` runtime library to `LDFLAGS`. `adb` generates a PIF (Probe Information Format) file which contains information about all the probes it has inserted. The application can then be distributed along with the `adb` runtime library.
- At startup time or during its execution, the application searches for consumers. Consumers can be special-purpose, using symbols and types from the program being monitored, or they can use `adb`'s generic type API (based on the Sun Compact ANSI-C Type Format or CTF) to access data in a generic way. Consumers request that specific categories of probes be activated.
- As consumers run, they perform monitoring or checking. They can collect, anonymize, and return data, which programmers then aggregate and process. For an excellent example of data aggregation from many clients, see Liblit [36].

Although this system involves deploying the application to customers, the customer need not be aware of `adb` at all (although it is common practice to request permission to send data to a central server, even with anonymization). This reduces the barrier to entry for end users to assist in the debugging process. The fact that the instrumentation is dynamic in nature (that is, probes can be activated and deactivated as needed) means that different consumers can be used to test for different problems or examine different aspects of the program's execution without the need to distribute a new version of the program.

As our results shown in Section 4.4 demonstrate, `adb` adheres well to overheads, even under high, rapidly-changing loads. In addition, introducing probes into a program incurs 13% overhead even for the most rigorous of real-world applications. `adb` is a significant step forward in the search for full debuggability at every stage of the software life-cycle.

This thesis is structured as follows. In Chapter 2, we discuss instrumentation and debugging, in particular compiler-aided instrumentation tools we have developed. Then, in Chapter 3, we discuss overhead control and the technologies we have developed to regulate overhead from instrumentation. Finally, in Chapter 4, we tie the material from the previous chapters together and present `adb`.

Chapter 2

Instrumentation and Debugging

We discuss existing approaches to compilation in Section 2.1 and debugging on the target machine in Section 2.2.

2.1 Compiler-based Instrumentation

All modern compilers have special support for debugging. The reason for this is that the compiler is typically the first part of the development *toolchain* to analyze an application, and maps programmer-generated artifacts to executable code. In order to fix problems with the executable code, developers must determine the relationship between the portion of the executable that failed and the artifacts that it was generated from. Consequently, most compilers store a mapping from artifacts to executable code; this mapping is typically known as *debugging information*.

Compilers typically insert debugging information into data packets that reside alongside the code they describe [50], or into separate sections of a binary file [26]. This debugging information documents several aspects of the source-executable mapping:

Line information: The compiler records which ranges of lines in the assembly code correspond to particular lines of the original source code. The DWARF format [26] also includes column information, to identify assembly instructions that correspond to individual portions of complex explanations, such as the individual clauses in a `for` statement.

Variable information: The compiler saves information about the local variables for a function, as well as the location of static and global variables. This information includes whether the variables are allocated on the stack or in registers, how they can be extracted, and what type they are. For variables that move between the stack and registers, DWARF allows compilers to emit *location lists*.

Function descriptions: To facilitate calling of functions and stack unwinding (see Section 2.2, compilers can emit function signatures that specify how functions should be called and where their code resides.

The usage model for debugging information is very specific: debuggers use it to inspect and manipulate program's state when it is paused. This inspection

and manipulation is either programmer-guided or very naïve, as we shall see in Section 2.2. For more sophisticated analyses, particularly those that occur without pausing the software, the compiler not only needs to add auxiliary information but must also modify the application so that it performs these analyses—or provides the data required to perform them—at run time.

In order to understand how the compiler does this, we must first explain the *intermediate representations* that the compiler maintains for an application as it transforms it into executable code. An intermediate representation is a data format (typically memory-resident) that serves as the interface between two parts of the compiler, or to permit a user-specifiable combination of similar components, such as optimizers, to operate on a portion of the software sequentially.

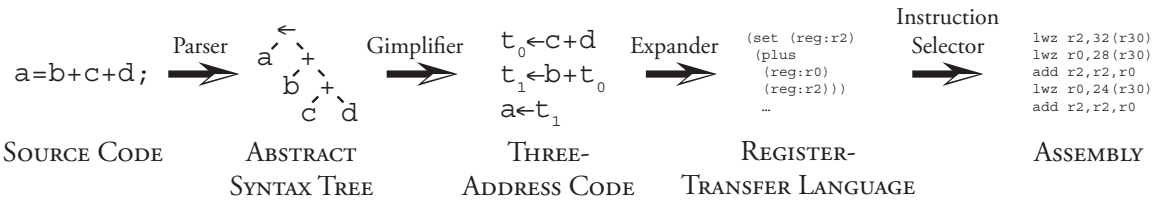


Figure 2.1: The architecture of GCC, with the intermediate representations it uses.

Our compiler-based instrumentation work has focused on the GNU Compiler Collection (GCC), whose components are illustrated in Figure 2.1. We now discuss the individual intermediate representations, and describe their respective characteristics and how each of them can be used for debugging.

Abstract Syntax Trees (ASTs): After parsing, GCC (like most compilers) represents a source file as a collection of trees that represent the syntactic structure of each function. These trees retain much of the original structure of the source file, including block information, loop structure and nesting, and compound statements. At the abstract syntax tree layer, transformations can most easily detect common programming idioms—such as use of iterators in a loop—without performing expensive and complicated analyses. Instrumentation, like source-level tracing, that reports information at the granularity of programmer-written code lines is best implemented at this level. Other tools, such as Cil [20], represent code in a similar way.

Three-Address Code: GCC converts the abstract-syntax trees into their semantic equivalents, reducing them to assignments that take at most two values per statement and combines them to produce a third. The assignments retain all the type information that was discovered during parsing, and share the building blocks of the abstract-syntax tree representation, but are much simpler to manipulate. To represent intermediate values, GCC generates temporary variables; additionally, it simplifies the control flow structure by constructing a *control-flow graph* and replacing more sophisticated structures with conditional `goto`s. For optimizations, GCC developers recommend this layer, which was designed explicitly for ease of manipulation by the pro-

grammer [48]. The reason for this is that most data-flow and control-flow analyses use a control-flow graph representation and prefer as simple a syntactic structure as possible because this reduces the number of side-effects that must be considered.

Register-Transfer Language: After giving optimizers the opportunity to transform the three-address code, GCC converts it into a format that closely resembles assembly code. It determines the kind of storage that each variable requires, what low-level operations must be performed on the variables, what classes of instructions provide them, and performs register allocation and final instruction selection based on this information. Although GCC performs some optimizations at this level, including instruction scheduling, the implementation of RTL in GCC is so complicated and fragile that GCC programmers recommend against using it for any kind of instrumentation.

We developed a plug-in based transformation system based on the GCC's GIMPLE intermediate representation [44], which it uses for three-address code. Despite its simplicity, the GIMPLE intermediate representation presents its own challenges during transformation development and testing for several reasons. First, the maturity of the GCC project and the fact that many system distributions depend on GCC to compile their system makes it difficult to get transformations integrated into GCC until they are very mature. Second, it may not be desirable to include and maintain transformations that do not have broad appeal as part of the core GCC distribution. Finally, it is an unattractive proposition to have to distribute experimental transformations as patches against a particular version of GCC and recompile the entire compiler when changes are made.

To solve these problems, we developed a plug-in system similar to that used by Eclipse [39]. Our system allows separate development and compilation of GIMPLE transformations, solving the problems listed above and offering new features like enhanced debuggability and better argument passing. We have already developed a variety of plug-ins using our system, and have realized two main benefits. First, we were able to take advantage of graphical debugging tools that we describe in Section 2.1.2 as well as significantly reduced development time because we were developing outside the GCC build system. Second, we were able to port our transformations from one version of GCC to another without changing a *single* line of code; once the plug-in support was ported to the new GCC release, the plug-ins needed recompilation and nothing more.

In the remainder of this section, we demonstrate the simplicity and power of GCC transformation plug-ins. In Section 2.1.1, we describe the modifications to GCC that make plug-in–based development possible. In Section 2.1.2, we describe some plug-ins that we have already built using this infrastructure, highlighting plug-ins that are useful to transformation developers. In Section 2.1.3, we discuss two parts of GCC that could be made into plug-ins. In Section 2.1.4, we describe plug-ins that could be created in the future, and we conclude in Section 2.1.5.

2.1.1 Modifications to GCC

Plug-ins are built based on an Autoconf-based template [14]. The template's `configure` script currently requires the headers from a built version of the GCC source code; when the plug-in is built, the Makefiles produce a shared object file suitable for loading using the host operating system's dynamic loader interface.

Only minor changes need to be made to GCC to support plug-in loading. These changes revolve around three tasks; we will discuss them below in turn. The first change is an addition to the GCC build sequence, compiling the Libtool `ltdl` library [18] into GCC and linking GCC with `-export-dynamic`. This allows GCC to load plug-ins, and allows plug-ins to access GCC interfaces. The second change is the addition of an optimization pass before all other GIMPLE transformations, and at the start and end of translation for each file. This allows plug-ins to maintain per-file state and perform code optimizations while referring to this state. The third change is the addition of a compiler flag that allows the user to specify plug-ins to load and provide arguments to those plug-ins either on the command line or through files.

To add the `ltdl` library to GCC, we modified the top-level top-level Makefile to add build rules for the `ltdl` library. Additionally, we modified the build rules for the `cc1` binary to make it compile with Libtool, export its symbols like a shared library (using the `-export-dynamic` option to Libtool), and use the `ltdl` library to load plug-ins. The ability to export symbols from an executable to plug-ins does not exist on every platform: Linux, Solaris, and Mac OS X support this functionality, for instance, but Cygwin does not. A build process in which the GCC back-end code is linked as a shared library, and `cc1` and all plug-ins are linked against it, would have eliminated this requirement. However, large amounts of state that is currently maintained as globals by the back-end would have to be converted to on-stack state because otherwise `cc1` and the plug-in would have differing copies of the back-end's global state.

To allow instrumentation plug-ins to run at the proper times, we added several new passes to `passes.c`, allowing plug-ins to run at various points in the compilation. We describe these in Table 2.1.

Finally, to allow the end user to specify which plug-ins should be loaded with which arguments, we provided a new argument, `-ftree-plugin`, which has the syntax shown in Table 2.2.

The first argument, *plug-in-name*, is a shared object file that contains functions for one or more of the passes described in Table 2.1. The list of *key-value* pairs specifies arguments to the plug-in, which are passed as arguments to the plug-in's individual functions. In addition, the special key `_CONF` specifies a file to be loaded and parsed for additional arguments; in this case, each line in the file is a key-value pair separated by an '=' sign.

2.1.2 Existing plug-ins

We will now enumerate some plug-ins that we have already developed: a verbose dump plug-in for GIMPLE meant for use by programmers in developing transfor-

Pass	Location	Purpose
`pre`	Before compilation	Allows plug-ins to perform data-structure initialization before compilation of a source file begins.
`ctrees`	After C parsing	Allows plug-ins to analyze the abstract syntax trees for a C program before it is converted to GIMPLE.
`cgraph`	Before IPA transformations	Allows plug-ins to perform *inter-procedural analyses*, which have access to every function's code and the call graph.
`gimple`	After IPA, per function	Allows plug-ins to manipulate the GIMPLE representation of each function, including the control-flow graph.
`rtl`	After conversion to RTL, per function	Allows plug-ins to manipulate the RTL for each function.
`post`	After compilation	Allows plug-ins to perform data-structure cleanup after compilation of a source file ends successfully.

Table 2.1: Plug-in transformation passes.

mations, and a call-trace plug-in for use by end users in tracing their code. We have also developed `malloc` checking and bounds-checking plug-ins; however, these will be superseded by a plug-in implementation of Mudflap (see Section 2.1.3).

Verbose Dump Plug-in. Transformation developers frequently require a view of the GIMPLE code that is as verbose as possible. They use this view for several purposes: to identify patterns that need to be transformed, to determine the proper form of GIMPLE structures that transformations should generate, and to verify that transformations are working correctly. We designed a verbose dump plug-in to facilitate this. We designed the verbose dump plug-in with extensibility in mind: as GIMPLE evolves and grows, the verbose dump plug-in will handle new GIMPLE objects, such as new tree codes or parameters, with little or no changes needing to be made. We achieved this by creating a new file, `parameter.def`, that resembles `tree.def` but formally specifies all the accessor macros that exist for tree attributes. The file contains lines of the form shown in Table 2.3.

The *name* field specifies the name of the macro; the *type* field specifies what type of data it returns (e.g., `SIZE_T` or `TREE`); the *macro* field specifies the macro used to extract the field; and the *code* fields constitute a list of `TREE_CODE`s for trees

```
-ftree-plugin=plug-in-name
   :key=value
   :...
```

Table 2.2: Syntax for specifying a plug-in.

```
DEFTREEPARAMETER(
   name,
   type,
   macro,
   code, ...
)
```

Table 2.3: Syntax of `parameter.def`

that have this parameter. For example, the parameter named `type_precision` has type `SIZE_T`, macro `TYPE_PRECISION`, and codes `INTEGER_TYPE`, `REAL_TYPE`, and `VECTOR_TYPE`.

Graphical Inspection of GIMPLE Code. As shown in Table 2.4, the output from the verbose-dump plug-in is so verbose as to be overwhelming in large quantities. Rather than adopt a simplified representation, we instead developed a Java-based tool called GIMPLE Viz to represent the output graphically. We chose Java as the development language due to its cross-platform compatibility, which allowed us to concentrate on the development of the actual tool itself as opposed to platform support and library dependencies. Figure 2.2 is a screen-shot of GIMPLE Viz displaying a file. The visualizer has three main areas: the Control Flow Graph area, the GIMPLE Tree View area, and the Source / Search area, which we describe below.

The control flow graph for each function is rendered as rectangles connected by arrows. Each colored rectangle represents a basic block. When the user clicks on a block, GIMPLE Viz highlights the selected block along with its predecessors and successors. The successor edges are highlighted as well. Additionally, it displays a tree representation of the corresponding GIMPLE nodes in the GIMPLE tree view area, and highlights corresponding code or dump lines in the source/search area.

The GIMPLE tree view area is a visual representation of the GIMPLE code for a particular basic block. The root node of each tree is a statement from the currently selected basic block, labeled with the result of applying `print_generic_stmt`. The other nodes are operands or parameters of their parents. The user interacts with the tree view in two ways: clicking and searching. Manually clicking a node will expand that node showing its children. This process can be repeated until the desired node is reached. Searching for a particular `TREE_CODE` will expand the tree to reveal the desired node, allowing the user to quickly locate specific nodes.

The source/search area can show search results, source code, and verbose-dump output. The results of searches—function searches, basic-block searches,

```
MODIFY_EXPR 1,2
 TREE_TYPE:
  INTEGER_TYPE 2,0
   TYPE_PRECISION=32
   TYPE_UNSIGNED=true
 VAR_DECL 2,0
  TREE_TYPE:
   INTEGER_TYPE 2,0
    TYPE_PRECISION=32
    TYPE_UNSIGNED=true
  DECL_ARTIFICIAL=true
 MULT_EXPR 1,2
  TREE_TYPE:
   INTEGER_TYPE 2,0
    TYPE_PRECISION=32
    TYPE_UNSIGNED=true
```

Table 2.4: A portion of the verbose dump output for one statement, leaving many node attributes out.

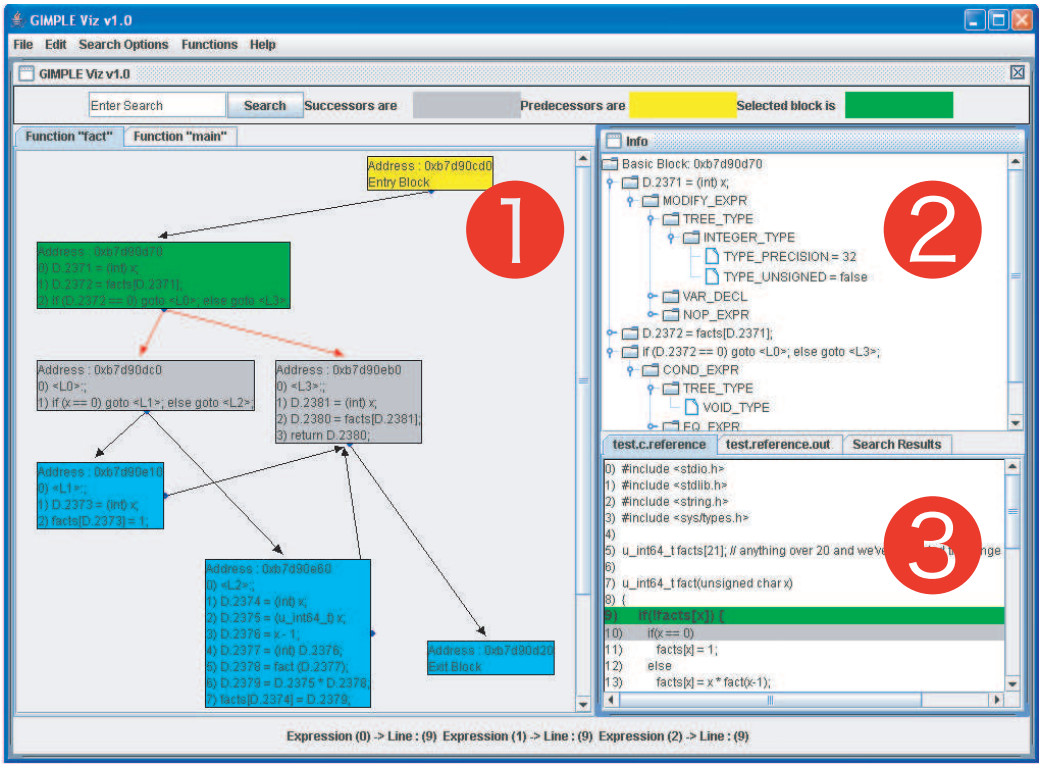


Figure 2.2: GIMPLE Viz displaying a file. 1 marks the CFG area, 2 marks the tree view, and 3 marks the source/search area.

```
*** CALL TO main [0]
Struct :**test** found in function
**main**
test->value = (int32_t)5
test->name = (char*)"contents"
** CALL TO foo [1]
* [1] testPtr = 0x0x7fffcef31770
*** CALL TO foo2 [2]
* [2] value = 0x0x7fffcef31748
Conditional found value = FALSE,
right branch taken...
*** [2] RETURNED null
```

Table 2.5: Call trace output

and type searches—are interactive: clicking on a function search result shows the control-flow graph for that function; clicking on a basic-block search result shows the containing function's CFG and highlights the block; and clicking on a `TREE_CODE` search highlights the containing basic block and expands the containing tree in the GIMPLE tree view to make the tree with that code visible.

GIMPLE Viz can also display the original source file that was compiled by GCC in the source/search window. For quick reference, line numbers are displayed for the user. Although the user cannot directly interact with this area, clicking a basic block or a search result will highlight the lines corresponding to that block, its predecessors and its successors. Finally, the source/search window can also display the raw verbose dump output.

Call Trace Plug-in. We have developed a plug-in called *call-trace* to allow full verbose tracing statements to be added to a program at compile time without requiring the programmer to add any code. This feature significantly reduces debugging time for many code problems by eliminating the need to add `printf` statements and other debugging statements to code, and by providing verbose tracing information in cases where the programmer would normally have needed to single-step the program in `gdb`.

This plug-in identifies control points in the GIMPLE code corresponding to conditional statements and function calls, as well as accesses to variables. Arguments control exactly which statements are logged, and which portions of the source code are to have logging added. The way events are reported is also configurable: logging statements can be printed using `fprintf` or sent to a custom logging function. Table 2.5 shows sample output from the call tracer.

We are currently developing an extension to GIMPLE Viz to display the output from the call-trace plug-in in a visual manner, giving the developer the ability to watch the internal execution of a program at run-time. We are also expanding the call-trace plug-in to detect not only conditionals but loops as well by tying into the C abstract-syntax tree intermediate representation.

2.1.3 Making Plug-ins from Existing Functionality

In this section, we describe portions of GCC's functionality that could be extracted into separate modules for use only when needed. This would have three benefits: first, it would enforce modularity for these components, ensuring that they can be maintained separately from the main code base and contributing to their stability as GCC internals change. Second, it would reduce the turnaround time for fixes to components that are plug-ins because they would not need to be subject to the scrutiny that core GCC patches are subjected to, and can be shipped on a faster release schedule. Third, it would reduce the size of the core GCC code base, resulting in less code for GCC's core developers to maintain and support, and less download and compilation time for end-users.

Mudflap. This utility provides pointer-debugging functionality including buffer overflow detection, matching-based leak detection, and reads to uninitialized objects. It is implemented as two GIMPLE optimization passes: one that executes before *lowering*, or conversion, to SSA (Static Single Assignment) so that all scopes are intact, and one that executes after lowering and optimization to get an accurate view of just those memory accesses that have actually been performed. Mudflap can be converted to a plug-in provided that plug-in hooks are provided at multiple stages in the optimization process. Our plug-in infrastructure supports transformation hooks at all locations where built-in GIMPLE transformations can take place, making this process straightforward.

gcov and gprof. These utilities consume call-graph information that is generated by GCC and by the running program, creating runtime profiles of the execution patterns for code that has been compiled with the `-p` or `-fprofile-arcs` flags. When profiling, GCC modifies the program to include *coverage counters* embedded in the program that provide runtime coverage information. It also generates a call-graph for the program. The transformation that performs these tasks runs as a transformation in a way analogous to Mudflap, but labels basic block edges with additional information that uses the `aux` field in the basic block structure, which is meant to hold miscellaneous transformation-specific data and can be overwritten by each transformation. This does not present a problem for these transformations, since they take place in one pass and do not need modifications of `aux` to be persistent. However, for other plug-ins that may need to do analyses at multiple times in compilation it may become desirable to expand `aux` to support addition of custom fields, perhaps keyed on a string, at runtime.

2.1.4 Future Work

Once the groundwork is in place that allows GCC transformations to be developed as plug-ins, we anticipate that many new transformations will be developed. In this section, we outline future applications of plug-ins, some of which we are currently developing for our own research.

Transformations in Python. Some developers only want to perform straightforward analyses or transformations that use the GIMPLE API. To reduce develop-

ment time for these developers, we are developing a plug-in that will expose the GIMPLE API to Python scripts. This plug-in links against the Python library and executes a user-specified Python script for each function being translated. It currently allows read-only access to basic blocks and trees; we are adding support for viewing and editing the control-flow graph, adding and removing statements, and modifying trees. In addition to reducing development time, this plug-in will allow developers to use Python data structures, reducing implementation time for optimizations that use sophisticated algorithms to perform static analyses on GIMPLE code.

