

Profiling Java Applications Using Code Hotswapping and Dynamic Call Graph Revelation

Mikhail Dmitriev
Sun Microsystems Laboratories
UMTV29-112, 2600 Casey Avenue
Mountain View, CA 94043, USA
Mikhail.Dmitriev@sun.com

ABSTRACT

Instrumentation-based profiling has many advantages and one serious disadvantage: usually high performance overhead. This overhead can be substantially reduced if only a small part of the target application (for example, one that has previously been identified as a performance bottleneck) is instrumented, while the rest of the application code continues to run at full speed. The value of such a profiling technology would increase further if the code could be instrumented and de-instrumented as many times as needed at run time.

In this paper we present an experimental profiling system called JFluid, which includes a modified Java™ VM and a GUI tool, and addresses both of the above issues. Our tool supports instrumentation of a group of methods defined as an arbitrary “root” method plus all methods that it calls (a call subgraph). It appears that static determination of all methods in a call subgraph is difficult in presence of virtual methods, but fortunately, with dynamic code hotswapping available, two schemes of *dynamic* call subgraph revelation and instrumentation can be suggested. Measurements that we obtained when performing full and partial program profiling using both schemes show that the overhead can be reduced substantially using this technique, and that one of the schemes generally results in a smaller number of instrumented methods and better performance. Furthermore, we observe that our approach generally works much better for large (for example, J2EE and Web) applications, than for small benchmarks.

1. INTRODUCTION

Growing size and complexity of modern software applications increase the demand for tools that automate collecting data about the dynamic behaviour of programs, and thus allow developers to identify performance bottlenecks in their applications with minimum effort. The process of automatic collection and presentation of data characterizing performance of running programs is called profiling. For an object-oriented language such as the Java™ programming language, that features automatic memory management, built-in multithreading and thread synchronization mechanisms, etc.,

several forms of profiling are useful in practice. CPU profiling determines how much time the program spends executing various parts of its code; memory profiling determines the number, types and lifetime of objects that the program allocates; hot lock profiling determines congested monitors, etc. For applications built according to higher-level standards, for example Enterprise Java (J2EE [20]) applications, specialized, high-level kinds of profiling exist, such as measuring the J2EE transactions throughput.

Instrumentation-based profiling works by inserting, or *injecting*, special packets of code, called instrumentation code, into the application to be profiled (we will call it *target application* or TA). Execution of the injected code generates events, such as method entry/exit or object allocation. This data, usually in the processed form (e.g. the total time spent in each method, or a total number of allocated objects of each type), is eventually presented to the user.

The main advantage of instrumentation-based profiling over other known techniques — sampling-based profiling and, in case of programs running on top of a virtual machine (VM), the so-called VM hooks¹, is its flexibility. Virtually any kind of data, ranging from low-level events to high-level data, such as EJB security check occurrences, or GUI event firing, can be captured using this technique. For high-level data, instrumentation (whether performed by a special tool or embedded into the application itself) is the only way of data collection. For CPU performance measurements, the advantage of instrumentation compared to its main rival, sampling-based profiling, is that instrumentation records the exact number of events such as method invocations; is capable of measuring precise timings (not a statistical approximation, as it happens with sampling); and can be used selectively (for example, on just a few methods, or when instrumented methods are called with a specific parameter value only, etc.). Thus, instrumentation profiling has an advantage when it is required to profile a number of short-running and infrequently executed methods, or in a system where total code profiling, even using sampling, will result in an unacceptable overhead. Furthermore, the fact that instrumentation records all events as they happen while the program runs, can help to restore the important details of program execution history, such as what methods a given method called and in what order, a critical execution path, and so on. Last but not least, instrumentation mechanism is relatively portable, i.e. with it one can implement many useful features

Permission to make digital or hard copies of all or part of this work for personal or classroom use is granted without fee provided that copies are not made or distributed for profit or commercial advantage and that copies bear this notice and the full citation on the first page. To copy otherwise, to republish, to post on servers or to redistribute to lists, requires prior specific permission and/or a fee.

WOSP'04, January 14-16, 2004, Redwood City, California, USA.

Copyright 2004 ACM 1-58113-673-0/04/0001 ...\$5.00.

¹The outcome of recent evaluation of JVM profiling hooks can be found in [10]. Based on these findings, the Expert Group established to define the new standard JVM profiling specification has recently decided that in this specification [1], many of the VM-generated events, including method entry/exit and object allocation, will be optional and not required to be supported by all conforming JVMs. Bytecode instrumentation is the recommended mechanism for their generation.

without any special support from the VM.