Library call error detection. When developing systems software, programmers frequently add large amounts of error checking for library function calls to detect problems that are ironed out in the early stages of development. This error-checking adds to code size, reduces code readability, and takes time. In addition, retroactively adding error-checking onto existing code if it fails can be a significant time investment. A GIMPLE transformation plug-in could be used to add error-checking to code at compile time, optionally warning when the code is not written to check the result of calls that commonly fail.

Interface profiling. Threaded applications typically have points at which threads wait for responses from other threads. These can take several forms: functions that are called to perform synchronous requests, or locks that the programs block on until data is ready. Additionally, even single-process applications can spend time waiting for library functions or system calls to complete. A GIMPLE transformation plug-in could accept a list of locks and interface functions to profile, and add entry-exit profiling to these locks and functions. This would be coupled to a runtime library that determines the amount of time spent waiting for these interfaces, credited to the functions that waited for them.

2.1.5 Conclusion

We have described a framework that we developed that allows GCC to load and execute plug-ins that implement custom GIMPLE transformations. This framework offers three compelling benefits:

- it reduces development time for new GCC transformations;
- it allows transformations to be developed and distributed that would otherwise be difficult to use or not available at all; and
- it reduces the workload for the GCC core developers by reducing GCC's code size and allowing many transformations to be maintained separately.

We have shown a verbose-dump plug-in and a compatible Java-based visualizer that help GCC developers develop and debug their transformations. We have also shown a call-trace plug-in that tracks function calls, variable accesses, and conditionals, providing a detailed view of the execution of a program. In addition to these existing plug-ins, we have shown examples of existing functionality in GCC that could be converted to plug-ins, and examples of new functionality that do not exist yet but would be well-suited to implementation as plug-ins.

2.2 Debugging

Traditionally, debuggers have been defined as command-line tools that have a relatively standard set of functions, controlled by a command-line interpreter. This kind of debugger is also called an *source-level debugger*. The interpreter evaluates expressions written in a language very similar to the original source code, using type information embedded by the compiler and data from a paused process or process image. Examples of source-level debuggers include GDB [19] and dbx [62]. The core mechanisms used by these tools are:

Process control: Modern Unix kernels provide debuggers with interfaces to stop, start, and single-step processes. Most other operations a debugger performs require a process to be paused first. Operating-system support for process control varies widely. Linux provides a system call, `ptrace`, which implements process stopping, starting, and single-stepping as kernel facilities [27]. Solaris exposes this functionality to user-space through the `/proc/`*pid*`/ctl` file, which is replicated for every process and every thread [42]. Mac OS X exports this functionality through the Mach task and thread port interfaces [2].

Watchpoints and signal handling: Users frequently want to stop a process when a particular event occurs, including when a signal arrives and when the process touches a particular area of memory. Debuggers can trace signals in various ways: Linux and Mac OS X provide the ability to trace signals through the `ptrace` interface. (Mac OS X does not provide Mach interfaces to do so because Mach does not use signals.) Solaris provides signal tracing via the `/proc/`*pid*`/ctl` interface. Watchpoints are typically implemented using dedicated CPU support, typically implemented as watch registers [72].

Memory inspection: Reading and writing a process's memory violates isolation, so this too requires special kernel support. It is nonetheless necessary for inspection of a program's variables, as well as the debugging information necessary to interpret the program's execution state. Linux and Solaris provide a special file that allows a debugger to read from a process's memory (`/proc/`*pid*`/mem` on Linux, and `/proc/`*pid*`/as` on Solaris), although Linux's version does not allow writing due to a security hole. Mac OS X provides a Mach call, `mach_vm_remap`, to map another task's memory into the current task's address space [56].

Source-level debuggers are a well-understood area; however, there are three areas in which they fall short of the requirements of programmers today. First, the source-level debugger interface is locked into a particular interaction model. Modern development environments such as Xcode [31] and Eclipse [21] must consequently rely on slow, text-only interfaces to the debugger. Second, source-level debugging is slow; the fact that the debugger is external to the process and typically interprets its command language makes it unsuitable for operations that need to be performed often, like verifying that a particular lock is held each time a variable is accessed [57]. Third, source-level debugging does not permit maintenance of auxiliary data structures to keep track of information, preventing checks like stale memory detection.

In this section, we will discuss existing alternatives to source-level debugging that others have developed, as well as interposition methods we have developed.

2.2.1 Operating system and hardware-assisted debugging

As we saw in our discussion of source-level debuggers, operating systems and hardware provide considerable support for debugging, which is exploited by a variety of tools; we will discuss some of these below.

The Solaris modular debugger. Solaris provides extensive user-level support for debugging [43]. The Solaris modular debugger, `mdb`, provides an API that allows programmers to write custom debugging tools that exploit these APIs [55]. Programmers implement these tools as *modules*, which they can compile as object files using a C compiler and load into `mdb`, allowing maintenance of auxiliary data structures using the standard C heap allocation APIs. The debugger provides a uniform command-line interface that allows users to compose the functionality provided by these modules, allowing quick inspection of large data structures and maintenance of auxiliary data structures. `mdb` can debug both user-space targets and the Solaris kernel, and Solaris developers have provided an extensive module infrastructure for debugging memory, inter-process communications, and other subsystems.

DTrace. Although its compiled module support makes `mdb` much more versatile than conventional source-level debuggers, `mdb` still pauses the process to perform its inspection. This makes `mdb`'s approach unsuitable for production environments and for diagnosing timing-sensitive bugs like performance bottlenecks and races. DTrace is an event-processing system that is intended to operate autonomously on a running system [11]. It runs inside the operating system's kernel, and can monitor events both in the kernel and in user processes. Users interact with DTrace by writing scripts and compiling them into a restricted byte-code, which runs in a virtual machine inside the kernel, reducing context-switch latencies and performing data collection and aggregation without requiring interaction with the user.

Hardware counter overflow profiling. Many microprocessors include performance counters that record instruction counts, cache misses, cache invalidations, pipeline stalls, branch mispredictions, and other statistics [35]. These counters increment each time a particular event occurs, and often generate CPU interrupts when they overflow. The operating system can read from and write to these registers. Many tools use these counters to measure overall execution characteristics [12], allowing the developer to get a general view of an application's execution characteristics. In cases where a counter overflow generates an interrupt, many tools also provide the ability to sample these events to determine their causes, by loading the counter with a value very close to an overflow and inspecting the code that caused the interrupt when an overflow occurs [75].

Hardware-assisted memory profiling. All modern microprocessors intended for server or desktop use have memory-management units. Operating systems take advantage of this hardware not only to provide isolation, but to measure appli-

cations' usage of memory. The canonical two-handed clock algorithm takes advantage of MMU page usage bits, swapping out unused pages [66]. Although the granularity of this approach is limited to the system's page size, SafeMem demonstrates that similar protections are possible using ECC memory, providing cache-line granularity [51]. To determine whether a particular cache-line is used, SafeMem disables ECC on it, scrambles it in a reversible manner, and then re-enables ECC. The ECC check is performed on the cache line when it is used; cache lines for which no ECC errors come in are consequently not being used. SafeMem uses this approach for bounds-checking as well, putting bad data into ECC lines to either side of a valid allocation. ElectricFence applies a similar approach using only the MMU [49].

2.2.2 Binary modification

When specific hardware support is unavailable, or to avoid the kernel-user context switches associated with hardware interaction, debuggers can rewrite the binary representation of the program being debugged. This can be accomplished in one of two ways. First, a tool can modify a binary before use; second, a tool can instrument a running binary. We will discuss examples of both.

ATOM. ATOM is a library that programmers can use to implement instrumentation tools [60]. Tools built with ATOM accept a program binary and add instrumentation code to it statically—that is, without running the program. ATOM-based instrumentation tools work by inserting the instrumentation code into free space between segments, and inserting calls to that instrumentation at relevant points in the executable. This is done to avoid having to modify offsets in the executable, which has already been linked and would be difficult to relocate again.

Kerninst. What ATOM does for user binaries, Kerninst does for a running Solaris kernel [65]. The tool takes object files containing instrumentation code and inserts them into the Solaris kernel, including any and all installed loadable modules, at runtime. This is done via a *springboard* mechanism: the assembly instruction before which instrumentation is to be inserted is placed at the beginning of a new piece of assembly code, which also includes the instrumentation function. A `ba,a` instruction, an unconditional branch that annuls the instruction in its delay slot, is inserted in its place; however, on the SPARC architecture, branches can only target code locations within 8 megabytes of the branch instruction. In most cases, there is not sufficient room to place the entire instrumentation function this close, but there is enough room to place a small springboard, which contains a `call` instruction that jumps to the actual instrumentation function, and a `nop` for its delay slot.

2.2.3 Compiler-assisted debugging

Binary modification has two problems. First, inserting instrumentation code into a program is difficult to do without performing a full relocation afterward. This is because code is tightly packed and there is no room to insert code in-line, meaning that instrumentation code must be located outside the instruction stream, reducing performance and increasing implementation complexity. Second, instrumentation

does not have access to all the rich type information and high-level structural information that the source code contains. Inserting instrumentation using the compiler solves both of these problems: it takes place before linking, and instrumentation tools have full access to the compiler's intermediate representations.

`gprof`. The `gprof` utility [24] post-processes data generated by specially compiled programs. The GNU C compiler can be instructed, via the `-pg` parameter, to instrument each time a function returns control to its caller, in such a way that they will increment a counter corresponding to the caller-callee pair. This produces a raw profile which is stored in an external file, `gmon.out`. The `gprof` tool uses this file to generate a call graph, identifying common calling sequences and cycles. This information is combined with information derived from program-counter sampling to produce a profile of the execution of the program.

2.2.4 Fixed tracepoints

Binary instrumentation and compiler-based instrumentation introduce significant implementation complexity. For some tasks, it is sufficient to simply modify the source code being instrumented by hand. This is particularly useful when instrumenting high-level events that cannot be inferred by compilers.

Lockmeter. The Lockmeter utility is a profiler for spin-lock access in the Linux kernel [7]. It consists of a patch that makes wrappers for the spin-lock access macros in the Linux kernel. Each time the wrappers are invoked, the current program counter is recorded. Lockmeter maintains a hash table of program counters for locations where locks are taken and released, to which each location is added each time it is first seen. The addresses of the locks taken, and how long they were held, are stored in a separate array, and can be used to generate a profile of lock accesses. This profile can be used to find bottlenecks that limit SMP scalability. To speed up access to the lock array, which is a read-write data structure, independent versions are kept for each processor and data is only aggregated when necessary.

Linux Trace Toolkit. This system instruments a variety of events in the Linux kernel, and allows filtering and formatting of these events and their contexts before logging to a disk file [74]. It instruments a cross-section of kernel events: system call entry and exit, interrupts, events related to processes and the file system, VM and cache events, and networking and IPC events, among others. Like Lockmeter, the instrumentation consists of a patch to the Linux kernel source code. When instrumentation functions are invoked, a trace module is invoked. This trace module filters events based on event type, process, user, or group ID, and augments them with information such as CPU ID or the instruction pointer of the calling process (in the case of a system call). This information is stored in a buffer, which is periodically swapped with another buffer that is exposed to user logging processes via the `/proc` interface. The authors developed a graphical tool to visualize events, as well as showing all context switches between user-space and the kernel, as well as different user-space applications.

Chapter 3

Controlling Overhead

A central component of our proposed system is the mechanism that we use to ensure that overhead is predictable and controllable. As we will see in Section 3.3, overhead-control mechanisms typically fall into one of two categories. Mechanisms in the first category have a rate control that they autonomously reduce when particular targets are met. This rate control is not an overhead control; rather, it represents a best-effort method for reducing overhead. The second category attempts to minimize overhead using some non-quantitative approach.

In Section 3.1, we discuss our first approach, Monte Carlo Monitoring (`MCM`) which falls into the first category, and demonstrate Aristotle, a system based on it for detecting reference-counting bugs in the Linux kernel. In `MCM`, the goal is to observe some target number of events and then reduce the sampling rate. Then, in Section 3.2, we show our second approach, Software Monitoring with Controlled Overhead (SMCO), which adjusts monitoring to achieve a set overhead target. Our proposal is based on SMCO. Finally, in Section 3.3, we discuss other work in the area of overhead reduction.

3.1 Reducing Overhead as Confidence Increases

In this section, we present a new approach to runtime verification that utilizes classical statistical techniques such as Monte Carlo simulation, hypothesis testing, and confidence interval estimation. Our algorithm, `MCM`, uses *sampling-policy automata* to vary its sampling rate dynamically as a function of the current confidence it has in the correctness of the deployed system. We implemented `MCM` using the instrumentation architecture discussed in Section 2.1. For a case study involving the dynamic allocation and deallocation of objects in the Linux kernel, our experimental results show that Aristotle reduces the runtime overhead due to monitoring, which is initially high when confidence is low, to levels low enough to be acceptable in the long term as confidence in the monitored system grows.

In previous work [25], Grosu and Smolka presented the $\texttt{MC}^2$ algorithm for *Monte Carlo Model Checking*. Given a (finite-state) reactive program P, a temporal property φ, and parameters ϵ and δ, $\texttt{MC}^2$ samples up to M random executions of P, where M is a function of ϵ and δ. Should a sample execution reveal a counterexample, $\texttt{MC}^2$ answers false to the model-checking problem $P \models \varphi$. Otherwise, it

decides with *confidence* $1 - \delta$ and *error margin* ϵ, that P indeed satisfies φ. Typically the number M of executions that MC^2 samples is much smaller than the actual number of executions of P. Moreover, each execution sampled starts in an initial state of P, and terminates after a finite number of execution steps, when a cycle in the state space of P is reached. In this paper, we show how the technique of Monte Carlo model checking can be extended to the problem of *Monte Carlo monitoring and runtime verification*. Our resulting algorithm, MCM, can be seen as a runtime adaptation of MC^2, one whose dynamic behavior is defined by *sampling-policy automata* (SPA). Such automata encode strategies for dynamically varying MCM's sampling rate as a function of the current confidence in the monitored system's correctness. A sampling-policy automaton may specify that when a counterexample is detected at runtime, the sampling rate should be increased since MCM's confidence in the monitored system is lower. Conversely, if after M samples the system is counterexample-free, the sampling rate may be reduced since MCM's confidence in the monitored system is greater.

The two key benefits derived from an SPA-based approach to runtime monitoring are the following:

- As confidence in the deployed system grows, the sampling rate decreases, thereby mitigating the overhead typically associated with long-term runtime monitoring.
- Because the sampling rate is automatically increased when the monitored system begins to exhibit erroneous behavior (due either to internal malfunction or external malevolence), Monte Carlo monitoring dynamically adapts to internal mode switches and to changes in the deployed system's operating environment.

A key issue addressed in our extension of Monte Carlo model checking to the runtime setting is: What constitutes an adequate notion of a *sample*? In the case of Monte Carlo runtime verification, the monitored program is already deployed, and restarting it after each sample to return the system to an initial state is not a practical option. Given that every reactive system is essentially a sense-process-actuate loop, in this paper we propose weaker notions of initial state that are sufficient for the purpose of dynamic sampling. One such notion pertains to the manipulation of instances of dynamic types: Java classes, dynamic data structures in C, etc. In this setting, a sample commences in the program state immediately preceding the allocation of an object o and terminates in the program state immediately following the deallocation of o, with these two states being considered equivalent with respect to o.

To illustrate this notion of runtime sampling, we consider the problem of verifying the safe use of *reference counts* (RCs) in the Linux *virtual file system* (VFS). The VFS is an abstraction layer that permits a variety of separately-developed file systems to share caches and present a uniform interface to other kernel subsystems and the user. Shared objects in the VFS have RCs so that the degree of sharing of a particular object can be measured. Objects are placed in the reusable pool when their RCs go to zero, objects with low RCs can be swapped out, but objects with

high RCs should remain in main memory. Proper use of RCs is essential to avoid serious correctness and performance problems for all file systems.

To apply Monte Carlo runtime monitoring to this problem, we have defined Real Time Linear Temporal Logic formulas that collectively specify what it means for RCs to be correctly manipulated by the VFS. We further implemented the `MCM` algorithm within the Aristotle environment for Monte Carlo monitoring. Aristotle provide a highly extensible, GCC-based architecture for instrumenting C programs for the purposes of runtime monitoring. Aristotle realizes this architecture via a simple modification of the GNU C compiler (GCC) that allows one to load an arbitrary number of plug-ins dynamically and invoke code from those plug-ins at the tree-optimization phase of compilation.

Using a very simple sampling policy, our results show that Aristotle brings runtime overhead, which is initially very high when confidence is low, down to long-term acceptable levels. For example, a benchmark designed to highlight overheads under worst-case conditions exhibited a 10x initial slowdown; 11 minutes into the run, however, we achieved 99.999% confidence that the error rate for both classes of reference counts was below one in 10^5. At this point, monitoring for that class was reduced, leaving an overhead of only 33% from other monitoring.

In addition to reference counts, Aristotle currently provides Monte Carlo monitoring support for the correct manipulation of pointer variables (bounds checking), lock-based synchronization primitives, and memory allocation library calls. Due to its extensible architecture based on plug-ins, support for other system features can be easily added.

The rest of the section is organized as follows. Section 3.1.1 describes our system design. Section 3.1.2 presents our Monte Carlo runtime monitoring algorithm. Section 3.1.3 details the Aristotle design and implementation. Section 3.1.4 gives an example application of Aristotle, and Section 3.1.5 contains our concluding remarks and directions for future work.

3.1.1 Aristotle Design Overview

Figure 3.1 depicts the various stages of operation for Aristotle as it processes a system's source code. A modified version of the GNU C compiler (GCC) parses the source code, invoking an *instrumenting plug-in* to process the control flow graph for each function. The instrumenting plug-in inserts calls to verification code at each point where an event occurs that could affect the property being checked. The verification code is part of a *runtime monitor*, which maintains auxiliary runtime data used for property verification and is bound into the software at link time.

The runtime monitor interacts with the *confidence engine*, which implements a sampling policy based on our Monte Carlo runtime monitoring algorithm (described in Section 3.1.2). The confidence engine maintains a confidence level for the properties being checked and may implement a sampling policy automaton to regulate the instrumentation or perform other actions. This regulation can be based on changes in the confidence level and could respond to other events in the system, such as the execution of rarely-used code paths.

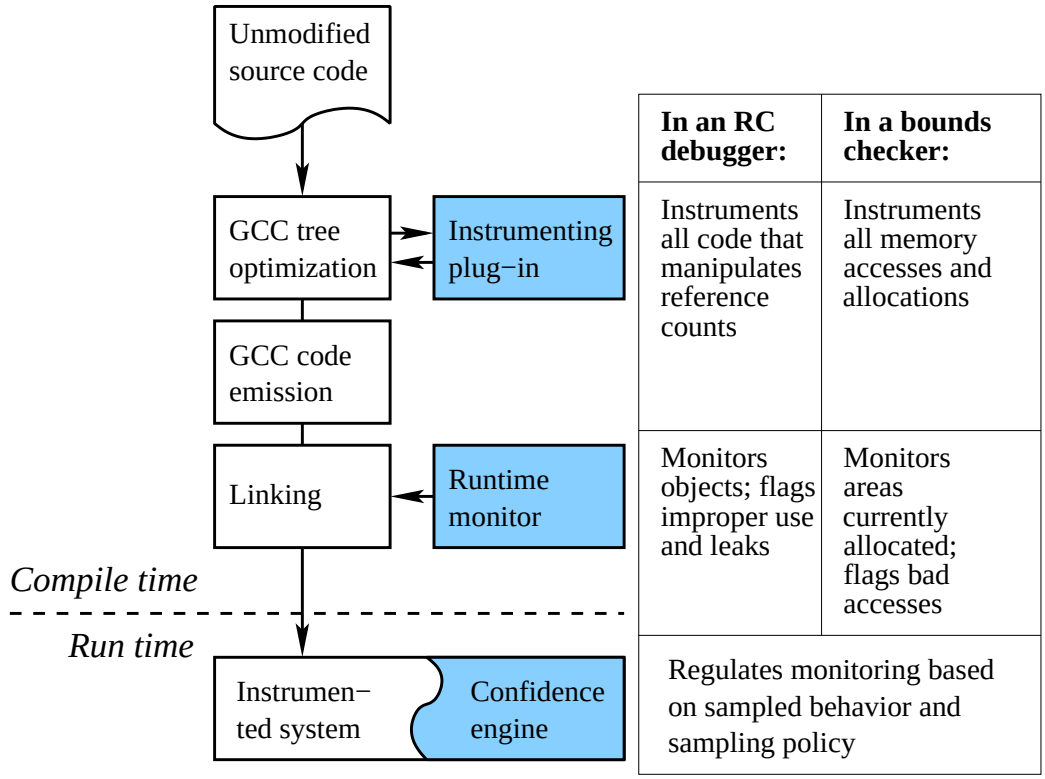


Figure 3.1: Architectural overview of the Aristotle system.

3.1.2 Monte Carlo Monitoring

In this section, we present our `MCM` algorithm for Monte Carlo monitoring and runtime verification. We first present `MCM` in the context of monitoring the correct manipulation of reference counts (RCs) in the Linux virtual file system (VFS). RCs are used throughout the Linux kernel, not only to prevent premature deallocation of objects, but also to allow different subsystems to indicate interest in an object without knowing about each other's internals. Safe use of reference counts is an important obligation of all kernel subsystems. We then consider generalizations of the algorithm to arbitrary dynamic types.

In the case of the Linux VFS, the objects of interest are *dentries* and *inodes*, which the VFS uses to maintain information about file names and data blocks, respectively. The VFS maintains a static pool of these objects and uses RCs for allocation and deallocation purposes: a free object has an RC of zero and may be allocated to a process; an object with a positive RC is considered in-use and may only be returned to the free pool when the state of the RC returns to zero. Additionally, an object with a high reference count is less likely to be swapped out to disk.

To apply Monte Carlo runtime monitoring to this problem, we first define the properties of interest. These are formally defined in Table 3.1.

Each of these properties is formalized using *Real-Time Linear Temporal Logic* [6], where `G`, `F` and `X` are unary temporal operators. `G` requires the sub-formula over which it operates to be true *Globally* (in all states of an execution), `F` requires it to

(stI)	$\forall o : C.\ \mathtt{G}\ o.\mathrm{rc} \geq 0$	RC values are always non-negative.
(trI)	$\forall o : C.\ \mathtt{G}\ \lvert o'.\mathrm{rc} - o.\mathrm{rc}\rvert \leq 1$	RC values are never incremented or decremented by more than 1.
(lkI)	$\forall o : C.\ \mathtt{G}\ o'.\mathrm{rc} \neq o.\mathrm{rc} \Rightarrow \mathtt{XF}_{\leq T}\ o'.\mathrm{rc} \leq o.\mathrm{rc}$	A change in the value of an RC is always followed within time T by a decrement.