However, instrumentation-based profiling is often associated with high temporal overhead. Injected instrumentation code takes its own time to execute; its presence may prevent some optimizations, such as method inlining, that could have otherwise been made to the TA code; finally, additional code injected into the original code may result in many more processor cache misses than when the original code is executed as is. For these reasons, total execution time overhead measured in “factors” rather than per cent is not uncommon [3, 4, 7]. Those who used modern profiling tools such as Optimizelt [8], JProbe [16] or VTune [13] in the “instrumentation profiling” mode can probably confirm this observation. The problem is made worse by the fact that presently most of the tools use static or (in case of Java) class load time instrumentation. That means that the code remains instrumented, and thus incurs execution overhead, during the whole run time of the target application.

One way to address this problem is to perform instrumentation selectively. For example, the overhead of instrumenting only a few known key pieces of the application may be just one or two per cent, making it possible to use this technique even for applications running in the field, as reported, for example, for some J2EE monitoring tools, e.g. [26]. The problem is that minimal and nonobtrusive instrumentation is usually good only to confirm that there is indeed a performance problem, or, at best, to roughly identify the code area responsible. On the other hand, even heavyweight instrumentation of the part of the application is likely to be tolerable in many situations, as long as it is there only when needed to pinpoint the real performance problem.

In this paper, we describe an experimental technology and tool, called JFluid, that address the above issues by allowing users to select and profile a limited subset of methods of a Java application, and repeat that as many times as needed while the application is running. The underlying mechanism enabling these features is *dynamic bytecode instrumentation*, that supports injecting (and removing) instrumentation bytecodes into/from methods of a running program. In its present shape, JFluid is more suitable for development-time profiling rather than for production-time problem diagnostics. However, it appears that even at development time the approach that we have taken is very useful, as confirmed by our own measurements and the feedback from numerous JFluid users.

Our present implementation consists of the JVMTM (currently based on Java HotSpotTM VM version 1.4.2) that has been modified to support dynamic bytecode instrumentation, and the GUI tool. The JVM allows the user to start it without any special preparation (such as special command line options, presently needed in most of the industrial JVMs to enable various profiling-related capabilities), then attach the tool to it at any moment, instrument the application, collect and analyse the data “on line”, and finally detach the tool, allowing the TA to run at full speed again. The tool currently supports CPU and memory (object allocation) profiling. The modified JVM, the tool, and the documentation are available for free download and evaluation at <http://research.sun.com/projects/jfluid>. The detailed technical description of this system can be found in our recent technical report [11].

This paper makes the following contributions:

1. While the idea of using dynamic bytecode instrumentation for profiling is not new, we make a contribution by suggesting how it can be used for CPU profiling in a new, more efficient way. Firstly, we suggest to instrument methods of a *call subgraph*, that the tool automatically reveals, based on a single “root” method specified by the user. Secondly, we show how dynamic bytecode instrumentation itself helps to solve the problem of fast and highly-precise identification of

all methods in a call subgraph.

2. We experimentally evaluate our technology on different types of applications, showing in what circumstances our approach is most beneficial.

The rest of this paper is structured as follows. In Section 2 we present the general architecture of our system. In Section 3 we describe the attachment mechanism used to attach our tool to a running JVM. In Section 4 we describe how method hotswapping works in our modified JVM. In Section 5 we discuss how the generated profiling events are recorded. In Section 6 we describe two schemes for dynamic revelation of a call subgraph that is triggered by the “instrument method transitively” command. In the next section, we present the results obtained by running our tool on several benchmarks, using both of the above schemes and either full or partial application profiling. In Section 8 we discuss related work, and finally, in Section 9 we present conclusions and some thoughts about the future work.

2. JFLUID ARCHITECTURE

Of the requirements to an introspection system, one of the most important is to keep its impact on the target VM as small as possible, in terms of CPU cycles, heap space usage and other internal resource consumption. On the other hand, ease of development, change and maintenance is also important, especially for a research tool. The present architecture of JFluid is an attempt to address both of these requirements.

In order to minimise the system’s impact on the target VM, a client-server model, depicted in Figure 1, was adopted for JFluid. The target VM acts as a *server*, with the JFluid server, or back end, code, executing on it in parallel with the target application (TA). The JFluid tool communicates with it using TCP/IP sockets and a shared-memory file (why we use both of these mechanisms will be explained a bit later).