Table 3.1: Reference-count correctness properties.

hold *Finally* (in some eventual state of an execution), and X requires it to hold *neXt* (in the next state of an execution). Also, an unprimed variable refers to its value in the current state and the primed version refers to its value in the next state. Each property uses universal quantification over all instances o of a dynamic type C.

The first property is a *state invariant* (stI) while the second property is a *transition invariant* (trI). The third property is a *leak invariant* (lkI) that is intended to capture the requirement that the RC of an actively used object eventually returns to zero. It is expressed as a time-bounded liveness constraint, with time bound T.

Since each of these properties can be proved false by examining a finite execution, they are safety properties, and one can therefore construct a deterministic finite automaton (DFA) A that recognizes violating executions [34, 70]. The synchronous composition (product) C_A of C with A is constructed by instrumenting C with A such that C violates the property in question iff an object o of type C can synchronize with A so as to lead A to an accepting state.

We view an object o of type C as executing in a closed system consisting of the OS and its environment. We assume that the OS is deterministic but the environment is a (possibly evolving) Markov chain; i.e., its transitions may have associated probabilities. As a consequence, C_A is also a Markov chain. Formally, a *Markov chain* $M = (X, E, p, p_0)$ consists of a set X of *states*; a set $E \subseteq X \times X$ of *transitions* (edges); an assignment of positive *transition probabilities* $p(x, y)$ to all transitions (x, y) so that for each state x, $\Sigma_{y \in X} p(x, y) = 1$; and an *initial probability distribution* p_0 on the states such that $\Sigma_{x \in X} p_0(x) = 1$. A *finite trajectory* of M is the finite sequence of states $\mathbf{x} = x_0, x_1, \ldots, x_n$, such that for all i, $(x_i, x_{i+1}) \in E$ and $p(x_i, x_{i+1}) > 0$. The probability of a finite trajectory $\mathbf{x} = x_0, x_1, \ldots, x_n$ is defined as $\mathbf{P}_M(\mathbf{x}) = p_0(x_0)p(x_0, x_1) \cdots p(x_{n-1}, x_n)$.

Each trajectory of C_A corresponds to an object execution. The more objects displaying the same execution behavior, the higher the probability of the associated trajectory. Hence, although the probabilities of C_A are not explicitly given, they can be learned via runtime monitoring.

Assuming that kernel-level objects have finite lifetimes (with the possible exception of objects such as the root file-system directory entry), and that state is dependent on the object's history, C_A is actually a Markov *tree*, since no object goes backward in time. The leaves of C_A fall into two categories: (i) violation-free executions of objects of type C which are deallocated after their RCs return to zero, and (ii) executions violating property stI, trI, or lkI.

Thus, a trajectory in C_A can be viewed as an object execution from its birth to its death or to an error state representing a property violation. We consider such a

trajectory to be a *Bernoulli random variable* Z such that $Z = 0$ if the object terminated normally, and $Z = 1$ otherwise. Further, let p_Z be the probability that $Z = 1$ and $q_Z = p_Z - 1$ be the probability that $Z = 0$. The question then becomes: *how many random samples of Z must one take to either find a property violation or to conclude with confidence ratio δ and error margin ϵ that no such violation exists?*

To answer this question, we rely, as we did in the case of Monte Carlo model checking, on the techniques of *acceptance sampling* and *confidence interval estimation*. We first define the *geometric* random variable X, with parameter p_Z, whose value is the number of independent trials required until success, i.e., until $Z = 1$. The *probability mass function* of X is $p(N) = \mathbf{P}[X = N] = q_Z^{N-1} p_Z$, and the *cumulative distribution function* (CDF) of X is

$$F(N) = \mathbf{P}[X \leq N] = \sum_{n \leq N} p(n) = 1 - q_Z^N$$

Requiring that $F(N)=1-\delta$ for *confidence ratio* δ yields:

$$N = \frac{\ln(\delta)}{\ln(1 - p_Z)}$$

which provides the number N of attempts needed to find a property violation with probability $1-\delta$.

In our case, p_Z is unknown. However, given *error margin* ϵ and assuming that $p_Z \geq \epsilon$, we obtain that

$$M = \frac{\ln(\delta)}{\ln(1 - \epsilon)} \geq N = \frac{\ln(\delta)}{\ln(1 - p_Z)}$$

and therefore that $\mathbf{P}[X \leq M] \geq \mathbf{P}[X \leq N] = 1 - \delta$. Summarizing, for $M = \frac{\ln(\delta)}{\ln(1-\epsilon)}$ we have:

$$p_Z \geq \epsilon \;\Rightarrow\; \mathbf{P}[X \leq M] \geq 1 - \delta \tag{3.1}$$

Inequality 3.1 gives us the minimal number of attempts M needed to achieve success with confidence ratio δ under the assumption that $p_Z \geq \epsilon$.

The standard way of discharging such an assumption is to use *statistical hypothesis testing* [46]. We define the *null hypothesis* H_0 as the assumption that $p_Z \geq \epsilon$. Rewriting inequality 3.1 with respect to H_0 we obtain:

$$\mathbf{P}[X \leq M \,|\, H_0] \geq 1 - \delta \tag{3.2}$$

We now perform M trials. If no counterexample is found, i.e., if $X > M$, then we reject H_0. This may introduce a type-I error: H_0 may be true even though we did not find a counterexample. However, the probability of making this error is bounded by δ; this is shown in inequality 3.3 which is obtained by taking the complement of $X \leq M$ in inequality 3.2:

$$\mathbf{P}[X > M \,|\, H_0] < \delta \tag{3.3}$$

With the above framework in place, we now present MCM, our Monte Carlo Monitoring algorithm. MCM, whose pseudo-code is given in Table 3.2, utilizes DFA A to monitor properties stI, trI, and lkI, while keeping track of the number of samples taken.

```
input:  ϵ, δ, C, t, d;
global: tn, cn;
tn=cn=ln(δ)/ln(1-ϵ); set(timeout,d);
when (created(o:C) && flip())
  if (tn>0) { tn--; o.to=t; o.rc=0};
when (destroyed(o:C)){
  cn--; if (cn=0) monitoring stop;}
when (monitored(o:C) && modified(o.rc)){
  if (o′.rc<0 || |o′.rc-o.rc|>1) safety stop;      /* stI, trI */
  if (o.rc-o′.rc==1) o.to=t;}
when (timeout(d))
  for each (monitored(o:C)){
  o.to--; if (o.to==0) leak stop;}                 /* lkI */
```

Table 3.2: The MCM algorithm.

MCM consists of an initialization part, which sets the target (tn) and current (cn) number of samples, and a monitoring part, derived from the properties to be verified. The latter is a state machine whose transitions (when statements) are triggered either by actions taken by objects of type C or by a kernel timer thread. The timer thread wakes up every d time units, and the time window used to sample object executions is t∗d, where t and d are inputs to the algorithm. When an object o:C is created and the random boolean variable flip() is true, the target number of samples is decremented. The random variable flip() represents one throw of a multi-sided, unweighted coin with one labeled side, and returns true precisely when the labeled side comes up. If enough objects have been sampled (tn=0), no further object is monitored. For a monitored object, its reference count rc and timeout interval to are appropriately initialized. When an object is destroyed, cn is decremented. If the target number of samples was reached (cn=0), the required level of confidence is achieved and monitoring can be disabled. When the RC of a monitored object is altered, we check for a violation of safety properties stI or trI, stopping execution if one has occurred. If an object's RC is decremented, we reset its timeout interval; moreover, should its RC reach zero, the object is destroyed or reclaimed. When the timer thread awakens, we adjust the timeout interval of all monitored objects. If an object's timeout interval has expired, leak invariant lkI has been violated and the algorithm halts.

Due to the random variable flip(), MCM does not monitor every instance o of type C. Rather, it uses a *sampling-policy automaton* to determine the rate at which instances of C are sampled. For example, consider the n-state policy automaton PA_n that, in state k, $1 \leq k \leq n$, MCM will only sample o if flip() returns true for

a 2^k-sided coin. Moreover, PA_n makes a transition from state k to $k + 1 \mod n$ after exactly M samples. Hence, after M samples (without detecting an error) the algorithm uses a 4-sided coin, after $2M$ samples an 8-sided coin, etc. For a given error margin ϵ, the associated confidence ratio δ will then be $(1-\epsilon)^M$, $(1-\epsilon)^{2M}$, $(1-\epsilon)^{3M}$ and so on. PA_n also makes a transition from state k to j, where $j < k$, when an undesirable event occurs, such as a counterexample, or perhaps an execution of as yet unexecuted code. Sampling policies such as the one encoded by PA_n assure that `MCM` can adapt to environmental changes, and that the samples taken by `MCM` are mutually independent (as n tends toward infinity).

`MCM` is very efficient in both time and space. For each random sample, it suffices to store two values (old and new) of the object's RC. Moreover, the number of samples taken is bounded by M. That M is optimal follows from inequality 3.3, which provides a tight lower bound on the number of trials needed to achieve success with confidence ratio δ and lower bound ϵ on p_Z.

Our kernel-level implementation of `MCM` is such that if a violating trajectory is observed during monitoring, it is usually the case that a sufficient amount of diagnostic information can be gleaned from the instrumentation to pinpoint the root cause of the error. For example, if an object's RC becomes negative, the application that executed the method that led to this event can be determined.

In another example, if the object's RC fails to return to zero and a leak is suspected, diagnostic information can be attained by identifying the object's containing type. Suppose the object is an inode; we can use this information to locate the corresponding file name and link it back to the offending application.

The `MCM` algorithm of Figure 3.2 can be extended by expanding the class of correctness properties supported by the algorithm. The third and fourth `when` branches of the algorithm correspond to safety or bounded-liveness checks, respectively. Hence, the `MCM` algorithm can be generalized in the obvious way, to allow the treatment of arbitrary safety and bounded-liveness properties for any reactive program involving dynamic types. For example, in addition to reference counts, Aristotle currently provides Monte Carlo monitoring support for the correct manipulation of pointer variables (bounds checking), lock synchronization primitives, and memory allocation library calls. Due to its extensible, plug-in-oriented architecture, support for other properties can easily be added.

3.1.3 Implementation

In Aristotle, we instrument a program with monitoring code using a modified version of the GNU C compiler (GCC), version 4. We modified the compiler to load an arbitrary number of plug-ins and invoke code from those plug-ins at the tree-optimization phase of a compilation. At that point in the compilation, the abstract syntax tree has been translated into the GIMPLE intermediate representation [22], which includes syntactic, control-flow, and type information. A plug-in is invoked that can use the GCC APIs to inspect each function body in turn and add or remove statements. The plug-in can even invoke other GCC passes to extract information; for example, one plug-in we developed for bounds checking uses the reference-

analysis pass to obtain a list of all variables used by a function.

Our use of GCC as the basis for Aristotle offers several advantages. First, it can be used to instrument any software that compiles with GCC. Prior static-checking and meta-compilation projects have used lightweight compilers [9, 28] that do not support all of the language extensions and features of GCC. Many of these extensions are used by open-source software, particularly the Linux kernel. Second, the modular architecture of Aristotle allows programmers to instrument source-code without actually changing it. Third, Aristotle users can take advantage of GCC's library of optimizations and ability to generate code for many architectures. Adding GCC support for plug-ins is very simple; we added a command-line option to load a plug-in and changed the way GCC is built to expose GCC's internal APIs to plug-ins.

The information collected at the instrumented locations in the system's source code is used by runtime monitors. A runtime monitor is a static library, linked with the system at compile time. The runtime monitor contains checking code which verifies that each detected event satisfies all safety properties; furthermore, it may spawn threads that periodically verify that all bounded liveness properties hold. The monitor interfaces with the confidence engine, reporting rule violations and regulating its operation according to the confidence engine's instructions, which reflect the operation of a sampling-policy automaton. Finally, it may also perform other operations, like verbose logging and network-based error reporting, which vary from application to application.

3.1.4 Case Study: The Linux VFS

The Linux Virtual File System (VFS) is an interface layer that manages installed file systems and storage media. Its function is to provide a uniform interface to the user and to other kernel subsystems, so that data on mass storage devices can be accessed in a consistent manner. To accomplish this, the VFS maintains unified caches of information about file names and data blocks: the *dentry* and *inode* caches, respectively. The entries in these caches are shared by all file systems. The VFS and file systems use reference counts to ensure that entries are not reused without a file system's knowledge and to prioritize highly-referenced objects for retention in main memory as opposed to being swapped out.

The fact that these caches are shared by different file systems, implemented by different authors and of varying degrees of maturity, introduces the potential for system resource leaks and faults arising from misuse of cached objects. For example, a misbehaving file system may prevent a storage device from being safely removed because the reference count for an object stored to that device was not safely reduced to zero. Worse, a misbehaving file system could hamper the performance of other file systems by failing to decrement the reference counts of cache data structures.

Using the Aristotle framework, we developed a tool that monitors reference counts in the Linux VFS. As described in Section 3.1.2, we enforced a state invariant (stI), a transition invariant (trI), and a leak invariant (lkI).

The plug-in for this case study instruments every point in the source code at which a reference count was modified. Because we had access to type information, we were able to classify reference counts for dentry and inode objects. Whenever it is invoked, the runtime monitor checks the operation to ensure that the safety properties hold. Additionally, if the operation is a decrement, the monitor updates a timestamp for that reference count, which is maintained in an auxiliary data structure. A separate thread periodically traverses the data structure to verify that all reference counts have been decremented more recently than time interval T. Additionally, all checked operations are optionally logged to disk.

The confidence engine maintains separate confidence levels for dentry and inode reference counts using our Monte Carlo model checking algorithm. For clarity, we demonstrate the system with a sampling policy automaton that disables checking when a 99.999% confidence level has been reached that the error rate for that reference counter category is less than 1 in 10^5 samples. As discussed in Section 3.1.2, a sample is defined as the lifetime of a cached object, that is, the period when the object's reference counter is nonzero. Other sampling policies, such as flipping an n-sided coin where n increases as confidence increases to determine whether to sample a given object, allow more fine-grained trade-offs of performance vs. confidence; additionally, it may be advisable to increase the sampling rate as the environment changes.

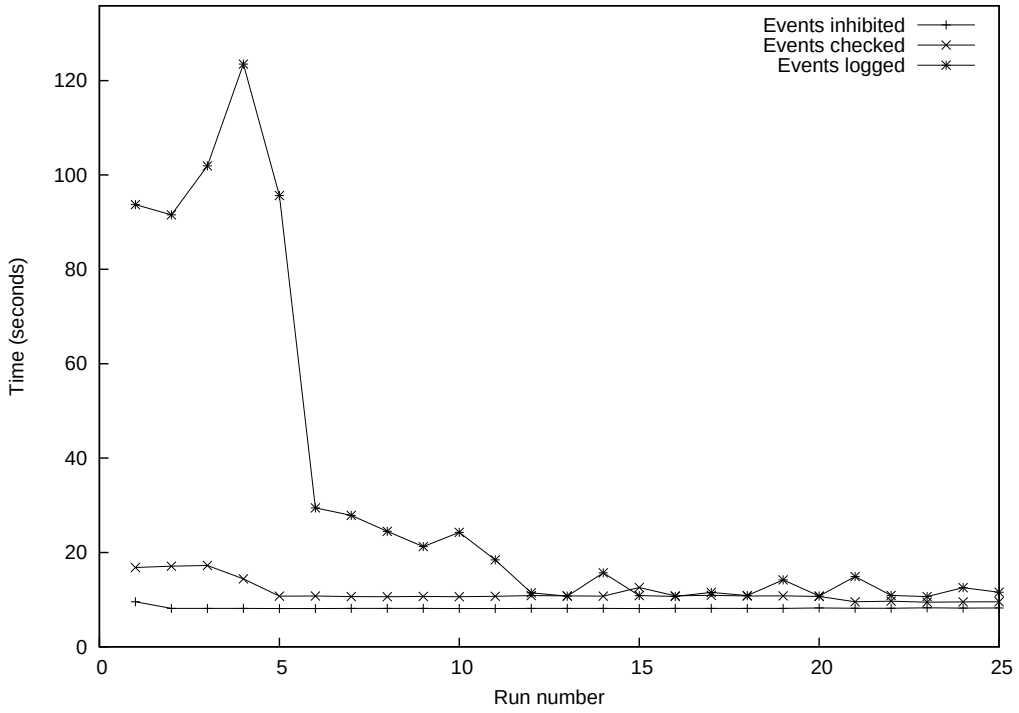


Figure 3.2: Overhead reduction for the directory-tree micro-benchmark as confidence increases

Figure 3.2 shows the performance overhead of the system with logging and checking enabled, logging disabled but checking enabled, and no instrumenta-

tion, under a micro-benchmark designed to exercise the file system caches. In each run, the micro-benchmark creates a tree of directories, does a depth-first traversal of that tree, and deletes the tree. Because directories are being created and deleted, on-disk data is being manipulated, causing creation and deletion of objects in the inode cache. Additionally, the directory traversal stress-tests the dentry cache. We observe an initial 10x overhead as both dentry and inode reference counts are being monitored and all accesses are being logged. After five runs, which take six minutes in total, dentry confidence reaches the target, and overhead falls to a factor of three. Finally, five minutes later, after eleven runs, overhead drops to 33% when inode confidence reaches the target. The remaining overhead is a characteristic of our prototype; we expect optimization to reduce it significantly.

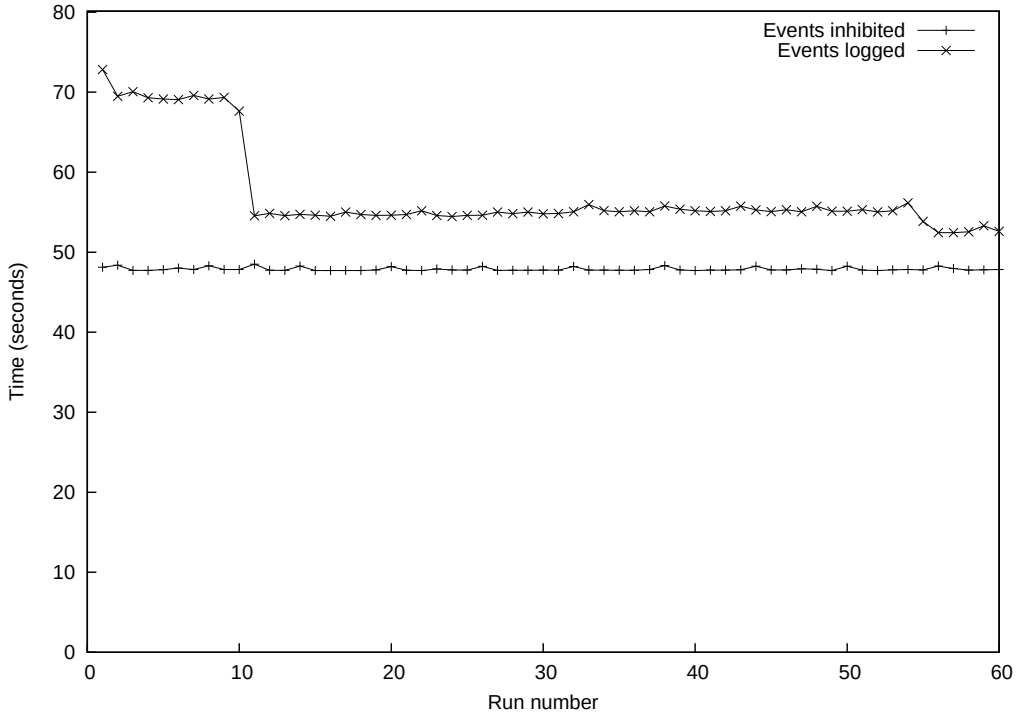


Figure 3.3: Overhead reduction for the compilation of GNU tar as confidence increases

Figure 3.3 shows the effects under a benchmark that puts less stress on the file system. Compiling the GNU `tar` utility involves less cache activity than the micro-benchmark described above, so the overheads from monitoring are lower; however, it also takes longer for confidence to reach the target. Initial overhead with logging was 46%. After ten runs, or eleven minutes, this overhead dropped to 14% as dentry confidence reached the target. Forty minutes later, at the 55th run, overheads dropped to 11% as inode confidence reached its target as well.

3.1.5 Conclusion

We have presented the `MCM` algorithm for Monte Carlo monitoring and runtime verification, which uses sampling-policy automata to vary its sampling rate dy-

namically as a function of the current confidence in the monitored system's correctness. We implemented `MCM` within the Aristotle tool environment, an extensible, GCC-based architecture for instrumenting C programs for the purposes of runtime monitoring. Aristotle realizes this architecture via a simple modification of GCC that allows one to load an arbitrary number of plug-ins dynamically and invoke code from those plug-ins at the tree-optimization phase of compilation. Our experimental results show that Aristotle reduces the runtime overhead due to monitoring, which is initially high when confidence is low, to long-term acceptable levels as confidence in the deployed system grows.

We are investigating the integration of auxiliary information, such as code coverage, into sampling policies. This would allow, for example, instrumentation to be increased when a rarely-used section of code is executed.

3.2 Bounding Overhead Using Supervisory Control

In this section, we introduce the new technique of *Software Monitoring with Controllable Overhead* (SMCO). SMCO is formally grounded in control theory, in particular, the *supervisory control of discrete event systems* [52, 1]. Overhead control, while maximizing confidence, is realized by disabling interrupts generated by the events being monitored—and hence avoiding the overhead associated with processing these interrupts—for as short a time as possible under the constraint of a user-supplied target overhead o_t. SMCO can be viewed as the problem of generating an optimal controller for a specific class of nonlinear systems that can be modeled as the composition of a set of timed automata. Our controller is designed in a *modular* way by composing a *global controller* with a set of *local controllers*, one for each monitored object in an application. Moreover, SMCO is a general monitoring technique that can be attached to *any* system interface or API.

We have applied SMCO to the problems of detecting *stale or underutilized memory* and checking for *bounds violations*. For memory staleness, we make novel use of the virtual memory hardware by utilizing the `mprotect` system call to protect each area suspected of being underutilized. If such an area is in fact accessed, the program generates a segmentation fault, informing the monitor that the area is not stale. If the time since the monitor protected an area is longer than a user-specified threshold, and there were no segmentation faults from that area, then it is stale. The SMCO controller controls the total overhead of memory underutilization checking by enabling and disabling the monitoring of each memory area appropriately. For bounds checking, we use an approach based on plug-ins as discussed in Section 2.1.

Experimental results of SMCO's performance on the `Lighttpd` Web server, the `vim` text editor, and our micro-benchmark suite are encouraging. SMCO maintains bounded overhead well for both applications. When local controllers behave linearly, SMCO controls overhead precisely; when local controllers behave nonlinearly, it becomes more challenging for SMCO to control overhead, but results are still acceptable. For `Lighttpd`, we also demonstrate a discovery, that one-third of its heap footprint is completely unused. Our micro-benchmarks demonstrate how

confidence grows monotonically with the target overhead up to CPU saturation, and that this is done consistently and predictably. Collectively, our benchmarking results show that using SMCO, it is indeed possible to achieve high-confidence monitoring with bounded overhead.

We organize the rest of this section in the following way. Section 3.2.1 explains SMCO's control-theoretic approach to bounding overhead while maximizing confidence. Section 3.2.2 presents our architectural framework for SMCO and describes how we apply it to bounds checking and staleness detection. Section 3.2.3 contains our performance evaluation and Section 3.2.4 offers concluding remarks and directions for future work.

3.2.1 Control-Theoretic Monitoring

The *controller design problem* attempts to regulate the input v to a process P, henceforth referred to as the *plant*, to make its output y adhere to a *reference input* x. The device that accepts x and y and produces v is called a *controller*; we write it Q. The composition of Q and P must make y approximate x with good dynamic response and small error (see Figure 3.4).

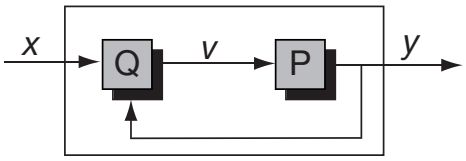


Figure 3.4: Plant (P) and Controller (Q) architecture.

Runtime monitoring can be beneficially stated as a controller-design problem, where the controller is the runtime monitor, the plant is a software application and the reference input x is the *target overhead* o_t. To ensure that the plant is *controllable*, one typically *instruments* the application so that it emits *events* of interest to the monitor. The monitor catches these events, and controls the plant by *enabling* or *disabling* event signaling (interrupts). Hence, the plant can be regarded as a *discrete event process*.

The classic theory of digital control [17] assumes that the plant and the controller are linear systems. This assumption allows one to apply a rich set of design and optimization techniques, such as the Z-transform, fast Fourier transform, root-locus analysis, frequency response analysis, and state-space optimal design. For nonlinear systems, however, these techniques are not directly applicable, and various linearization and adaptation techniques must be applied as pre- and post-processing, respectively.

Because of the enabling and disabling of interrupts, the problem we are considering is nonlinear: intuitively, the interrupt signal is multiplied by a control signal which is 1 when interrupts are enabled and 0 otherwise. Although linearization is one possible approach for this kind of nonlinear system, automata theory suggests a better approach, recasting the controller design (synthesis) problem as one of *supervisory control* [52, 1].

The main idea of supervisory control we exploit to enable and disable inter-

rupts is the synchronization inherent in the *parallel composition* of state machines. In this setting, the plant P is a state machine, the desired outcome (tracking the reference input) is a language L, and the controller design problem is that of designing a controller Q, which is also a state machine, such that the language $L(Q\|P)$ of the composition of Q and P is included in L. This problem is decidable for *finite* state machines [52, 1].

The monitoring overhead depends on the timing of events and the monitor's per-event processing time. The specification language L therefore consists of *timed words* $a_1, t_1, \ldots, a_n, t_n$ where each a_i is an (access) event and t_i is the time at which a_i has occurred. Consequently, the state machines used to model P and Q must also include a notion of time. Previous work has shown that supervisory control is decidable for *timed automata* [3, 73] and for *timed transition models* [53]. In our setting, we use a more expressive version of timed automata that allows clocks to be compared to variables, and for such automata decidability is not guaranteed. We therefore design our controller manually, but we are currently investigating techniques for the automated synthesis of an approximate controller. The controller we designed consists of the composition of a *global controller* and a set of *local controllers*, one for each plant (object in the application software) that we monitor. We define these two controllers later in this section.

Plant model. We describe the plant P (see Figure 3.5) as an extended timed automaton whose alphabet consists of input and output events. We use timing constraints to label its locations and transitions. These constraints take the form $x \sim c$, where x is a *clock*, c is a natural constant or variable, and $\sim$ is one of $<$, $\leq$, $=$, $\geq$, and $>$. We write transition labels in the form `[guard]In/Out, Asgn`, where `guard` is a predicate over the automaton's variables; `In` is a sequence of input events of the form $v?e$ denoting the receipt of value e on channel v; `Out` is a sequence of output events of the form $y!a$ denoting the sending of value a on channel y; and `Asgn` is a sequence of assignments to the (local) variables. All fields in a label are optional. A transition is *enabled* when its guard is true and the event (if specified) has arrived. A transition is not *forced* to be taken unless letting time flow would violate the condition (invariant) labeling the current location.

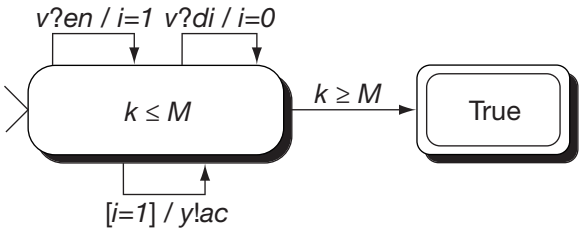


Figure 3.5: State machine for the plant P of one monitored object.

The plant P has an input channel v where it may receive *enable* and *disable* commands, denoted en and di, respectively. It has an output channel y where it may send an *access* message ac. Upon receipt of $v?di$, the interrupt bit i is set to zero which prevents the plant from sending further messages. Upon receipt of

$v?en$, the interrupt bit is set to one which allows the plant to send messages at arbitrary moments in time. The plant terminates when the maximum monitoring time M, a parameter of the model, is reached; i.e., when the clock k reaches value M. Initially, $i = 1$ and $k = 0$.

Target specification. The specification for a single controlled plant is given as a timed language L. Let $\mathtt{N}$ denote the natural numbers, $\mathtt{R}^+$ the positive reals, and $\mathtt{A}$ the set of events. Then:

$$L = \{a_1, t_1, \ldots, a_n, t_n \mid n \in \mathtt{N}, a_i \in \mathtt{A}, t_i \in \mathtt{R}^+\}$$

where the following conditions hold:

1. The average overhead $\overline{o} = (n\, p_a)/(t_n - t_1)$ is $\leq o_t$, where p_a is the average event-processing time.
2. If the strict inequality $\overline{o} < o_t$ holds, then the overhead undershoot is due to time intervals (with low activity) during which all access events are monitored.

The first condition talks only about the mean overhead $\overline{o}$ within a timed word $w \in L$. Hence, various policies for handling overhead, and thus enabling/disabling interrupts, are allowed. The second condition is a *best-effort* condition which guarantees that if the target overhead is not reached, this is only because the plant does not throw enough interrupts. Our policy, which we describe next, satisfies these conditions and will also be shown to be optimal in a specific sense.

The local controller. Each monitored plant P has a local controller Q, the state machine for which is given in Figure 3.6. Within each iteration of its main control loop, Q disables interrupts by sending message di along v upon receiving an access event ac along y, and subsequently enables interrupts by sending en along v. Consider the i-th execution of Q's control loop, and let τ_i be the *time monitoring is on* within this cycle; i.e., the time between events $v!en$ and $y?ac$. Let p_i be the time required to *process* event $y?ac$, and let d_i be the *delay time* until monitoring is restarted; i.e., until event $v!en$ is sent again. See Figure 3.7 for a graphical illustration of these intervals. Then $c_i = \tau_i + p_i + d_i$ is the total amount of time Q spends in the i-th cycle, and we refer to $o_i = p_i/c_i$ as the *overhead ratio* at i.

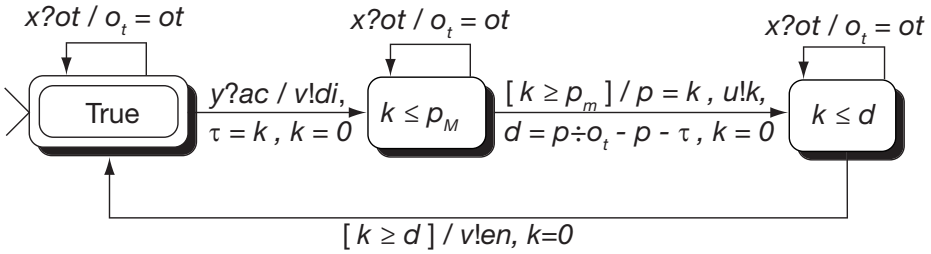


Figure 3.6: State machine for local controller Q.

To ensure that $o_i = o_t$ whenever the plant is throwing access events at a high rate, the local controller computes d_i as the least positive integer greater than or equal to $p_i/o_t - p_i - \tau_i$. If the plant throws events at a low rate, then all events are monitored and $d_i = 0$. Whenever processing of event $y?ac$ is finished, the local

controller sends along u the processing time k to the global controller, which is discussed following the soundness and optimality proofs for the local controller. The processing time is assumed to lie within the interval $[p_m, p_M]$.

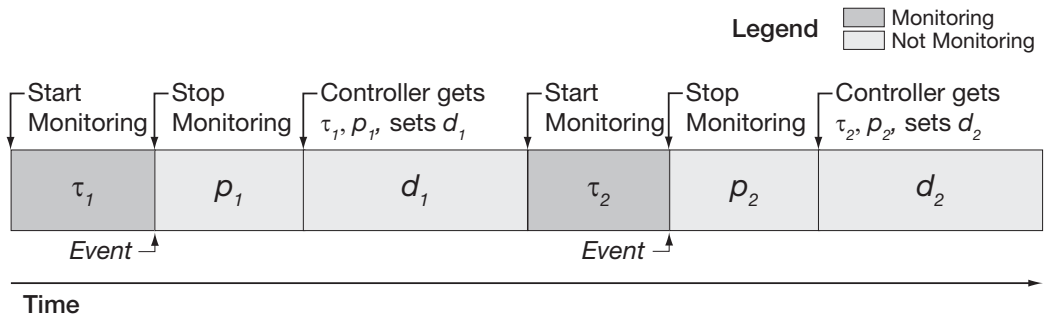


Figure 3.7: Time-line for local controller.

Soundness and optimality of the local controller. We provide informal soundness and optimality proofs for our local controller.

Theorem 3.2.1 (Soundness)**.** *The language $L(Q\|P)$ of the parallel composition of the local controller Q with the plant P is included in the target specification language L.*

Proof. The soundness follows from the definitions of Q and P. If P throws events at a high rate, then Q maintains the mean overhead rate $\overline{o} = o_t$. If P throws events at a low enough rate, then Q monitors all events, and $\overline{o} < o_t$. If P alternates between intervals of high and low rates of event throwing, then $\overline{o} < o_t$; the difference between $\overline{o}$ and o_t is due to the low-rate intervals during which all events are monitored. □

The optimality condition we consider for the controller is with respect to the *space and time locality* of the plant. In particular, a useful property of our controller is that it tends to monitor a representative sample of "independent" events. This is because of its fine-grained control strategy; i.e., when the event rate is high, our controller (briefly) disables interrupts after *each* processed event. Since, by the space and time locality of the plant, consecutive events are likely to be similar or related, this strategy helps avoid monitoring similar events.

Theorem 3.2.2 (Locality-based optimality)**.** *The controller Q is optimal with respect to space and time* locality*.*

Proof. If an event is thrown at time t_i by a statement s or memory location m, then due to space locality, another event is likely to be thrown at a statement t or memory location n close to s and m, respectively. Therefore, the time t_j when the second event is thrown is also close to time t_i. Since Q disables interrupts immediately following occurrence of an event, optimality follows. □

The two applications of SMCO we consider are the detection of stale memory and bounds violations. For stale memory detection, once an event is thrown, we

are certain that the corresponding object is not stale, so we can ignore interrupts for a definite interval of time, without compromising soundness and at the same time lowering the monitoring overhead. For array-bounds violations, we would like to analyze the program in a uniform way. Two bounds violations close to each other are likely to be caused by the same statement in the program. Hence, the first interrupt is enough to identify the bug, while also lowering the monitoring overhead.

The global controller. The local controller Q achieves its target overhead o_t only if the plant P throws events at a sufficiently high rate. Otherwise the mean overhead $\overline{o}$ is less than o_t. In case we monitor a large number of plants P_i simultaneously, it is possible to take advantage of this under-utilization of o_t by increasing the overhead o_t of those controllers Q_i associated with plants P_i that throw interrupts at a high rate. In fact, we can scale the target overhead o_t of *all* local controllers Q_i with the same factor λ, as the controllers Q_j of plants P_j with low rate of interrupts will not take advantage of this scaling. Furthermore, we do this every T seconds, a period of time we call the *adjustment-interval*. The periodic adjustment of the local target overheads is the task of the global controller GQ. The architecture of our overall control framework for SMCO is shown in Figure 3.8.

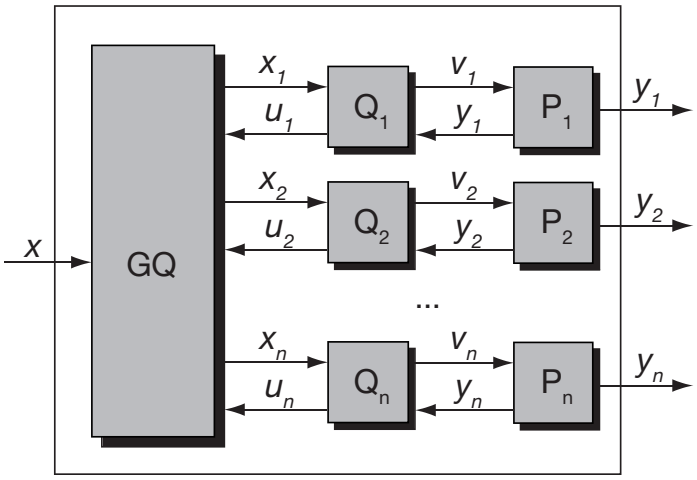


Figure 3.8: Overall control architecture.

The timed state machine for the global controller GQ is given in Figure 3.9. It inputs on x the user-specified target overhead ot, which it then assigns to local variable o_{gt} representing the global target overhead. It further outputs ot/n to the local controllers and assigns ot/n to local variable o_t, representing the target overhead for the local controllers. The idea is that the global target overhead is evenly partitioned among the n local controllers. It also maintains an array of total processing time p, initially zero, such that $p[i]$ is the processing time used by local controller Q_i within the last adjustment-interval of T seconds. Array entry $p[i]$ is updated whenever Q_i sends the processing time p_j of the most recent event a_j; i.e., $p[i]$ is the sum of the p_j that local controller Q_i generates during the current adjustment

interval.

Whenever the time bound of T seconds is reached, GQ computes a scaling factor $\lambda = \sum_{i=1}^{n} p[i]/(T \cdot o_{gt})$ as the overall observed processing time divided by the product of T, n and the global target overhead o_{gt}. This factor represents the under- or over-utilization of o_{gt}. The new local target overhead o_t is then computed by scaling the previous o_t by λ.

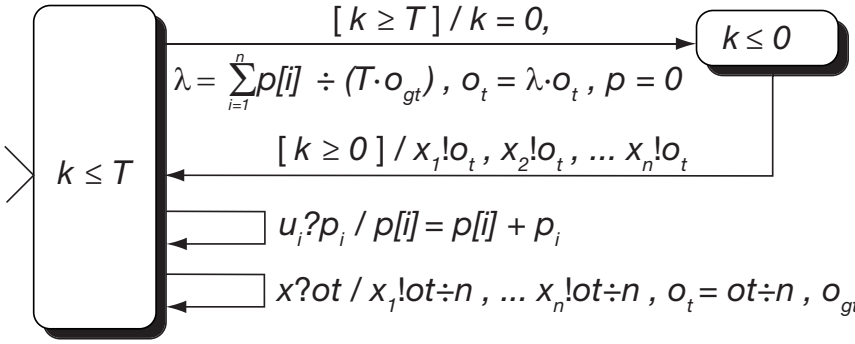


Figure 3.9: State machine for the global controller.

The *target specification language* L_G is defined in a fashion similar to the one for the local controllers, except that the events of the plant P are replaced by the events of the parallel composition $P_1 \parallel P_2 \parallel \ldots \parallel P_n$ of all plants.

Theorem 3.2.3 (Global soundness)**.** *Let S be defined as $GQ \| Q_1 \| \ldots \| Q_n \| P_1 \| \ldots \| P_n$, the parallel composition of the global controller GQ, local controllers Q_i and plants P_i, $i \in [1..n]$. Then the language $L(S)$ is included in the target specification language L_G. Moreover, the discrepancy between $\overline{o}$ and o_{gt} is the minimal that can be achieved for the parallel composition of the plants and the adjustment interval of T seconds.*

Proof. We derive o_t so that $n \times o_t = o_{gt}$, where n is the number of plants. Each local controller Q_i achieves observed overhead $\overline{o_i} \leq o_t$, so $\sum_{i=1}^{n} \overline{o_i} \leq o_{gt}$. If the total is less than o_{gt}, then this is because some plants P_i are experiencing a low rate of interrupts, but in that case those plants have reduced their delays d_i to 0 so they are observing all possible events. Furthermore, because their rate is already as high as possible, under-utilized local controllers will be unaffected by λ-scaling, whereas others benefit. This fact can be used to prove minimal discrepancy. □

GQ also balances the load of local controllers in an optimal way with respect to the space and time locality of access events.

3.2.2 Design

In this section, we discuss the two applications that we have implemented for SMCO, namely memory under-utilization detection and bounds checking. An architecture overview of the system is shown in Figure 3.10. The *controller* in Figure 3.10 implements the global controller GQ and each local controller Q_i. The controller receives an event from the instrumented program each time the program

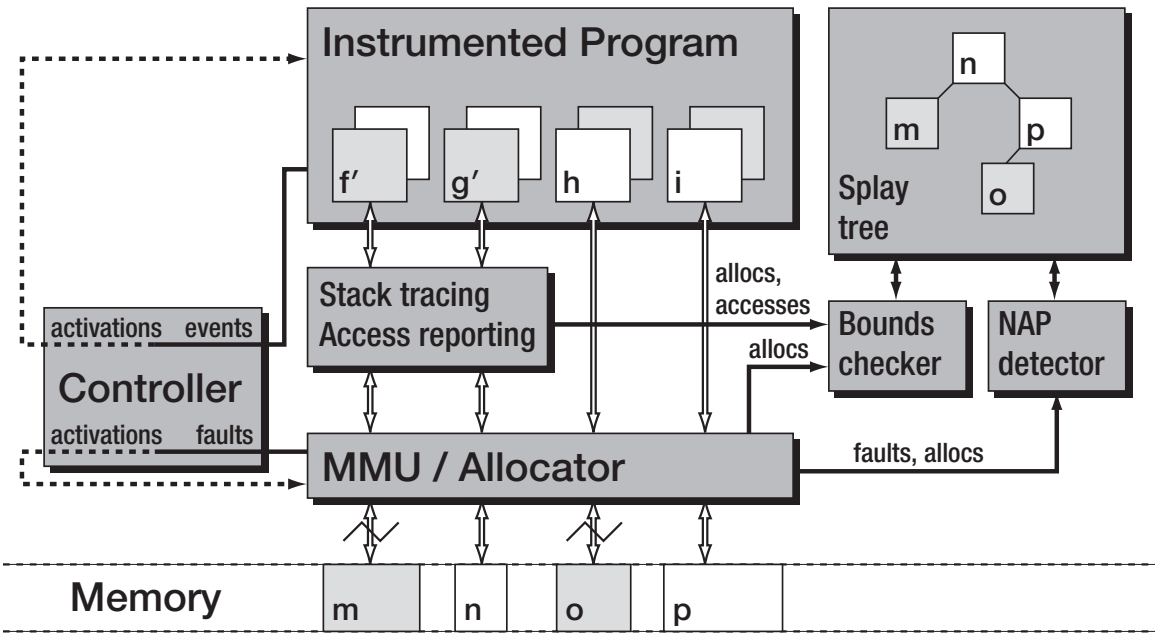


Figure 3.10: SMCO architecture for bounds checking and memory under-utilization detection.

executes a bounds check and from the Memory Management Unit (MMU) each time the program accesses a protected area. Based on the total time spent processing these events, the controller activates and deactivates monitoring of functions and memory areas.

The bounds checker and NAP (Non-Accessed Period) detector are responsible for detecting and reporting errors. Together, they maintain a splay tree of memory ranges, including stack areas and dynamic memory allocations. The bounds checker uses the splay tree to determine which accesses are out-of-bounds, and the NAP detector searches dynamic allocations in the splay tree to find regions that have not reported accesses in a prescribed amount of time. The *stack tracing/access reporting* module intercepts stack-area creations/destructions and pointer dereferences from instrumented functions and reports them to the bounds checker. Note that our architecture cleanly separates the overhead controller from the modules that perform fault detection and reporting.

Functions f and g and memory areas m and o in Figure 3.10 are rendered in gray to indicate that they are in the activated state. Function calls to f or g will therefore result in the execution of their instrumented versions f' and g', respectively, so that bounds checking, with controllable overhead, can be performed. Similarly, the MMU will intercept accesses to m and o so that events can be generated for processing by the NAP detector.

We now describe the controller, the NAP detector, and the bounds checker in more detail.

Controller Design. The controller's role is to limit the number of events generated by the instrumentation in order to meet a target overhead goal, where *overhead*

refers to the percentage of time an instrumented program spends processing the events. To this end, after every event, the controller temporarily disables events from the entity (activated function or memory area, in our case) that generated the event. Consider bounds checking. A memory access within a function call generates a bounds-checking event. The controller measures the total amount of time the bounds check takes, and then computes a delay using the function's *local controller*, as described in Section 3.2.1. The function runs with bounds checking turned off until the delay passes and the controller reactivates it. A similar mechanism temporarily deactivates a protected memory area when it generates an access event.

NAP **Detection.** We have implemented an SMCO-based under-utilization detector which identifies areas that are not accessed for a user-definable period of time. We refer to such a time period as a *Non-Accessed Period*, or NAP. Figure 3.11 depicts the error model for the under-utilization detector. Note that we are not detecting areas that are never touched (i.e., leaks), but rather areas that are not touched for a sufficiently long period of time to raise concerns about memory-usage efficiency.