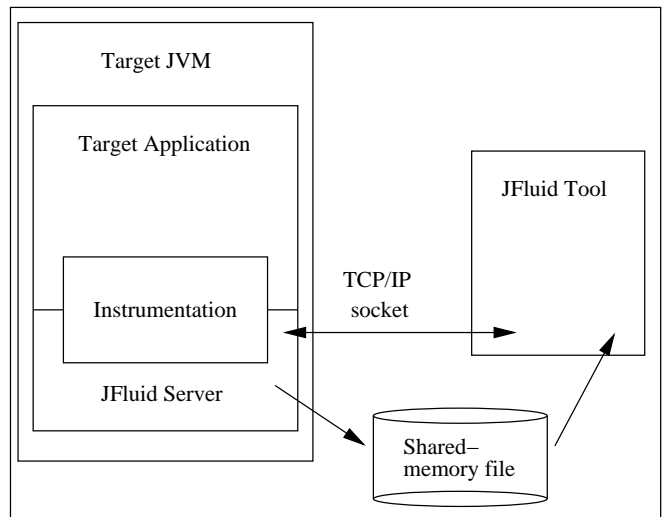


Figure 1: JFluid Architecture

The server is a relatively small, but most important part of JFluid, since its properties affect the performance and usability of the system to the greatest extent. Once activated, the server starts a single thread that handles the communication with the tool. It receives

and executes the tool's commands, and also informs the tool of certain events that may occur while the TA is running. The injected instrumentation code executes on behalf of the TA, but structurally is also a part of the server code. It collects and records the profiling data, and may trigger some events, that are handled by the server and then, in some cases, by the tool.

The JFluid server is written in Java, with only a small amount of C code. This code acts simply as a bridge between the server and our special VM-internal API, which is similar to JVMDI (JVM native debugger interface [23]). This API can be viewed as a subset of JVMDI: it provides a small number of calls to get VM-internal information (for example, to get all loaded classes or running threads), handle some VM events (e.g. class loading), and to hotswap the code of running methods (which is how dynamic byte-code instrumentation is performed). The rest of the server code is written in Java. That includes, in particular, the code that records profiling events and transfers this data to the tool, and the code responsible for general communication between the server and the tool.

The advantages of the back end written in Java are: ease of development, increased portability, and even, possibly, a better performance of the instrumentation code. The latter is due to the fact that crossing the boundary between Java and native code is a relatively expensive operation. Thus, frequently executed instrumentation code written in Java and compiled with a sufficiently smart dynamic compiler, such as the one available in HotSpot, may execute even faster than the native code.

Writing the back end of an introspection tool in Java does not, however, seem to be a universally accepted approach, since, for one thing, the Java classes that belong to the tool, and the data structures that they create in the Java heap, inevitably distort the normal memory layout, and possibly the performance, of the TA. While this is generally true, we believe that for large applications that are the primary target of JFluid, the impact of this additional code and data is negligible. To ensure that, we took the following measures:

- Retained as much profiler code as possible at the tool side;
- Designed the system in such a way that the size of the data generated by the server and retained at the target VM side remains limited during the TA execution lifetime.
- Implemented our wire protocol avoiding the use of Java Object Serialization (see below).

Also, when judging whether or not Java code is appropriate for an introspection tool back end, we believe one should realize the difference between types of such tools. Specifically a debugger back end written in Java would be problematic due to a high probability of deadlocks. They will most probably become an unsurmountable problem, since both the back end and the TA would use Java threads and compete for the same VM internal resources, such as an internal class dictionary or various heap locks, while the back end would need to perform some VM internal functions, e.g. asynchronous thread suspension, that a normal Java application can never use. In our profiling code, however, this does not appear to be a problem, since its interaction with the target VM internals is quite limited and is mostly in the form of queries. Asynchronous thread suspension/resumption is simply not used. Thus, so far we did not have any serious problems due to the JFluid server being written in Java, and the time spent on fixing occasional bugs in this area is fully compensated by the increased maintainability and other advantages of the Java code. The performance of our system

also looks comparable to that of several commercial profiling tools that we tried.