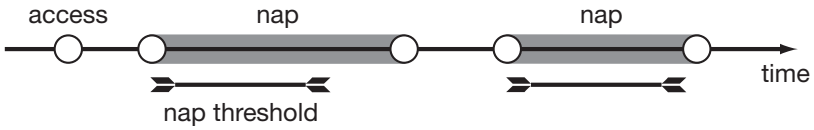


Figure 3.11: Our memory under-utilization detector reports non-accessed periods. NAPS *can vary in length, and multiple* NAPS *can be reported for the same area.*

The implementation of a memory under-utilization detector would normally involve instrumenting memory-access instructions. This technique, however, introduces a number of issues, both practical and theoretical. First, there is the practical issue of finding accesses. This can be done using a compiler or by using tools like Valgrind; compiler tools only works for programs with available source, and both introduce significant overheads. Our under-utilization detector controls its overhead using sampling. However, if one attempts to find NAPS by sampling a subset of memory-access instructions, this introduces a theoretical problem: in order to be able to say with certainty whether or not a particular area was accessed in a particular time period, *all* memory-access instructions must be monitored during that period, which could again result in considerable overhead.

To address these problems, we introduce a memory-access interposition mechanism called `memcov` that intercepts accesses to particular areas, not accesses by particular instructions. We take advantage of the memory-protection hardware by using the `mprotect` interface, which allows a programmer to control access to a particular memory region. Accesses that violate the access controls set in this way cause segmentation fault signals (`SIGSEGV` on Linux) to be sent to the process in question. By intercepting such faults, which include the faulting address, `memcov` can determine which areas are being accessed by the program and when.

To perform our memory-access interposition, we implemented a shared library

that replaces the standard memory-allocation functions, notably `malloc` and `free`, with functions that handle memory in multiples of the block size that `mprotect` can protect. Due to the implementation of memory protection in hardware, this block size is nearly always larger than the smallest addressable unit: on x86-based platforms, it is usually 4,096 bytes. After allocating an area, our custom allocator adds an entry to a splay tree that contains information about its size, the last time an access was observed, and data to support our controller, which controls each area individually.

When the controller instructs `memcov` to monitor an area, `memcov` uses `mprotect` to disallow reads and writes that reference that area. Then, when the program attempts to access that area, the memory protection hardware intercepts the access and the kernel passes a `SIGSEGV` to the process. The signal is then handled by `memcov`, which performs a lookup in the splay tree and registers a hit with the appropriate controller. Memcov periodically checks for areas that have been monitored and unaccessed for longer than the user-defined threshold, and reports them as NAPs if that NAP has not already been reported.

Bounds Checking. Our second application is a more traditional problem: bounds checking. Bounds checking may be broadly defined as ensuring that pointers are dereferenced only when they are *valid*, which typically means that they point to memory addresses located in properly-typed regions of the stack, heap, or static (including text, data, and BSS) segments of the program's address space. Our definition of a valid pointer is one that points to a region that

- has been allocated using the system's heap memory allocation functions (notably `malloc`),
- corresponds to some instance of a stack variable (either a local variable or a function parameter), or
- corresponds to a static variable.

We consider any dereferenced pointer to be valid if its target matches the above criteria, regardless of the pointer's type or the region it originally pointed to. This means that we do not need to keep track of each pointer update, which would impose additional overheads. Instead, we need only keep track of areas as they are allocated and deallocated. To accomplish this, we use the splay tree that we use for NAP detection. At the entry to each function, the function's stack variables and static variables are registered in the splay tree. At each function's exit points, the function's stack variables are deregistered.

To add instrumentation to a program, we use a branch of the GNU C compiler modified to use plug-ins [10]. Plug-ins are written as normal GCC-optimization passes that modify GCC's GIMPLE intermediate representation, but can be compiled separately from GCC and loaded dynamically. This dramatically reduces turnaround time for modifications and facilitates debugging. Our bounds-checker plug-in, called `meminst`, performs three tasks, which we discuss in detail below: emitting registrations and deregistrations, duplicating the source code for each function, and emitting instrumentation into one of the copies. Figure 3.12 shows an example duplicated function along with its added instrumentation and the con-

trol block that switches between the two copies.

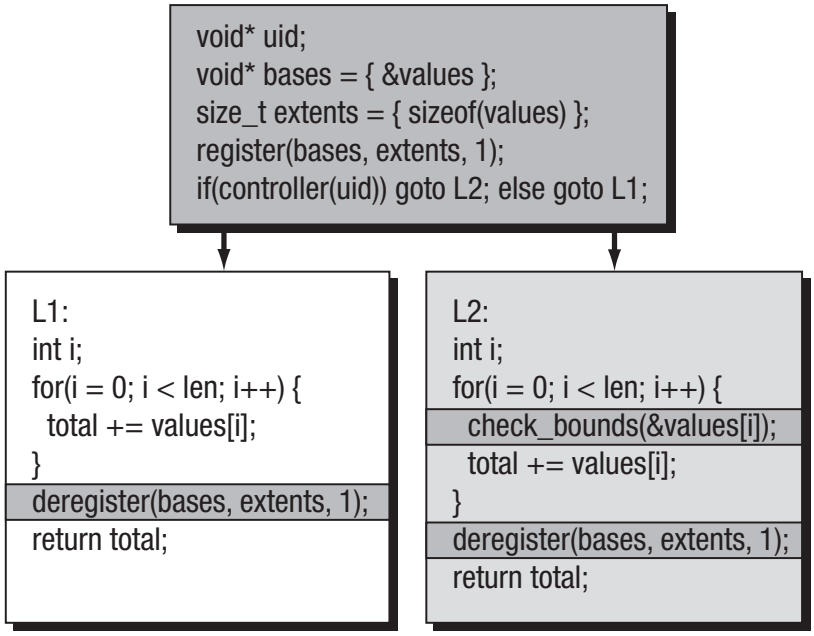


Figure 3.12: `meminst` *adds initial registrations and a call to the controller in a function's first block; the rest is duplicated, and one copy (left) of the function only has deregistrations, whereas the instrumented copy (right) also includes bounds checking.*

Emitting registrations/deregistrations. `meminst` first locates each addressable variable in the internal representation of the function being transformed, and adds it to a list. This takes $O(n + r^2)$ time, where n is the size of the function's IR and r is the number of such variables (the r^2 is due to the fact that we enforce uniqueness in the list). It then builds an array containing the address of each variable, and another array containing the size of each variable. The plug-in adds a call to an area-registration function at the beginning of the function, and a call to an area-deregistration function at each return point from the function.

Duplicating the source code. To create instrumented and uninstrumented versions of the program, `meminst` duplicates the basic blocks in the control-flow graph for each function. This takes $O(n)$ time, where n is the size of the function's internal representation. In order for the controller to determine which set of basic blocks is executed before the beginning of each function, `meminst` inserts a call to the controller. The controller maintains a data structure corresponding to each function, which contains the computed τ for that function and the most recent value of p; `meminst` adds a static variable to the function that is passed to the controller and which the controller sets to point to this structure.

Emitting instrumentation. At each pointer dereference or array-member access in the instrumented copy of the code, `meminst` adds a call to the bounds checker. This step takes $O(n)$ time.

3.2.3 Evaluation

In this section, we describe a series of benchmarks we ran to validate our implementation and determine its runtime characteristics. The results show that SMCO fulfills its goals: it closely adheres to the desired overhead for a range of target overheads, and it observes events at higher rates, and catches bugs with greater effectiveness, as more overhead is allowed. We begin with a real-world demonstration using the Lighttpd Web server [33] and the Vim 7.1 text editor [71]. Then we further investigate the effectiveness of SMCO by demonstrating its usage with a micro-benchmark that causes bounds violations.

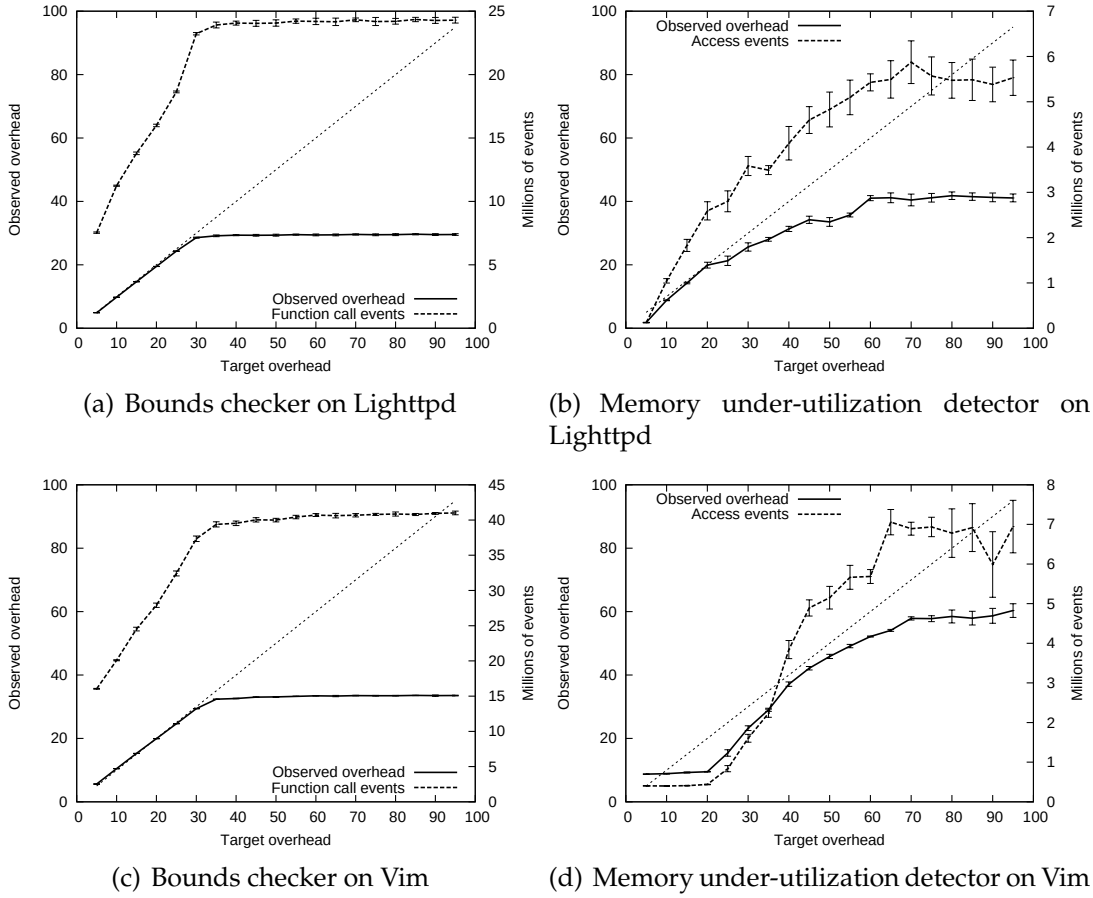
We ran our benchmarks on a group of identically configured machines, each with two 2.8GHz EM64T Intel Xeon processors with 2 megabytes of L2 cache each. The computers each had 1 gigabyte of memory and were installed with the Fedora Core 7 distribution of GNU/Linux. The installed kernel was a vendor version of Linux 2.6.23. We built all packages tested from source: we built the instrumented programs with a custom 4.3-series GCC compiler modified to load plug-ins [10], and we built other utility programs using a vendor version of GCC 4.1.2. Our Lighttpd benchmarks use Lighttpd version 1.4.18. Graphs that have confidence intervals show the 95% confidence interval over 10 runs, assuming a sample mean distributed according to the Student's-t distribution.

Overhead Control Benchmark Results

SMCO's main goal is to monitor as much as possible while regulating overhead so that it adheres closely to the specified target overhead. This adherence should be largely independent of the load conditions of the system. As our theoretical result in Section 3.2.1 shows this to be achievable, any deviation of the measured performance results from user specification must arise from implementation limitations.

The first and most obvious limitation is saturation: at high enough overhead, events stay enabled all the time. Increasing the desired overhead past this point will not generate more events to process. All programs eventually reach peak overhead, since a program must spend at least some percent of its time outside of event processing in order to generate events. A less obvious limitation is the latency of global controller updates. Changing conditions can cause overhead increases that require a quick response from the global controller; when the target overhead is low and the load is high, the actual overhead may temporarily exceed the target overhead.

Figure 3.13 shows observed overhead vs. target overhead for the Lighttpd server and the Vim text editor, each tested separately with bounds checking and memory under-utilization detection. For Lighttpd, we use the `curl-loader` tool to hit the server with one request per second from each of 75 simulated clients. We ran Vim with a scripted workload that loads a large (1.2MB) text file and alternates between sorting and reversing its contents. We ran Lighttpd and Vim with target overheads from 5% to 100% in increments of 5%. The solid line shows the observed percent overhead (left axis), which should ideally adhere to the thin dotted $y = x$ line. The dotted line shows the number of events processed—function-call events for the



(a) Bounds checker on Lighttpd

(b) Memory under-utilization detector on Lighttpd

(c) Bounds checker on Vim

(d) Memory under-utilization detector on Vim

Figure 3.13: Observed load versus desired load for the Lighttpd server with 75 clients issuing one request per second and the Vim text editor with an automated workload. Observed overhead is shown in % (y axis), and the number of observed functions calls (for the bounds checker) and memory accesses (for the under-utilization detector) are shown in millions (y2 axis).

bounds checking benchmark and memory-access events for the under-utilization detector—in millions of events (right axis).

For the bounds checker, the observed overhead closely tracks the target overhead up to a target overhead of 30%. At higher target overheads, the system saturates: every function call runs with bounds checking on, leaving no opportunity to produce higher overhead.

In the Lighttpd memory under-utilization results, we observe that the system meets its overhead target in the region from 5% to 20%. In the region from 20% to 60%, the local controllers start to show instability. After deactivation, each memory area waits for reactivation on a priority queue. In the unstable region, memory regions spend most of their time on this priority queue. When the queue size gets large, dequeuing a memory region takes longer, adding to its wait time and preventing it from meeting its overhead goal. This effect is non-linear—changing the desired overhead changes the average queue size—so our global controller does not accurately compensate for it, though the system is able to keep actual

overhead below the bound in all cases.

Above 60% target overhead, the system achieves its maximum possible overhead: memory regions skip the priority queue and reactivate as fast as possible. The Vim under-utilization results also show instability, with the global controller unable to use all the overhead it is allowed, up to 70% desired overhead.

During our benchmarking, we did not observe any bounds violations resulting from bugs in Lighttpd. However, we observed a number of NAPs (non-accessed periods, see Section 3.2.2). This can be seen in Figure 3.14, which shows the proportion of areas that have been monitored for various periods of time over a single run of Lighttpd. Unused regions in the run were classified into eight buckets based on how long the region remained active with no access. Each set of stacked vertical bars shows the number of bytes in regions from each bucket at a time during Lighttpd's run, with the lightest shaded bar showing the allocations that have gone longest without an access.

This graph shows that a comparatively large amount of memory goes unused for almost all of the program's run. Lighttpd is intended as an embedded Web server with a low memory footprint. Its total heap footprint is 540 kilobytes—so the unused 180 kilobytes are of particular interest and comprise a significant reduction in Lighttpd's heap memory footprint (one-third less). We have verified that at least some of these areas come from a pre-loaded MIME type database that could be loaded incrementally on demand.

Micro-Benchmark Results

Having demonstrated the effectiveness of SMCO with real-world applications, we turn to the micro-benchmarks to demonstrate the high-confidence nature of SMCO. Specifically, we demonstrate that an SMCO-based monitor will detect more faults in a buggy system when it is allowed to use more overhead.

We first designed a micro-benchmark called MICRO-BOUNDS that runs for ten seconds, accessing a single memory area as fast as it can. Ten times per second, it issues an out-of-bounds access. This micro-benchmark allows us to examine the performance of SMCO in more detail.

Figure 3.15 shows our effectiveness at detecting bounds violations in this micro-benchmark for different target overhead settings. The solid line shows the percent of bounds violations caught, and the dotted line shows how many events SMCO observed overall. (Under-utilization detection is still active, but we do not show the results because MICRO-BOUNDS does not use heap-allocated memory.) Initially, we observe a linearly increasing number of accesses, which saturates near 100% of accesses observed, confirming that we are not only achieving our overhead targets, but we are in fact getting something for that overhead: we are monitoring as much as possible given the overhead constraints.

Figure 3.16 demonstrates the bounds-checking characteristics of our micro-benchmark over time with different target overheads. Each line shows a single 10 second run of the micro-benchmark, with the y-values being the total number of bounds violations observed up until each point in time. The graph demonstrates that the

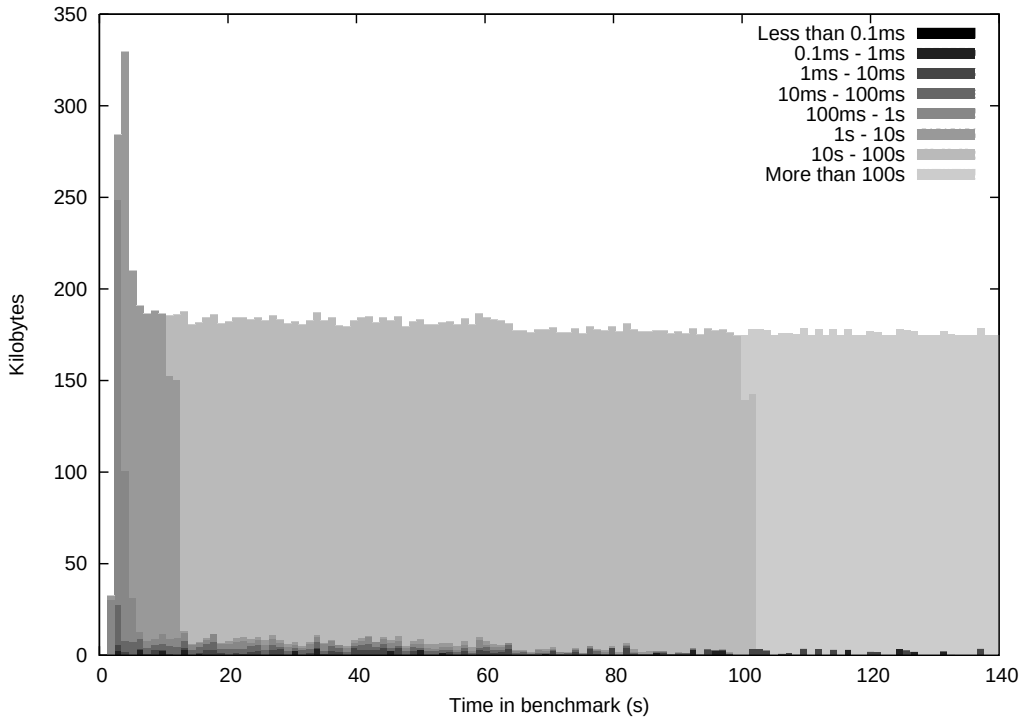


Figure 3.14: Age of areas in one run of Lighttpd. Each stack of bars represents one point in time under the medium load benchmark. The individual bars correspond to ages of areas; their size indicates the number of kilobytes of areas that have that age.

SMCO-based monitor continues to observe bounds violations at a roughly uniform rate. This demonstrates the difference between SMCO and most existing adaptive sampling tools [29], which reduce overhead over time, making violations occurring later less likely to be caught than early violations.

Finally, we designed a micro-benchmark called MICRO-NAP that runs for one minute. It maintains 100 separately-allocated heap areas—allowing the benchmark's auxiliary data structures to reside comfortably in CPU caches—and uses a pseudo-random number generator to generate access intervals for each of these areas. Initially, and whenever it performs an access, MICRO-NAP generates a random interval between one and eight seconds (a NAP is three seconds, and we left time for monitoring to resume); after this interval, it performs an access. Figure 3.17 shows that given more overhead, the NAP detector finds more NAPs. We observe that NAP detection works well even with low overheads, because underutilized memory areas require little overhead to monitor so their local controllers can afford to monitor them regardless of global targets.

The MICRO-BOUNDS and MICRO-NAP micro-benchmarks demonstrate that both bounds checking and NAP detection can use additional overhead effectively.

Summary of Experimental Results

In this evaluation section, we have demonstrated two things:

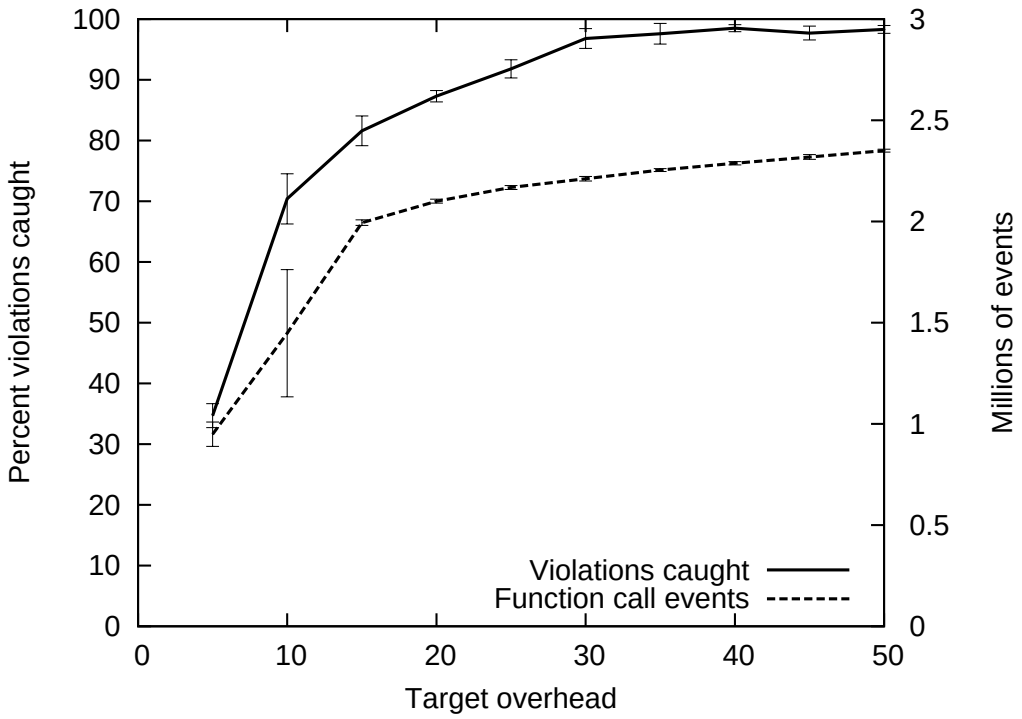


Figure 3.15: Number of function executions bounds-checked and number of bounds violations caught, versus target overhead for the MICRO-BOUNDS *micro-benchmark.*

1. SMCO is zealous in enforcing the overhead goal specified by the user while making a best effort to observe increasing amounts of events, and
2. tools using SMCO are effective at detecting memory under-utilization and bounds violations.

When the local controllers behave linearly, SMCO maximizes the number of events it observes by using as much overhead as it is allowed. With non-linear local controllers, the overhead control problem is more difficult, but SMCO still enforces an upper bound on overhead. We have also shown that SMCO-based monitoring tools observe more events as they are given more overhead, and can use this information to catch real as well as injected errors. In Lighttpd, we found that 33% of the heap footprint is spent on memory that is completely unused, even under load.

3.2.4 Conclusion

We have presented Software Monitoring with Controllable Overhead (SMCO), an approach to overhead control for the runtime monitoring of instrumented software. SMCO is high-confidence because, as we have shown in the paper, it monitors as many events as possible without exceeding the target overhead level. This is distinct from other approaches to software monitoring which promise low or adaptive overhead, but where overhead, in fact, varies per application and under changing usage conditions. The key to SMCO's performance is an underlying

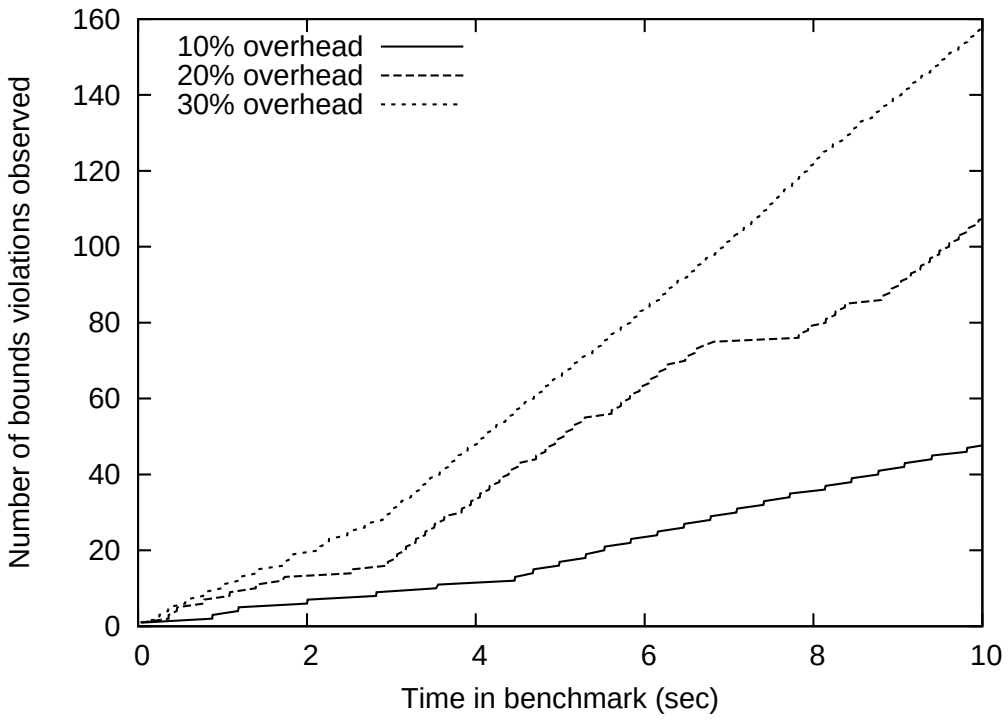


Figure 3.16: Cumulative number of bounds violations caught over time in runs of the MICROBOUNDS *micro-benchmark with 10%, 20%, and 30% overhead*

control strategy based on an optimal controller for a nonlinear control problem represented in terms of the composition of timed automata.

Using SMCO as a foundation, we have developed two sophisticated monitoring tools: a memory staleness detector and a bounds checker. The staleness detector detects memory areas that are unused for longer than a user-definable interval. This is achieved by taking advantage of memory-protection hardware, a technique normally used in the kernel to evict pages from physical memory but rarely seen in user-space. The bounds checker instruments memory accesses and checks them against a splay tree of valid areas. Both the per-area checks in the staleness detector and the per-function checks in the bounds checker are activated and deactivated by the same generic controller, which achieves a desired target overhead with both of these systems running.

Our benchmarking results demonstrate that it is possible to perform correctness monitoring of large software systems with fixed overhead guarantees. As such, the promise of SMCO is attractive to both developers and system administrators; developers desire maximal monitoring coverage, and system administrators need a way to effectively manage the overhead runtime monitoring imposes on system performance. Moreover, our system is fully responsive to changes in system load, both increases and decreases, which means that administrators need not worry about load spikes causing unusual effects in instrumented software. We also demonstrated the effectiveness of our system at detecting real-world bugs: for example, we found out that one-third of the Lighttpd Web server's heap footprint

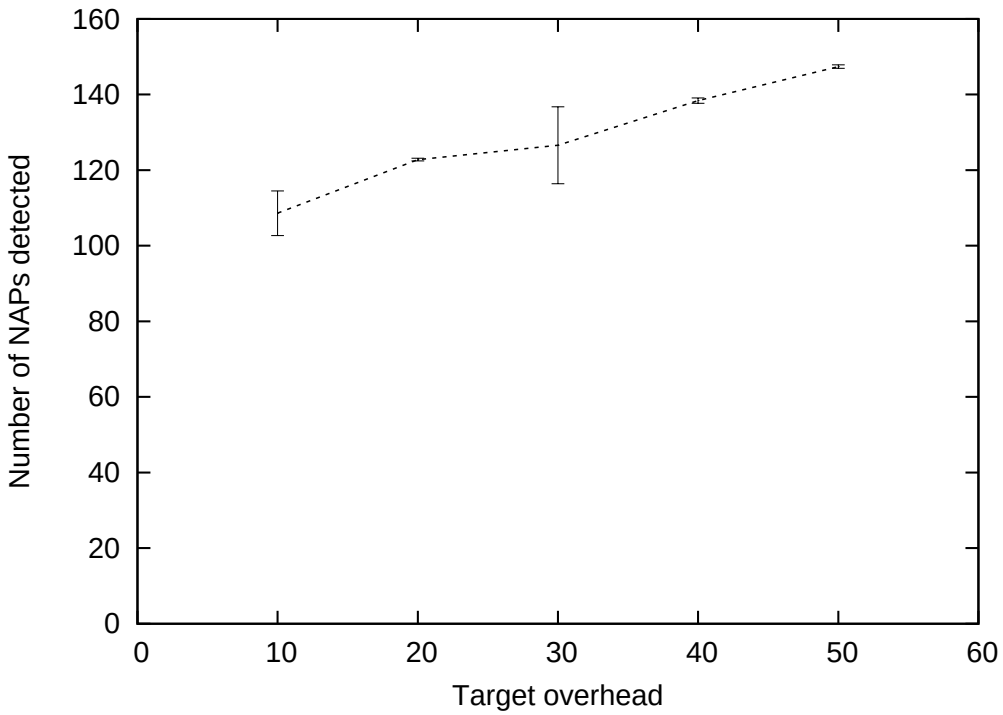


Figure 3.17: Observed NAPs *increase with target overhead for the* MICRO-NAP *micro-benchmark.*

is unused.

3.3 Other Approaches to Controlling Overhead

In this section, we discuss approaches to overhead control that others have implemented, and which provide context for our own approach.

Java-based code replication. Arnold and Ryder developed a system that performs profiling by replicating code using the Java just-in-time (JIT) compiler [4]. This was implemented as a compilation phase for the Jikes research virtual machine [67]. In this approach, instrumentation activates when a counter expires. This is similar to couter overflow sampling, which we discussed in Section 2.2.1. This gives instrumentation developers a knob to control instrumentation, adding another input to the system. However, it does not provide any feedback mechanism except benchmarks, and consequently is not suited to in-line control.

Context-based overhead reduction. Artemis reduces overhead from runtime checks by enabling them for only certain function executions [16]. To observe as many behaviors as possible, Artemis always monitors a function when the function runs in a *context* that it has not seen before, where a function's execution context consists of the values of global variables and arguments. Artemis's context-based filtering can, when the developer specifies the contexts correctly, be very effective for focusing instrumentation on areas where it is needed. Artemis, however, does not address the case where the target overhead is prescribed by the user. Also, Artemis

does not address timing issues because timing is not part of an Artemis context.

Leak detection using adaptive profiling. SWAT is a leak-detection tool that uses a binary instrumentation framework to periodically rewrite pieces of code, enabling monitoring for those pieces of code [29]. The monitoring observes the memory accesses those code fragments make, and use that information to infer which memory areas are unused. SWAT reduces the rate at which it activates individual regions as they execute, meaning that commonly-used code-paths are monitored less intensively. This means that commonly-used pieces of code use less overhead. This approach resembles `MCM`, which we discussed in Section 3.1 in that it keeps monitoring high for rarely-used code, but there is no formal definition of confidence used.

Chapter 4

The Asynchronous Debugging Framework

The Asynchronous Debugging framework (`adb`) is an extensible, general-purpose remote debugging tool based on the GNU compiler collection (GCC) [22]. In this chapter, we describe the features `adb` provides to the user. We also provide implementation details for the `adb` system, a guide to extending `adb` using its generic *provider* mechanism, and a performance analysis substantiating the performance guarantees made by the `adb` API.

The users of debugging systems are some of the most demanding software users in the world. In most cases, debugging systems are not subject to the same critical reliability requirements that medical software or certain kinds of mechanical control or communications software are; however, users expect them to fit into their development model, which can vary significantly from site to site. Although many vendors provide graphical interfaces to debuggers as part of their development environments, they are usually built on mechanisms that expose very low-level interfaces to the user in order to allow the maximum amount of customization.

The most commonly-used debugger today is the source-level debugger [19, 62]. Source-level debuggers go to great lengths to provide an interface that closely resembles code in the target language. For example, GDB interprets a large set of the C language and uses linker information and debugging information in the target binary file to evaluate C expressions as they would be evaluated in the target program. This allows the programmer to use the source language's syntax to exploit the functionality and data available in the target program to debug it. (Source-level debuggers do this inefficiently, but we have addressed that in Section 2.2.)

The interface to debuggers has become even more programmatic with the advent of DTrace [11], which allows the user to specify points in the target program using a uniform syntax and then write snippets of code in a C-like language that execute at those points. We have designed `adb` to follow this trend; we provide a similar execution model—specify points in the target program and run code at those points—but the snippets of code execute natively, in the address space of the target process, rather than as a separate process. To this compelling debugging

model we add comprehensive overhead auditing as well as an overhead-control system based on the SMCO mechanism, which we discussed in Section 3.2.

This chapter is organized as follows. Section 4.1 provides an overview of `adb`'s salient features and how they can be used for debugging. Section 4.2 describes the `adb` architecture and how it provides these features. Section 4.3 describes some implementation details for `adb` providers, which create the instrumentation points that allow the insertion of debugging code. Section 4.4 demonstrates `adb` at work, providing benchmarks on real-world applications, micro-benchmarks, and SPEC. In Section 5, we conclude and discuss future development directions for `adb`.

4.1 Overview of `adb`

The `adb` system is intended to enable remote debugging of software with limited interactivity. Debugging is the process of removing faults in a program, typically by examining its execution. To obtain information about a program's execution, programmers typically choose one of two approaches: traditional debugging tools that allow the programmer to pause the program and inspect its state interactively, and tracing or profiling tools that do not stop the program but rather collect simple information regularly during its execution. Traditional debugging tools have the following problems:

- many bugs only appear in production environments and are difficult to reproduce under controlled conditions,
- bugs can take a long time to manifest, and it is onerous to step through a program to determine when a bug occurred, and
- many bugs manifest themselves as corruption in data structures, and only cause crashes long after the corruption occurs.

On the other hand, tracing tools have their own problems:

- the information they can collect is often severely limited because the program has been optimized,
- performing thorough auditing, even when possible, imposes severe performance penalties, and
- compiling for any but the simplest kinds of tracing usually requires a full recompile, so changing the tracing after deployment is infeasible.

The `adb` framework overcomes these limitations by hybridizing the two approaches. It combines the capability of traditional debuggers to inspect data with the capacity of tracing tools to inspect entire runs of a program, and does this while limiting the overhead it imposes on the program's execution and allowing modification of the tracing apparatus after compilation.

4.1.1 Distinctive features of `adb`

`adb` presents a suite of innovative features for debugging C programs after deployment. We enumerate the most important of these features below, and compare them to existing tools in each field.

Ease of compilation. Compiling a program for use with `adb` requires only that the user add a flag to the GCC command line for each source file that will be instrumented, and add one library to the application's final link step. Often this can be achieved simply through the use of the `CFLAGS` and `LDFLAGS` variables. This results from the fact that `adb`'s implementation is based on GCC; it contrasts with tools like Cil [20] or Atom [58], which require separate compilation phases. Such tools are not only less convenient to use, but they also introduce their own set of dependencies.

Rich hooks. Because it needs to allow debugging after deployment, `adb` is a *dynamic* instrumentation tool that allows runtime insertion of debugging code. This approach is similar to DTrace and Dyninst in philosophy [11, 8]; much like these tools, `adb` places hooks, called *probes*, in the program. (Dyninst uses the term *points* analogously.) DTrace and Dyninst are *binary* instrumenters, which means that they use symbolic information and debugging information to insert probes. In practice, they only use symbolic information because debugging information is complex to parse, and performing any analyses is considerably more difficult than in compilers. This information is of limited utility because compiler optimizations affect the ordering of code, and there is no support for any kind of analyses. In contrast, `adb` takes advantage of GCC's full access to the program's source code to insert tracepoints and provide the necessary infrastructure to pass program data to instrumentation code. Because these probes are inserted during compilation, optimizations respect the ordering and data-layout constraints that probes impose, ensuring that the information they expose is correct.

Reflection on C data. Although some applications of program tracing involve the use of special-purpose code intended specifically for use at particular tracepoints (such as a sanity check of a data structure when a function that modifies it returns), many tools are not aware *a priori* of the context available to them at a tracepoint. For example, function argument value profilers, locking-policy verifiers, or bounds-checkers need to know type information but are typically implemented in a generic fashion. To allow such tools to handle a variety of data types, `adb` provides type information along with pointers to the data. Inserted code that is aware of application-specific types can simply cast the pointers to the appropriate types, but generic code can use the CTF API, discussed in Section 4.2, to examine record and array types as well as simple integral types. DTrace has a similar mechanism, but it fails when values are not in memory, for example, when the register allocator has placed them in registers or when they have been optimized out.

Comprehensive overhead management. The `adb` system uses high-resolution timers based on the CPU's cycle counter to audit instrumentation code on a per-tracepoint basis. It uses the SMCO overhead-management policy, discussed in more detail in Section 3.2, to ensure that the aggregate time spent in instrumentation is no more than a fixed proportion of total runtime. This puts `adb` in a category of *sampling* instrumentation that includes tools like Liblit et al.'s statistical sampling technique [37], Chilimbi and Hauswirth's bursty sampling [29], and Arnold

et al.'s QVM [5]. All of these tools control overhead using parameters that have a non-linear relationship to time; of these tools, only QVM attempts to measure the effect of these adjustments on overhead, which they measure in terms of time. SMCO, on the other hand, regulates the time until a probe is activated, a parameter that is directly related to overhead.

4.1.2 Using `adb`

The `adb` framework is implemented as a GCC plug-in and associated runtime library. We describe the plug-in mechanism in more detail in Section 2.1. The procedure for compiling a program with `adb` is:

- Determine a location for the CTF and PIF files (described in detail in Section 4.2) that will accompany the program and provide all the type information required by `adb`'s reflection mechanism.
- Compile each source file that will contain tracepoints using the `adb` instrumentation plug-in, passing it the location of the CTF and PIF files as an argument.
- Link the final executable with `libadb`, which provides definitions for the runtime symbols that `adb` tracepoints call.

A program compiled with `adb` requires `libadb` to be available if it is linked dynamically; however, in all other respects the program can be executed normally. In particular, it does not require a wrapper program in order to run, as tools like DTrace [11] and Pin [38] do. We will explain the `adb` execution process in more detail in Section 4.2.

4.2 `adb` Architecture

The `adb` architecture consists of two main components: a *compiler-based* component that is responsible for adding probes into a program, and a *run-time* component that is responsible for managing the probes as the program runs. Probes can be defined as points in the program's execution at which *reflection*—access to C data via a meta-linguistic API—becomes possible. Reflection is typically a feature of languages, and is closely linked to the term *dynamic*, which describes a language that produces programs whose structure can be modified at run-time. One early example of language reflection is the Lisp programming language; Lisp code is represented as lists called *s-expressions* which are passed to the `eval` function for execution. Lisp data is also represented as lists, and the `type-of` function can be used to determine the structure of a particular piece of data without *a priori* knowledge [61]. Lisp is also *dynamic* because evaluation of expressions can be completely replaced using the `*evalhook*` mechanism.

Smalltalk is a more recent example of a dynamic language [23]. Smalltalk programs consist entirely of objects, and objects pass each other *messages* to do work. A Smalltalk object's methods can be overridden using the `addSelector:withMethod:` mechanism, and member variables can be modified using the `at:put:` mechanism. The programmer can determine what type a Smalltalk object has by sending the `class` message. The Objective-C programming language, which is largely

based on Smalltalk, combines Smalltalk's dynamic message dispatch with statically-compiled C code [40]. Programmers can override methods using the `class_addMethod` runtime function, modify object member variables using the `object_setIvar` runtime function [41], and determine the type of an existing object using the `class` message. However, this dynamic behavior extends only to objects created using the Objective-C object system; statically-compiled C code does not benefit from this reflection.

Philosophically, `adb` arises from the desire to provide language-level reflection for C. As discussed above, reflection has two aspects: *code* reflection, in which it is possible to modify or replace code, and *data* reflection, in which it is possible to alter data. In `adb`, code reflection is provided by means of *probes*. These are specific locations in the program's source code, and are inserted by *providers* that closely resemble DTrace's provider mechanism [11]. Providers work with the compiler to make it possible to insert code at arbitrary locations in a program. These locations can be syntactic (entry points to functions) or semantic (accesses to global variables). We will discuss the way providers do this in full in Section 4.3. `adb` provides data reflection by allowing providers to expose arbitrary program data at probes; a type API allows clients to determine the type of this program data and modify it in a type-safe manner.

The `adb` system adds awareness of overhead to the features above. For some applications, particularly ones with strict performance requirements, adding debugging into the program can be unacceptable unless the overhead it incurs is strictly controlled. Other approaches, such as bursty sampling [29] and context-based sampling [16], attempt to address this issue using *sampling*, a concept we adopt. Sampling is the technique of monitoring only a subset of the events that a program generates. However, these other approaches attempt to *minimize*, not *control* overhead. We choose, instead, to let the end-user of the software specify a tolerable amount of overhead, and regulate instrumentation in order to ensure that it meets these overhead requirements. This regulation imposes an important restriction: instrumentation must be tolerant of missing certain events.

In Section 4.2.1, we discuss the mechanism `adb` provides for code reflection, and how to write clients that activate specific probes. Then, in Section 4.2.2, we describe how clients can access program data, and the means `adb` uses to provide this functionality. Finally, in Section 4.2.3, we describe the way the SMCO runtime regulates instrumentation at a high level.

4.2.1 Using providers and probes

We illustrate the high-level architecture of the `adb` compile-time infrastructure in Figure 4.1.

A modified version of the GNU C compiler (described in Section 2.1) loads the `adb` instrumenter, which is implemented as a plug-in. The instrumenter has access to GCC's intermediate representation, called GIMPLE, and can modify it to insert probes. These probes are implemented as function calls which, as the program runs, pass the program's internal data to the `adb` runtime, which in turn

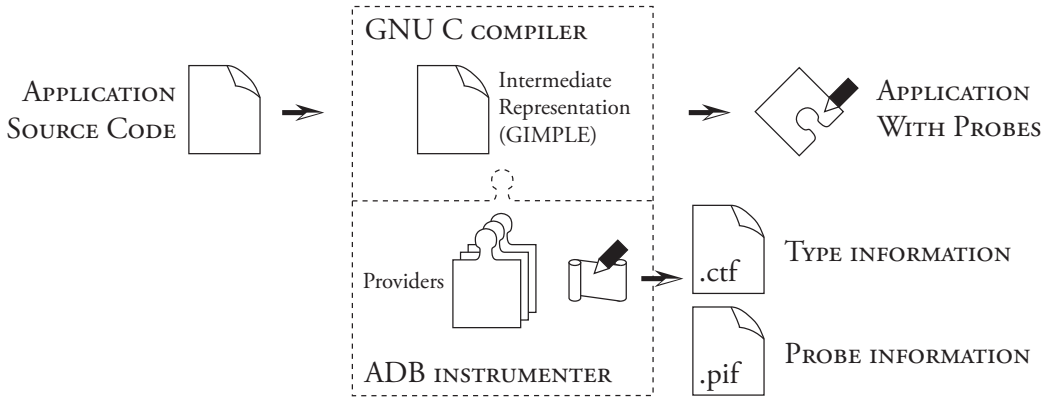


Figure 4.1: The ADB compile-time system.

distributes it to consumers. Determining where probes are installed, and what information they provide, is the role of providers. We will discuss existing and possible future providers in Section 4.3. Probes can be activated and deactivated at runtime as needed by consumers, and are regulated by the SMCO policy as described in Section 3.2.

Consumers activate probes using *probe specifiers*. A probe specifier can be initialized with the desired provider, file, and function. Any of these can be null, in which case the runtime assumes that the consumer is interested in probes that have any value for that category. (In the extreme, a consumer that specifies a null provider, file, and function will activate all probes in the program.) If multiple providers, files, or functions are desired, a consumer can use multiple probe specifiers. Although SMCO regulates individual probes to reduce overhead when probes are active, it is better for consumers to activate only relevant probes, because other probes will consume overhead that could be used to monitor events of interest. `adb` performs reference-counting so consumers can be loaded and unloaded safely as the program runs.

Information about probes is recorded in a PIF (Probe Informatio Format) file, which contains an entry for each probe installed into the system. The PIF format records the information necessary to classify probes, as well as a unique ID that is generated for each probe, and which the probe passes to the runtime component of `adb` to allow it to identify the probe correctly. The PIF file also includes the types of all pieces of data that are exposed to the consumer. The information required to read the data types in the PIF file is recorded in a separate CTF (Compact ANSI-C Type Format) file, which we discuss in the next section.