To transmit information between the tool and the server we use both a custom, packet-based wire protocol, similar to e.g. JDWP [24] over TCP/IP sockets, and a shared memory file. While commands, responses and the data that they carry (the amount of which is relatively small) is transmitted using TCP/IP sockets, the acquired rough profiling data is transmitted using a shared memory file. This is due to the high volume of this data and the need to transmit it as fast as possible to minimise the run time profiling overhead. We use both sockets and shared memory as opposed to just shared memory, because in future we plan to extend our system such that the target VM and the tool can run on separate machines. In that case, TCP/IP sockets will be the only universal communication mechanism. However, to retain advantages of processing rough profiling data outside the target VM, we will still have a small "proxy" component running on the same machine, that would get the rough data through the shared-memory file, process it and send relatively compact intermediate representation to the tool over the network.

To minimise the impact of the communication code written in Java on the target VM, we implemented our own custom mechanism of data transmission over TCP/IP sockets, which does not use standard Java Object Serialization. Commands of our wire protocol are mostly simple, each consisting of a few integers and strings, or at most a few arrays of those, so it was not difficult to write our own custom serialization code. This helped us to avoid "polluting" the Java heap with many additional classes that are loaded and even automatically generated by the standard Serialization mechanism. The performance of our mechanism is also superior to that of the Java Object Serialization.

Finally, the JFluid GUI tool is a Java application taking advantage of automatic memory management, portable graphics libraries, and other merits of the Java platform. It can either start the target VM or attach to an already running one (see Section 3 for details). As the TA executes, the tool processes the rough profiling data generated by the server and builds a compact and informative representation of profiling results (see Section 5), that can be viewed by the user at any moment.

3. ESTABLISHING CONNECTION WITH THE TARGET VM

Like most other profiling tools, JFluid can work with the target VM/application in two modes: by controlled application startup and by attaching to a running VM. Obviously, the first mode is much easier to implement. In our implementation, the tool would simply start the target JVM with its own `ProfilerServer` main class, passing it all the information about the actual target application (that the user previously entered in the tool) through the command line. The server class' main method first spawns a dedicated tool communication thread, and then invokes the main method of the target application.

It appears, however, that attaching to an already running JVM is presently much more popular with JFluid users. "Ergonomics" is the main reason for using this mode even at the development phase, since many large Java applications are started with a very long and cumbersome set of command line options, class path entries, and so on. These options may be spread among several script files, and therefore copying them all into the tool's "Options" dialog for controlled startup, even if done just once, may be quite painful. It is much more convenient to just start the application as usual, and then attach the tool to it. In future, as we mentioned in the intro-

duction, we hope that the capability to attach the diagnostic tool to any running JVM, started without any special preparation, will become one of the key pieces of the general “emergency servicing” mechanism.

To our best knowledge, no existing introspection tools for Java that need to perform some activity within the running JVM, support attachment without preparation. Instead, they require that the target JVM is started with special command line options that typically activate some additional code (an equivalent of our profiler back end) right from the beginning. This code would then listen on a port or an alternative communication channel, waiting for the tool to come up and initiate an active session. One good reason for these tools to activate the back end very early, is that it is the only way for them to intercept and instrument all application classes.

In JFluid, we do not have the latter concern, and we wanted to avoid any special JVM startup-time preparation completely. Therefore, we came up with a solution, which is simple, and yet, to the best of our knowledge, is not presently used in any other Java VMs. To activate the introspection back end (in fact, this mechanism can be used for any other code as well) we use an OS signal handler in the VM. An OS signal in UNIX^(R) does not carry any additional information with it, so in order to make this mechanism flexible enough, we suggest the use of a convention, according to which, once the VM receives a predefined OS signal, it goes to some predefined file system directory, and looks for a file with a predefined name. If the file is not there, nothing happens. If the file is there (it is the tool’s responsibility to generate it, and then delete it when the connection is established), it should contain the full path to the native library to start, and any parameters to the function (with the predefined or specified name) that serves as an entrypoint. The VM then would load the library and start the function with the given parameters in a specially created thread.

The implementation of this mechanism appeared to be straightforward. The HotSpot VM already has some signal handlers. One of them, for the UNIX signal SIGQUIT, can also be activated by pressing Ctrl-\ (on Solaris) or Ctrl-Break (on Windows) on the keyboard. This signal handler presently dumps the stacks of all Java threads currently running in the VM. We simply added code to it that would, after dumping threads, look for a file and perform other operations as described above.