4.2.2 Accessing program data

One of adb's salient features is the fact that it allows consumers to modify program data as it runs. This feature is similar to one found in debuggers, but is implemented quite differently. Debuggers manipulate programs' variables by editing the memory and registers using an API provided by the operating system. In Solaris, this API is exposed through the `/proc` file system. Writing to a special file

called `/proc/pid/ctl` allows a debugger to read or modify the register state and memory of a paused thread [63]. In Linux, a similar (though slightly less efficient, because memory writes are in units of one word) API is provided by the `ptrace` system call [27]. Mac OS X allows similar manipulation through Mach ports [32]. DTrace allows interaction with memory through a restricted pointer interface [45].

Although it is possible in each of these cases to access a program's memory, this access is highly inefficient because in each case a separate process is interacting with the program. Although DTrace scripts run in kernel space, allowing memory accesses to take place with just one memory copy (from the process to the kernel, or vice versa), the Linux and Solaris approaches require a copy from user to kernel memory and back into user memory. The Mach approach may be the quickest of these (because it allows remapping of another process's memory into the debugger process); however, modifying register state is still cumbersome. In addition, all of these have to map variable names to locations in memory, which can become very difficult when optimization is enabled [68].

Our approach relies on the compiler to permit access to variables when probes execute. Probes expose pointers to variables; when a variable is exposed, it is as if the original code had been written to pass a pointer to the variable to the consumer. This feature has its own (far more modest) set of associated overheads, which we will discuss in more detail in Section 4.3 and demonstrate in Section 4.4. To extract the data that is the target of these pointers, the consumer consults an API that wraps the CTF file, obtaining an object that can be used to read and write the target object. The CTF file contains data in the Compact ANSI-C type format [64], which was originally developed for DTrace and provides support for all types, integral, pointer, and composite, in ANSI C. (Although CTF provides support for function pointers, and `adb` generates proper CTF data for functions, calling function pointers has not yet been implemented in the `adb` runtime.)

4.2.3 Regulating overhead

We have described the general operation of SMCO in detail in Section 3.2. As a result, we will provide only a brief overview of SMCO's operation here, and leave the details to Section 4.3. Figure 4.2 illustrates the ADB runtime overhead-control system.

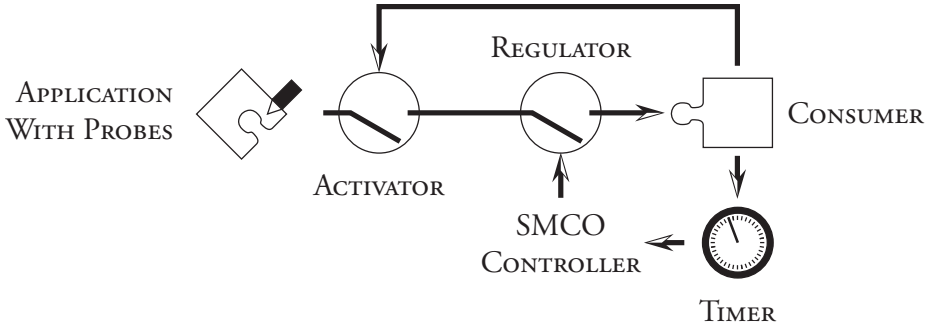


Figure 4.2: The `adb` overhead-control system.

At runtime, all probes in the monitored program generate data that can be processed by consumers. Whether this data arrives at consumers is determined by two separate decisions. First, this data is only processed if some consumer has requested it. An *activator*, which we will discuss in more detail in Section 4.3, serves as the first filter and admits events from activated probes. It induces a small overhead even when the probe is disabled; this overhead will be discussed in Section 4.4. The next decision is made by a *regulator*, which determines whether the SMCO policy permits the current event to be processed.

The SMCO policy is implemented as follows. When a consumer processes an event, a *timer* measures the processing time P_i, which includes the time taken by the consumer and the time taken by SMCO to compute the next cycle time. This time is saved and passed to SMCO when the consumer runs next. (It cannot be used for the current run because p_i is computed after the delay has already been set.) Consequently, the value used in place of p_i in the SMCO calculation is actually p_{i-1}, the processing time for the previous monitored execution of the probe. We also use a simplification of the delay computation. Figure 4.3 shows the relevant variables in our implementation of the SMCO local controller.

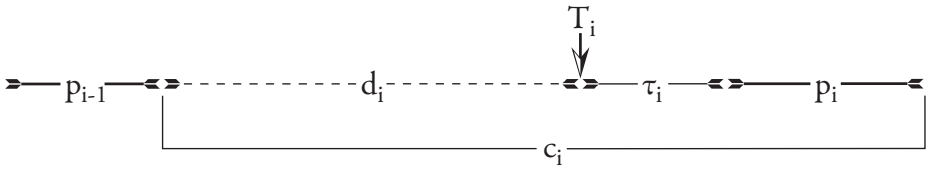


Figure 4.3: Variables used in `adb`'s implementation of SMCO.

The time c_i is the SMCO cycle time, which is the sum of the delay d_i before the probe was reactivated, wait time τ_i between the activation of the probe and the time the probe was executed, and the processing time p_i for the execution. Given the local target overhead O, we can compute the local instrumentation rate $I = O/(1 + O)$, which expresses the proportion of total runtime that should be consumed by processing. The relationship between p_i and c_i can be expressed as $p_i = Ic_i$, or $c_i = p_i/I$. The time T_i marks the time the probe was when the probe was activated for the current cycle, and T_{i+1} can be computed from T_i by adding c_i. As stated earlier, because we do not have access to p_i yet when T_{i+1} is computed, we use p_{i-1} instead. This means that `adb`'s response to changes in p remains linear, but that it may be delayed.

`adb` also employs an SMCO global controller, which monitors the total processing time accrued by the system over a fixed period of time, and adjusts a factor λ that is applied to the target instrumentation rate I for each local controller, as described in more detail in Section 3.2. This λ is computed by a separate global controller thread.

4.3 How `adb` is implemented

The core of `adb` is implemented as a plug-in for the GNU C compiler. As described in Section 2.1, GCC plug-ins have access to the compiler's intermediate representation for programs, called GIMPLE. In order to perform its function, `adb` must be able to perform the following tasks:

- `adb` must allow consumers to run, and give them read-write access to variables, at every enabled probe.
- In order to permit overhead control, `adb` must obtain the accurate processing time p for each probe.
- Each probe must permit activation and deactivation, so `adb` must add high-performance mechanisms for executing a probe only when it is active.

This section discusses how we implement these features. In Section 4.3.1, we provide a brief overview of relevant details of the GIMPLE intermediate representation. Then, in Section 4.3.2, we describe the structure of an SMCO probe, hilighting important design details. Finally, in Section 4.3.3, we describe currently-implemented and future providers.

4.3.1 GIMPLE overview

GIMPLE is a representation for a program as it is transformed by a compiler in preparation for the emission of assembly code. GIMPLE is a *three-address code*, which means that every operation (except for a function call) has at most two operands, and most operations produce a result. Complex statements in the original code are broken into sequences of simpler statements in GIMPLE in order to satisfy this constraint.

We will begin by describing control flow structures in GIMPLE. The control flow of a function is described by the *control-flow graph*, a directed graph. Vertices in this graph are called *basic blocks*, sequences of statements with a single entry point and a single exit point. Many basic blocks have *labels* which serve as a form of identification. The edges between basic blocks determine the feasible control flows in the program. A basic block can have up to two outgoing edges; if there are two, the block ends with a conditional expression, which jumps to one of two blocks based on the result of a test. All conditional expressions and loops in C are expressed as basic blocks and edges; intuitively speaking, GIMPLE's control flow can be thought of as C control flow limited to `if-then-else` and `goto` statements.

Now we will describe data flow primitives in GIMPLE. The basic unit of data in GIMPLE is a *variable declaration*. The attributes of variable declarations determine their semantics. There are two main kinds of variables: *registers*, which are subject to a wide variety of optimizations, and *virtuals*, which are guaranteed to reference a location in memory.

The value of a register can be used in any expression except reference-taking operations like C's `&` operator; however, a register must be referred to using *SSA names*, which obey the rules of single static assignment form [13]. An SSA name is assigned to in one unique location; it may be read from at arbitrary points. In cases where two different definitions of a register reach the same basic block (for

example, at the end of an `if-then-else` in which a variable is assigned 1 in one branch and 2 in another), a *ϕ-node* serves as a use of both SSA names and defines a new one for use in the current basic block. Because the effect of ϕ-nodes is associated with the entry point of basic blocks, and because the number of operands to a ϕ-node varies with the number of incoming edges, ϕ-nodes are not considered normal GIMPLE statements, but are rather kept in a separate list attached to each basic block.

Virtuals may (given the appropriate attributes) have their addresses taken; however, before an expression can use the value of a virtual, the virtual's value must first be loaded into a register. Virtuals can be written to directly. Virtuals can have several attributes:

- *Static* virtuals retain their value across multiple executions of the same function; their values are maintained in static storage such as a binary's `data` segment. Non-static virtuals are typically stored on the stack.
- *External* virtuals are undefined in the current translation unit, and a reference will be generated by the assembler to be resolved later by the linker.
- *Addressable* virtuals may be referenced.

Because several of GCC's source languages allow in-line assembly, GIMPLE also has facilities for in-line assembly. An in-line assembly statement is exceptional in the sense that it reads from and writes to a number of variables determined by the CPU architecture; however, the rules of Tree-SSA still apply. If assembly statements are marked as *volatile*, their side-effects are presumed to be critical to the proper operation of the software, so they are neither reordered nor optimized out.

4.3.2 Probe structure

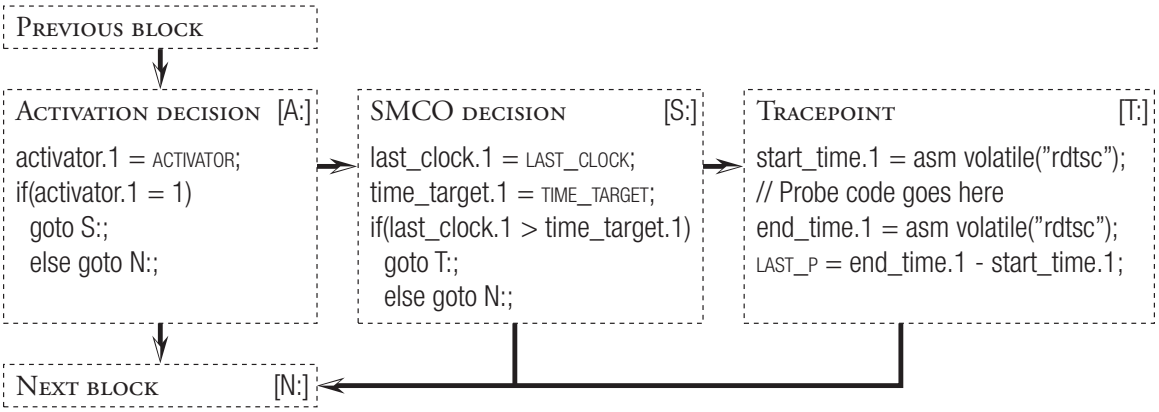


Figure 4.4: High-level structure of an `adb` tracepoint. Virtuals are shown in small caps, and registers are shown in lower case with a suffix uniquely identifying each SSA name.

The overall structure of an `adb` probe is shown in Figure 4.4. The probe consists of three basic blocks; if the probe is intended to lie inside another basic block, `adb`'s plug-in splits that basic block to make room. Although this structure may appear

large, in fact it avoids consuming overhead by allowing control to pass to the *next block*—that is, the normal program code following the probe—at every available opportunity. There are three basic blocks, whose function we describe below.

- The *activation decision* consults a static, addressable virtual called the *activator* to determine whether the current probe is enabled. If there are no consumers interested in the probe, then the activator will read 0. If consumers are interested in the probe, then the activator will read 1. The address of the activator is passed to the runtime whenever the probe runs, so the runtime can enable the probe at any time by setting the activator to 1. This approach resembles the is-enabled probes employed by DTrace to reduce overhead. If the activator is 0, then control passes to the next block; otherwise, it passes to the SMCO decision block.
- The *SMCO decision* consults an extern virtual that contains the time of the last tick of the *fast clock mechanism*, which we will discuss in detail below. It also reads in the target time (i.e., T_i) set by SMCO in the previous execution. If the time T_i has passed (i.e., it is less than the current time), then the probe should fire, so control passes through to the tracepoint block; otherwise, it passes to the next block.
- The *tracepoint* computes p_i using the high-resolution in-line assembly instruction `readtsc`. All probe computation should take place between the writes to the start-time and end-time variables; indeed, the `adb` implementation is written in such a way that providers are only able to write code inside the tracepoint block, and the location inside the tracepoint that they are given to write code at is between the start-time and end-time assignments.

At first glance, it may appear odd that `adb` uses two distinct timing mechanisms in a probe. The base mechanism for both of these, however, is the Intel `rdtsc` instruction. (SPARC has the `tick` register, and PowerPC has the `mftb/mftbu` instructions that achieve the same goal.) The `rdtsc` instruction allows the programmer to read a register that reflects the current value of the CPU time-step counter (TSC). The time-step counter increments by one for each cycle the CPU executes; on a multiprocessor computer, the operating system synchronizes the time-step counters during boot. We have micro-benchmarked the `rdtsc` instruction, however, and shown that executing it on the Intel Xeon microprocessors we tested takes between 70 and 100 cycles. This would add a considerable slow-down in the SMCO decision block for disabled probes, so we implemented a fast clock mechanism that leverages `rdtsc` but updates a global variable from a separate thread that executes at 1kHz. Referring to that variable instead of the time-step counter dramatically reduces overhead, and the thread can safely run on another core.

We now turn our attention to the code that implements the transfer of control between the monitored program and the `adb` run-time. The code shown in Figure 4.5 shows the GIMPLE code for a typical probe that exposes two variables, one register and one virtual, to the client.

The first item of note is that `adb` creates addressable virtuals to hold the value of any registers. This requires making a new SSA name for the version of the

```
TRACEPOINT                                                                    [T:]
...
A_CONTAINER = a.1;
POINTERS[0] = &A_CONTAINER;
POINTERS[1] = &B;
last_p.1 = LAST_P;
time_target.2 = TIME_TARGET;
TIME_TARGET = hook(id, &ACTIVATOR, &POINTERS[0], last_clock.1, time_target.2, last_p.1);
a.2 = A_CONTAINER;
...
```

Figure 4.5: GIMPLE code for a probe that exposes a register a and a virtual `B` *to the* `adb` *run-time.* id *is the tracepoint identifier.*

register after the probe runs; in the figure, the addressable container for `a` is called `a_container` and the new name is called `a.2`. Since this new definition of the variable is visible from the next block, we add a new ϕ-node to the next block to unify the versions of each register that is used by the probe. Virtuals do not need this treatment, as they do not adhere to SSA. The pointers to the containers and virtuals are put into an array which is passed to the hook function. Along with them the probe passes several other variables:

- The *probe identifier* allows the runtime to look the probe up in the PIF file (see Section 4.2.1). This is necessary to identify the probe for activation purposes and to determine the data types of the entries in the pointer array.
- The *last clock* is simply the value of the fast clock when the decision was made to run the probe, in the SMCO decision block. This value is used for debugging.
- The *time target* is T_i. The SMCO controller uses this to compute T_{i+1}, as described in Section 4.2.3.
- The *last processing time*, better known as p_{i-1}. The SMCO controller uses this value to compute T_{i+1}.

The hook function is defined in the `adb` runtime library, and returns T_{i+1}.

4.3.3 `adb` providers

Having described the generic way in which probes are implemented in `adb`, we now turn to the implementation of `adb` providers. Providers are subclasses of the virtual class `Provider`, which implements all the functionality discussed above transparently. Providers only need to specify which variables are to be exposed, and where the probes are to be located. Only if they affect the control flow of the program (such as inserting a return statement) do they need to ensure that this modification does not conflict with the time-keeping necessary for SMCO.

Function entry provider. The function entry provider places a probe at the entry point to each function in a program. This provider exposes each of the function's

arguments to consumers, and allows them to rewrite the arguments before the body of the function is executed. To do this, it places a probe before the first basic block in each function. The function entry provider is implemented in 35 lines of C++ code.

Function return provider. The function return provider places a probe at every return statement for each function in a program. The provider exposes the return value to consumers, and allows them to modify the return value before the function returns. To do this, it locates each return statement in the function. However, in GIMPLE, return statements do not necessarily return variables but rather return special constructs called *result declarations* which may not be used in any other context. As a result, the function return provider must construct a temporary variable to hold the return declaration; the address of this variable, then, is passed to the probe. Figure 4.6 shows an example transformation.

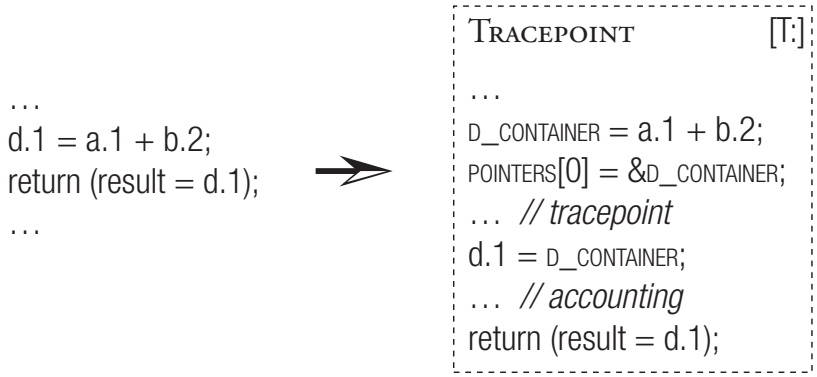


Figure 4.6: GIMPLE code for a return probe, showing the return statement before the probe is inserted and as it appears in the tracepoint. `result` *is a result declaration.*

The function return provider is implemented in 176 lines of C++.

4.4 Performance characteristics

In this section, we turn to an evaluation of `adb`'s performance characteristics. We examine the actual overheads incurred by `adb` in a variety of usage scenarios. We also investigate worst-case performance characteristics when `adb` is saturated with events. These results demonstrate that `adb` fulfills the performance guarantees made by SMCO. The overhead `adb` incurs is divided into two parts: *mandatory* overhead, which is incurred regardless of the overhead target, and *discretionary* overhead, which is subject to regulation using the SMCO policy. We will discuss each of these effects along with their causes.

4.4.1 Benchmark setup

The main benchmark we use in this evaluation is a portion of the SPEC CPU2006 benchmark suite [30]. This portion consists of the integer benchmarks implemented in C, which are:

- `400.perlbench`, a cut-down version of the Perl 5.8.7 interpreter running several mail workloads and a file-difference workload;
- `401.bzip2`, a modified version of the bzip2 1.0.3 compression tool compressing images, binaries, source code, HTML, and synthetic data;
- `403.gcc`, the GCC 3.2 suite generating AMD Opteron code for a variety of benchmark source files;
- `445.gobmk`, a benchmark derived from the GNU Go engine that analyzes a repository of Go games;
- `456.hmmer`, a gene sequence analyzer that uses finite state machines to search a reference database for a particular set of sequences;
- `458.sjeng`, a modified version of the Sjeng 11.2 chess engine, which uses α-β search to analyze chess positions from a repository of chess games; and
- `464.h264ref`, a modified version of the H.264 reference video encoder, which encodes several videos using a variety of profiles.

There are two additional integer benchmarks implemented in C, `mcf` (a public transport simulation), and `libquantum` (a quantum computer simulator). We omit `mcf` because of excessive runtime (both instrumented and uninstrumented), and `libquantum` because it relies on a compiler-supplied complex number data type that we are extending `adb` to support.

We selected the SPEC CPU2006 benchmarks for two reasons. First, there is a long tradition of using SPEC benchmarks as measures of performance both for compilers and for instrumentation suites. For example, the evaluation for ATOM, a binary instrumenter from 1994, uses the SPECint92 benchmark [59], the evaluation for Liblit et al.'s distributed sampling tool uses the SPEC int95 benchmark [37], and the evaluation of Artemis, a context-based overhead-control system, uses the SPEC CPU2000 benchmark [16]. Second, the SPEC benchmark series is intended as a set of algorithms representative of very CPU-intensive workloads found in the real world. The algorithms are designed to remove sources of external latency like disk reads and writes, network I/O, and user interaction. As a result, they provide enough probe hits to allow us to demonstrate `adb`'s use of SMCO to control overhead under situations of high, yet realistic, load.

We also developed a synthetic micro-benchmark called `erbench` in order to demonstrate the base overhead and regulation behavior of `adb` under the highest possible load. The `erbench` benchmark contains one leaf function that takes two arguments and returns their sum. GCC emits this function as two Intel assembly instructions: an addition and a return instruction. The main benchmark loop conducts five sample runs; in each sample run, the benchmark executes the function five billion times and divides the total runtime of the loop by five billion to measure how many cycles a single iteration of the loop took. The slowdown experienced by this benchmark after `adb` has added entry and exit probes to the leaf function provides an estimate of the overhead a probe imposes on a single function (hence the name, an abbreviation of *entry-return benchmark*). In addition, the further rise in `erbench`'s runtime as SMCO's target overhead increases provides an estimate of SMCO's ability to control overhead under artificially high load.

All benchmarks were performed on a Dell PowerEdge 1425 1U server computer with dual 2.8GHz Intel Xeon microprocessors. Each microprocessor had 2MiB of L2 cache, and the computer had 2GiB of memory. We used the CentOS 5.2 distribution of Linux (a free distribution consisting of the open-source portions of the Red Hat Enterprise Linux distribution) under a vendor-patched version of Linux 2.6.18, in 64-bit mode. All benchmarks were compiled using a version of the GCC 4.3 compiler modified to use plug-ins, under optimization level `-O2`.

4.4.2 Mandatory overhead

The first portion of our study concerns mandatory overhead. `adb` imposes mandatory overhead for three reasons. First, there is overhead from an auxiliary thread that updates the fast clock device (discussed in detail in Section 4.2. Second, there is overhead from the code necessary to perform the SMCO checks. Third, the presence of probes in the system limits the ability of GCC to optimize code. Specifically, functions that were previously leaf functions may now contain probes and therefore no longer be leaf functions. Also, because any variable passed to a probe can be modified by that probe, GCC can no longer perform certain operations that require the data flow to be known at compile time, like constant propagation.

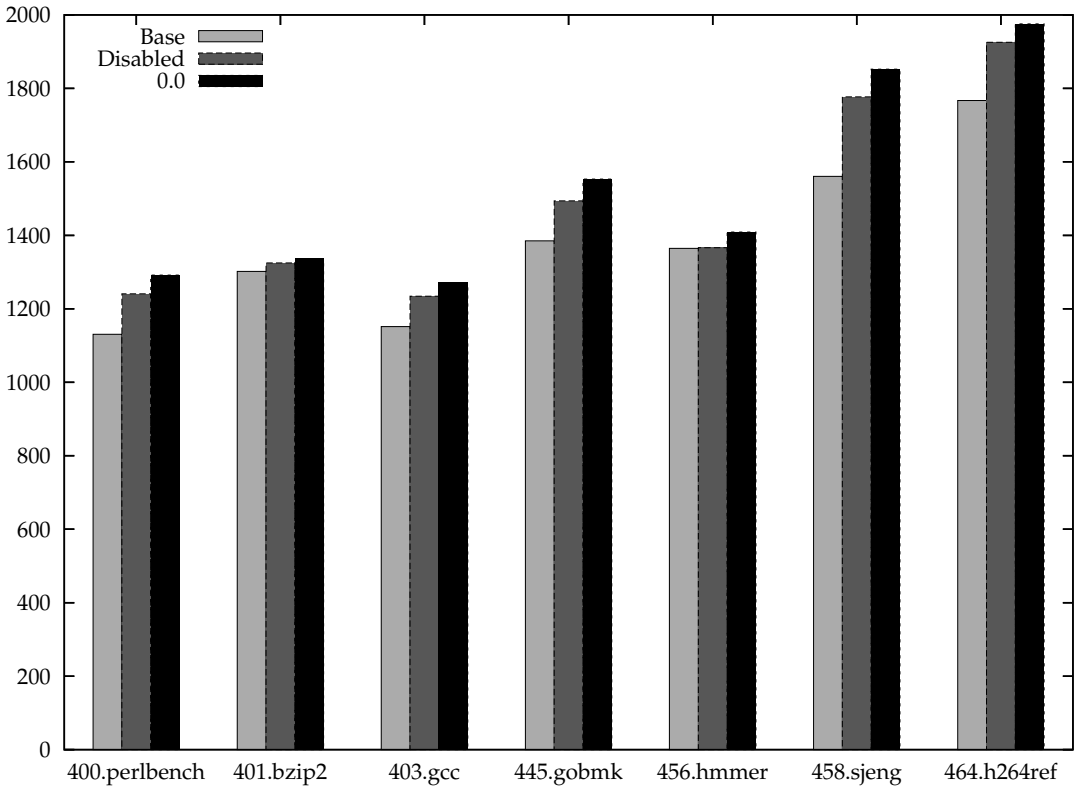


Figure 4.7: SPEC benchmark runtimes with no instrumentation (light bars), `adb` instrumentation with probes disabled (dark bars), and `adb` instrumentation with probes enabled, but with 0% target overhead (black bars).

Figure 4.7 shows the mandatory overhead imposed by `adb` on benchmarks from the SPEC CPU2006 suite. Overheads range from a minimum of 2% for `401.bzip2` to 18% for `458.sjeng` when all probes are enabled. The degree of overhead reflects the architecture of the algorithms: `bzip2`'s core is an iterative compression algorithm that performs many computations per function call, whereas `sjeng`'s core is a highly recursive α-β search algorithm with auxiliary heuristic functions. This range of mandatory overheads is competitive with other sampling-based approaches; for example, Artemis's stated theoretical asymptotic lower bound is 11% [16], and Liblit et al. found a similar range (2–22%) for a set of benchmarks including ones from SPECint95 [37]. We can therefore conclude that the base overhead for our approach is comparable with other approaches. Disabling probes further improves runtime, bringing it into the range 0.1% for `456.hmmer` to 13% for `458.sjeng`.

We continue with a more detailed examination of `adb`'s base overhead using `erbench`. As described in Section 4.4.1, the `erbench` leaf function is very simple: GCC emits it as two lines of assembly code. When the leaf function is uninstrumented, one execution of the `erbench` benchmarking loop takes 18 cycles (standard deviation 0.1 cycle, or 0.5% of the mean, for 5 runs), including loop counter maintenance and the call to the leaf function. When the leaf function is instrumented using entry and return probes, but the probes are disabled, one execution of the benchmarking loop takes 33 cycles (standard deviation 0.4 cycles for 5 runs). When `adb` overhead target is set to 0%, one execution of the benchmarking loop takes 40 cycles (standard deviation 0.2 cycles, or 0.5% of the mean, for 5 runs).

An examination of the way GCC emits the `erbench` code gives insight into these overhead numbers. The `erbench` leaf function was previously emitted with no stack frame; now, it has a stack frame 296 bytes in size. The function's preamble and postamble each now have 6 instructions to perform stack maintenance. Each probe takes 2 instructions if there are no consumers using it (a compare and a conditional jump); if there are consumers but the probe is disabled by SMCO policy, it takes four more instructions (two loads, a compare, and a conditional jump). The contents of the probe are regulated by SMCO; their overhead is measured using the `rdtsc` instructions. On our test machine, the `rdtsc` instructions introduce approximately 128 cycles of additional overhead.

4.4.3 Discretionary overhead

Having determined the base overhead of simply having probes in a program, we continue to a discussion of SMCO's ability to regulate overhead. For this discussion, we use the `403.gcc` benchmark from SPEC CPU2006, as well as the `erbench` benchmark. There are two effects we seek to confirm. First, observed overhead must track desired overhead correctly; this is a property of SMCO. Second, as allowed overhead increases, the number of events should increase as well; otherwise, there is no benefit to sacrifices in runtime. We confirm both of these in two different, but very challenging environments: `403.gcc` is a multi-phase program with a rapidly-changing execution profile, whereas `erbench` is a single-phase

benchmark with extremely high throughput. Afterwards, we investigate details of `403.gcc`'s multi-phase behavior through the eyes of SMCO, observing as λ, the compensation factor that increases individual probes' share of global overhead when some probes are underused, compensates for changes in the number of probes hit over time.

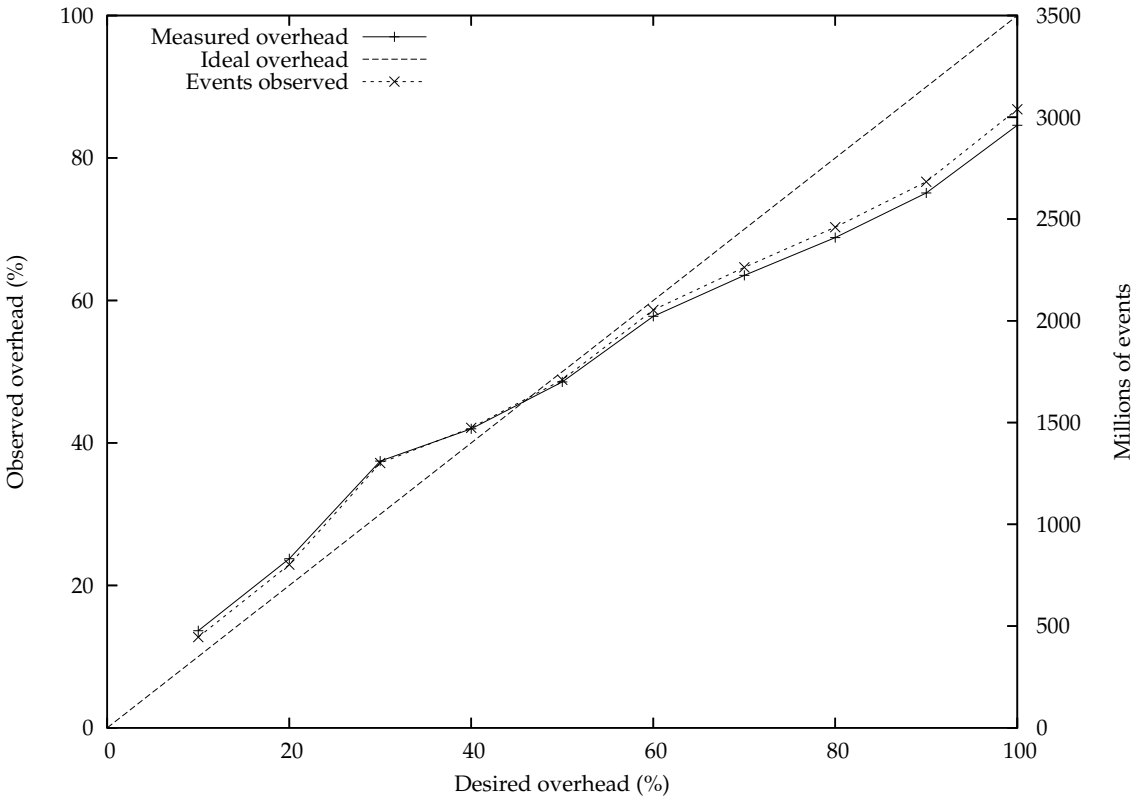


Figure 4.8: Observed overhead (y axis) versus target overhead (x axis) with SMCO control for the `403.gcc` benchmark. The dotted line is ideal (a 1:1 ratio), and the solid line is measured.

Figure 4.8 shows SMCO regulating the `403.gcc` benchmark. The graph shows two curves besides the ideal overhead curve. The first is the measured overhead for each value of target overhead, computed by dividing the wall-clock runtime of the `403.gcc` run by the wall-clock runtime of a run with target overhead set to 0%; the second is the number of events observed for each value of target overhead. At first, the observed overhead tracks the desired overhead accurately, until reaching the 60% mark. (These are stable results: the standard deviation of three runs is below 5% of the mean). Afterwards, the observed overhead lags behind. This drop in overhead is observed by SMCO as well: overhead under `adb` varies in a range of 10% based on the particular `gcc` input file. (The results are still stable in the sense that they do not vary significantly between runs on the same source file.)

What we are observing is a crucial point about the SMCO controller: instability in the program's execution profile is constant, so as the desired overhead increases, SMCO must increase the value of λ and consequently be more affected

by this instability. Hence asking for high overhead in a large program like GCC with a complicated execution profile implies that the SMCO controller's obtained overhead will tend to fluctuate more. We inspect GCC's execution profile more in Figure 4.10.

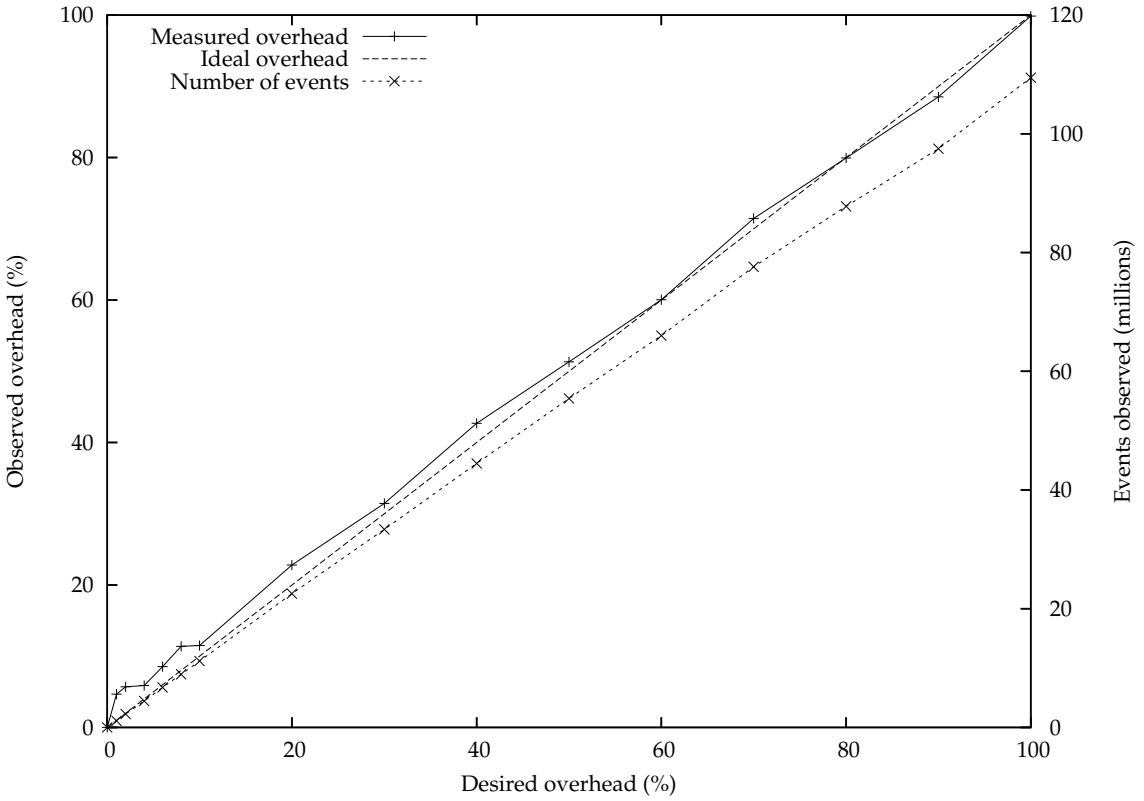


Figure 4.9: Observed overhead and number of events monitored versus target overhead with SMCO control for `erbench`*. The dashed diagonal line is the ideal 1:1 line for observed overhead.*

Figure 4.9 shows SMCO regulating the `erbench` benchmark. The curves have the same meanings as in Figure 4.8, but we have included runs at 0.1%, 0.2%, 0.4%, 0.6%, and 0.8%. We observe that SMCO does an excellent job of adhering to overhead targets in general, but at very low desired overheads the observed overhead exceeds the desired overhead somewhat. This overshoot is not due to problems in the SMCO controller; the controller's internal statistics, as opposed to wall-clock time, indicate overhead extremely close to the target. Rather, the overshoot occurs due to cache misses in the inlined SMCO code. The conclusion that the control scheme is not at fault in this case is further supported by the rigidly linear increase in the number of events observed: SMCO is clearly throttling the probes correctly, but there are fluctuations in the unmeasured overhead.

Figure 4.10 shows the operation of the SMCO global controller as a single execution of `gcc` runs. A single run of the `403.gcc` benchmark consists of multiple executions of the `gcc` executable on different test files; hence, although the full run took 1,691 seconds, this execution only took 127 seconds. This figure shows data

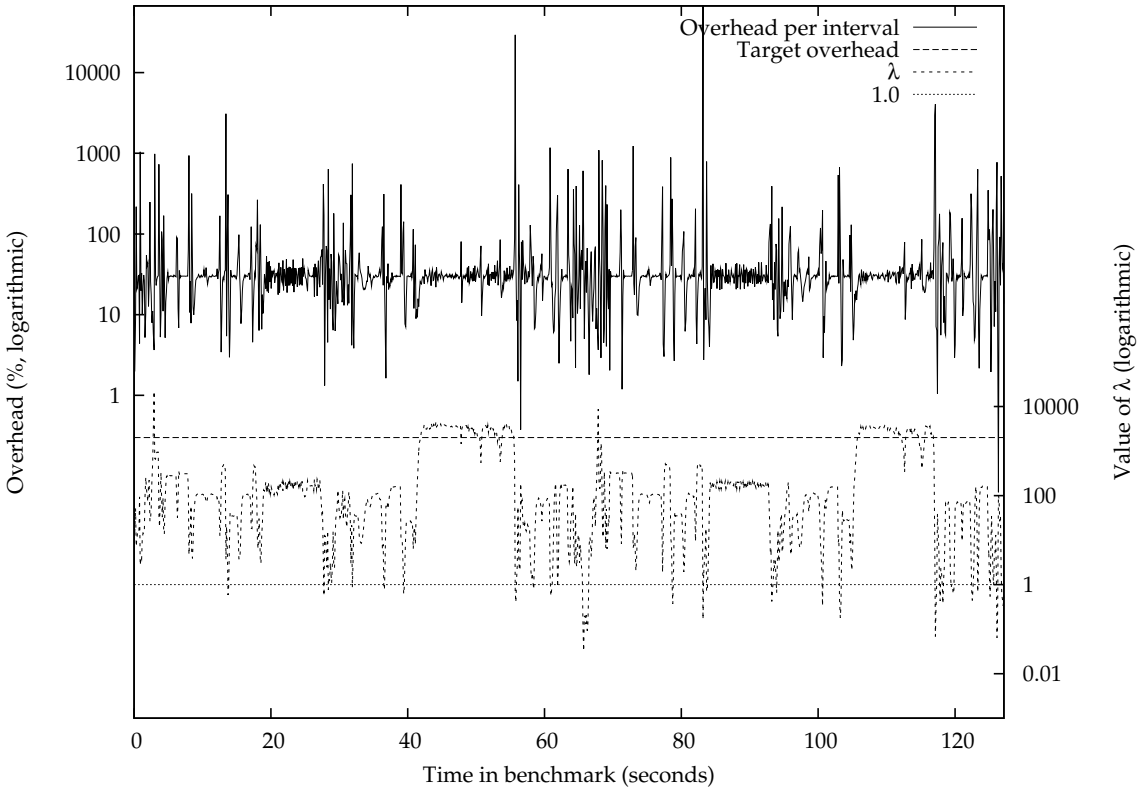


Figure 4.10: Observed overhead per interval and values of λ throughout a single `gcc` *invocation from* `403.gcc` *with target overhead set to 30%. Both y axes are logarithmic, but λ (right-hand y axis) is plotted below overhead (left-hand y axis) and their units are independent.*

collected at each interval by the SMCO global controller, which runs at the end of each 0.1-second interval. The controller determines the current overhead, which is represented by the upper data series. The ratio of the desired overhead to this overhead is the *error*, an estimate of the accuracy of the previous value of λ. λ is then corrected by multiplying it by this error; this and λ's effect on overhead constitute a feedback loop.

In the execution of `gcc` depicted in Figure 4.10, target overhead is set to 30%. Observed overhead stays close to this target, and, when it is stable, λ is greater than 1. We expect a large positive value of λ in all but trivial programs because only a few portions of a program's code are executed in any particular period of time, limiting the number of probes that can fire. In GCC, for example, each phase of compilation—parsing, optimization, register allocation, instruction selection—has its own set of functions.

Chapter 5

Conclusion

Internet connectivity is ubiquitous. Internet gaming and Web-based applications are two of the largest applications for personal computers; handheld computers without an Internet connection, whether through WiFi or cellular services, are becoming curiosities. The server space now largely exists to provide services on the Internet. Software development is changing too, with user input, both in the form of posts on support forums and in the form of crash reports—becoming one of the primary ways software developers have to find new bugs and prioritize existing ones.

User participation in the debugging process is helpful, but users are not experts. There are certain sectors where the end-user is a trained system administrator or developer. In such sectors, interactive tools like DTrace are invaluable for diagnosing correctness and performance problems in software. In other cases, users should be able to opt in to a debugging system that allows developers to track down bugs remotely. Such a debugging system will not be fully interactive, because developers have neither the time nor the privilege to interactively query customer computers; rather, a developer will write agents that represent hypotheses about bugs, and deploy these agents to existing installations of the software being debugged.

`adb` is precisely the mechanism for this new form of debugging. As we have seen, `adb` provides a clean separation between the *provider*, which adds multipurpose probes to an application, and the *consumer*, which can be deployed later, be developed entirely separately from the program's source base, and yet be capable of full data reflection on the application by using `adb`'s generic APIs. In addition, we have observed that `adb` represents the user's interests by regulating the overhead that the instrumentation imposes, ensuring that it does not slow down the user experience unacceptably. This is crucial to continuing user participation in any voluntary debugging effort.

In addition to developing `adb` itself, we have contributed a variety of other technologies which promise to have significant impact themselves.

- GCC plug-ins are a mechanism for loading new transformation passes into GCC as it compiles a program. These transformation passes have full access to the GCC internal API, and can manipulate the intermediate representa-

tion of the program being compiled as if they were a part of GCC. The GCC plug-in technology promises to make GCC accessible to a variety of new developers, including researchers, application developers with domain-specific transformations, and developers of experimental transformations that are not yet mature enough to be included in mainline GCC. For each of these clients, plug-ins offer the ability to develop compiler code without the inconvenience of maintaining a patch series and rebuilding the whole compiler tool-chain when the developer changes the transformation. Additionally, for the maintainers of GCC, plug-ins hold the promise of less maintenance overhead because non-essential functionality can be separated into plug-ins. GCC plug-ins is scheduled to appear in GCC 4.5.

- Compiler development tools are used to assist developers in implementing compilers and transformations. We have developed a tool called GIMPLE Viz that helps developers inspect the intermediate representation for code being compiled by GCC; by using GIMPLE Viz, a GCC developer can find out how GCC compiles particular code fragments, and what the exact results of a certain compiler optimization are. We are currently extending GIMPLE Viz to allow dumping of the GIMPLE intermediate representation into a database, and are integrating it with GDB to allow interactive debugging of GCC code.
- Debugging tools based on plug-ins leverage our GCC plug-in technology to perform useful software diagnoses. For example, we have developed plug-ins for array bounds-checking, execution tracing, race condition detection, memory leak detection, and reference counter validation. We have also developed a plug-in that embeds Python in GCC, exposing the GCC intermediate representation to programs written in the Python scripting language [54]. Programmers can use this plug-in to prototype algorithm-intensive optimizations using Python's easy-to-use data structures and extensive standard library, saving time and implementation effort.
- Overhead-control policies for instrumentation control the degree to which instrumentation affects performance. During our research, we developed two innovative overhead-control schemes: Monte Carlo Monitoring (MCM), based on Monte Carlo Model Checking [25], and Software Monitoring with Controllable Overhead (SMCO). MCM initially monitors all possible events, checking if a certain correctness property for the system holds true at every event. When the confidence that the property is always true for a given class of events passes a threshold (say, 99.999%), MCM disables the checks for that class of events. SMCO regulates the delay between monitored events to make the observed overhead match a particular desired value.

5.1 Future Work

Whereas `adb` is the best tool for the job at the moment, there are improvements that could be made. Specifically, it should not be required to specify in advance what probe-points are necessary. To facilitate this, we propose an extension of the *superblocking* technique common in VLIW compilers [15]. A superblock is a con-

catenation of basic blocks (see Section 4.3.1) that is optimized for a particular important code path. Entry and exit points from the middle of a superblock exist, and the compiler guarantees that if control passes in or out that the proper instructions will be issued, but those paths are comparatively slow.

We propose an application of superblocking in which variables are optimized as desired in the fast path, but for each variable for which operations are out of order in the fast path, there is a sequence of slow paths that performs the same operations. To improve performance, there would be no branches to these slow paths; rather, each path would be associated with an instruction that could be rewritten to an unconditional branch to enable that path. Each slow path could then be further modified, allowing any portion of the code to be rewritten (in this case, for instrumentation purposes). This would require extensive compiler support, but provide full code reflection with no performance penalty.

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