One remaining question is how to choose the directory that the target JVM would use to lookup the session startup file. We initially made our JVM use the directory from which it was started, thus requiring the tool user to specify both the JVM process PID and this directory to establish connection. Then we came up with a better, though non-general solution, which uses the non-standard mechanism known as `jvmsstat`[25], available in HotSpot starting from version 1.4.1. This mechanism makes any HotSpot JVM create on startup a special, one-per-user directory, that is accessible only to that user. The VM then places a file into this directory, that contains information allowing the `jvmsstat` tools to read certain performance data that the VM dumps periodically. This is in fact another “introspection always on” mechanism available in HotSpot, although it supports only data reading, in contrast with JFluid’s active interaction with the JVM. The bottom line is that for any running HotSpot VM there is now a write-protected directory, that can be unambiguously identified by both the target VM and the tool, given the user ID and the target JVM PID — which is exactly what we need.

As a final note, we would like to add that our mechanism is as secure as the underlying OS. In particular, in UNIX only the user who started a process, or a super-user, can send any signal to it. The signal can travel only within the same machine. Furthermore,

the directory which we use to pass the information is inaccessible to other users.

4. DYNAMIC BYTECODE INSTRUMENTATION

4.1 General Approach

At the time when the JFluid project started, the *dynamic class redefinition* capability, in the form of the `RedefineClasses()` call in JVMDI [23, 9], was already available in the HotSpot VM. However, it turned out that the general class redefinition functionality provided by this call is technically not quite suitable for possibly massive, yet individually small changes to methods, that characterize bytecode instrumentation. `RedefineClasses()` takes the arguments that are, essentially, the pointer to the “old” class object, and the byte array representing the whole “new” class file. Before actually hotswapping the two classes, it parses the new class file, installs an internal class object for the new class version, compares the two versions to make sure that only supported changes have been made in the new version, etc. (see [9] for a detailed description). So if, for example, we need to instrument 1000 methods in 1000 different classes, with each of these classes containing a few tens of other methods, the overhead due to generating 1000 whole rewritten class files, transferring them over the wire, and then redefining each of these classes completely, may be very significant.

Fortunately, if it is known in advance that modifications that we are going to apply are, for example, injection of method calls into existing bytecodes, or, generally, any modifications that obey certain technical restrictions, an optimized solution can be suggested. Given the way in which classes are represented in memory in the HotSpot JVM [9], and other properties of this system, these restrictions are:

1. Nothing in a class except its method bodies is modified.
2. No existing *constant pool* [14] entries are changed or removed.

The former constraint saves us a lot of run time work needed to restructure and/or replace the whole internal class object if, for example, a method or a data field is added. The latter one saves us time parsing and installing the whole new constant pool, and also, what is very important, guarantees that both old and new method versions can use the same new constant pool.

The optimized API applicable if the above constraints are obeyed consists of just two calls: `RedefineMethods(methodIds[], byte[][] newMethodBytecodes)` and `ExtendConstantPool(classId, byte[] addContents)`. We chose to support extending only one constant pool in one go, since this operation is relatively rare and does not have any effect until methods that may use the added constant pool contents are changed. In contrast, atomic redefinition of multiple methods is often necessary. Furthermore, methods may be redefined frequently and in large groups, and therefore aggregating multiple redefinitions into one call, that performs some common operations only once, reduces the overhead significantly.

4.2 Implementation

Technically, runtime hotswapping of a method is not such a challenging issue as it might seem. The task is simplified by the fact that our current policy for switching between the original and the instrumented method version is “all active invocations of the old method version complete as is, and all calls to this method that occur after hotswapping go to the new method version”. That is, if a

method that we want to instrument is currently running, we don't attempt to immediately switch execution to the instrumented code. The latter feature does not currently seem to be very valuable, or at least worth the effort, from the practical point of view.

Given this policy, method hotswapping means essentially locating all pointers to old method versions and switching them to the respective new method versions everywhere in the program. However, this may be a real challenge in a VM that, like the HotSpot VM, runs Java applications in mixed mode, when initially the program is interpreted, and gradually the most actively used methods are compiled into native machine code [22]. One compiled method can call another using a direct `call` machine instruction; furthermore, some methods may get inlined into their callers.

Fortunately, the so-called *deoptimization* mechanism (initially introduced in the SELF system [12]), that solves this problem, is already available in HotSpot. In short, it works by recording, at compile time, the information about methods called directly, and about “caller - callee” pairs when a callee is inlined. Actual deoptimization is performed if we need to switch back to interpretation of some compiled method — for example to step through it in a debugger, or because it is a virtual method that cannot be inlined anymore (a class in which this method is overridden has been loaded). Deoptimization is performed in two phases. On the first, eager phase, the execution is suspended, the stacks of all application threads are scanned, and all compiled stack frames for methods that should be deoptimized are patched in a special way. The execution then resumes, and the second phase happens when a callee method is about to return to the method that was deoptimized (let us call it `m()`). At that time, the stack frame of `m()`, which is now the topmost, is converted into the format of the interpreter, and the current instruction pointer is set to the point in the bytecode that corresponds to the current point in the machine code. The procedure is complicated by the fact that `m()` itself, and possibly its callers, may be inlined; thus a single native stack frame may be replaced with several interpreted stack frames.

The procedure of replacing methods with their instrumentation copies, performed by our `RedefinedMethods()` call, consists of two phases:

1. Parsing method bytecodes and creating new internal method objects.
2. Activating the instrumented code.

Since on the first phase we create new method and constant pool versions (which means, among other things, allocating the corresponding objects on the Java heap), this phase is performed in the same ordinary Java thread that requested method hotswapping, possibly in parallel with other running Java threads. The latter phase, on the contrary, has to be performed atomically, with all Java threads suspended. On this phase, we deoptimize all methods that depend on our instrumented methods, and then switch pointers in all affected objects on the heap (constant pools and virtual method tables), so that they now point to the instrumented method versions. Further details of the hotswapping procedure can be found in [11, 9].

After hotswapping is complete, the application threads are resumed, and the next call the target application makes to an instrumented method, goes to its new version. The invocations of original method versions that are currently active complete as is.

5. PROFILING DATA COLLECTION

Currently JFluid supports collection of two kinds of CPU profiling data. The first, more sophisticated kind (which, however,

imposes a much higher run time CPU overhead) is a Context Call Tree (CCT) (explained below). The second kind of profiling data (usually collected with virtually no overhead) is gross time for a single code region. Since this profiling technique is very simple (it is essentially injection of two `getCurrentTime()` calls into a single chosen TA method), it is not discussed further in this paper.

The *calling context tree* (CCT) format of profiling results representation was first introduced by Larus et al. in [3], and is presently used, for example, in the popular Optimizelt [8] commercial profiling tool. The reader can find a detailed explanation for this and other formats in the above work; a short example in Figure 2 illustrates it and is hopefully self-explanatory. We chose this presentation format for JFluid, since in our opinion, it is the most compact (which is facilitated by the GUI support for expanding and closing tree nodes) and yet informative one.

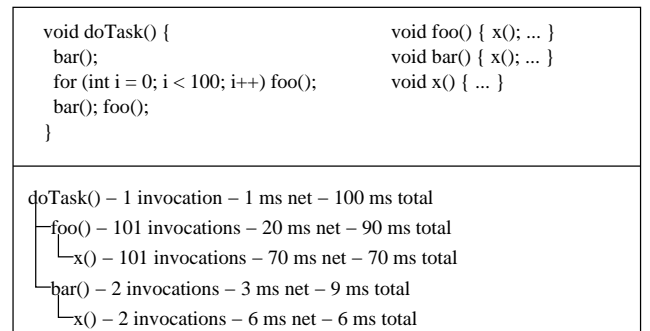


Figure 2: A program and its Calling Context Tree (CCT)

When collecting data in this format, we inject instrumentation bytecodes into all methods that are reachable from an arbitrary root method specified by the user (`doTask()` in Figure 2). Section 6 explains how these methods are identified. Our instrumentation consists of calls to the following two methods: `methodEntry(char methodId)` and `methodExit(char methodId)`. Both of them are public static void methods, defined in our own `ProfilerRuntime` class. We arrange that the target VM loads it using the bootstrap class loader, to avoid any class resolution problems when calling our instrumentation methods from any class loaded by the target VM, including the bootstrap classes. Each instrumented method of the TA is assigned its own char identifier, which is hard-coded into the calls to `methodEntry()` and `methodExit()`.

The instrumentation code is relatively complex, since, in addition to its main responsibility — taking the current timestamp and recording the relevant event — it needs to perform a number of other operations necessary for correct data collection in the CCT format. The main reasons why these additional operations are needed are:

1. A limited subset of the TA methods is profiled, but any method that is within a call subgraph can also be called from a site which is outside this subgraph. Therefore, the instrumentation has to detect whether it is called in the profiled subgraph context or not, and in the latter case, has to return as quickly as possible.
2. Instrumentation itself may call some Java core classes code, which also may be instrumented. We need to prevent recursive instrumentation calls to avoid infinite recursion, misleading measurements, and other problems, such as deadlocks.

3. The TA code may throw exceptions, which, if measures are not taken, would result in `methodEntry()` calls with no matching `methodExit()`.

To address these concerns, we maintain a special per-thread data structure in the JFluid server, called `ThreadInfo`. It contains, in particular, two boolean fields (flags) called `inCallGraph` and `inProfilerRuntimeMethod`. Both of them are initially set to `false`. They are further used in the instrumentation code as shown in Figure 3, where the relevant parts of the `methodEntry()` method are presented in a slightly simplified form. The comments in the code make clear how these flags are utilized. The structure of `methodExit()` method is largely the same, except that, after determining that we are inside the call graph, we first check if the simulated stack depth is zero. If so, it means that we are in the topmost invocation of the root method, and thus will leave the call graph when this invocation completes. Therefore, if `ti.stackDepth == 0`, we set the `inCallGraph` flag to `false` before leaving `methodExit()`.

In order to handle exceptions properly, we add to each instrumented method the bytecode equivalent of the Java `try{ ... } finally { methodExit(); }` statement. In this way, even if a method exits abruptly, our instrumentation is still called by it, ensuring the consistency of collected data — that is, the exact match between the real and the simulated stacks.

6. DYNAMIC REVELATION AND INSTRUMENTATION OF A CALL SUBGRAPH

Given the inevitable complexity of instrumentation code that we previously explained, it is quite important to be able to instrument an interesting group of methods rather than all of them in order to reduce the overhead. However, to the best of our knowledge, in all existing profiling tools for Java reduction of profiled code volume is implemented quite primitively. These tools, for example `Optimizelt` [8], `JProbe` [16], `VTune` [13] or `JRockit Management Console` [6] allow the user to limit the number of methods to profile by manual selection only. The user may pick up methods that they want (or don't want) to profile by hand, or by specifying whole classes or packages. Manual selection can become very tedious and error-prone as soon as the number of interesting methods exceeds a few tens, whereas more coarse-grain selection often leads to increased run time overhead with no additional useful information.

A better alternative in many situations could be the tool itself “discovering” interesting methods to profile, based on some user-specified criterion, that is more sophisticated than class or package name. Of such criteria, one seems to us to be of a particular sense, and that is a *call subgraph* defined as a set of all methods called directly or transitively by an arbitrary, user-specified root method. A technique where the user specifies just a single root method, and the tool determines all methods reachable from it directly or transitively is very easy to use, and, most importantly, looks quite useful, since a call graph seems to match the typical idea of a “task” in the program. Indeed, one method typically performs some task, with other methods that it calls performing, logically, sub-tasks of this task. It is natural to ask questions like “how much time this task takes to complete”, or “how many objects have been allocated by that task”, then go to the most expensive sub-task (a bottleneck), ignoring the cheaper ones, etc. Call graph instrumentation allows one to do exactly this sort of thing, avoiding the run time overhead due to instrumented methods that are not called within the selected task. Furthermore, instrumenting a call subgraph and presenting data in the CCT format fit together very well: we instrument only those methods that we want to see measured.

However, it appears that identifying and instrumenting methods within an arbitrary call subgraph of Java methods is not simple. To understand the reasons for that, consider how we can actually determine all the methods that can be called, directly or transitively, by an arbitrary method. This can be done statically, by scanning and analysing bytecodes. But to begin with, static bytecode analysis will not allow us to determine what methods are called using the Java reflection mechanism. Furthermore, if virtual methods and call sites are present in our code, special analysis, such as *class hierarchy analysis* (CHA) or *whole program class analysis* will be required to determine concrete methods that are reachable from a given virtual call site (see e.g. [17], where an overview and extensive bibliography on these techniques is presented). It appears [17], that all of these techniques generally give a greater number of virtual methods than the program would actually call. In the case of simple techniques (CHA), overestimation may be as high as 10-20 times. More complex techniques, such as *points-to* analysis, which takes into account what classes are actually instantiated in the program and where, result in a higher precision. However, they would not work for objects allocated using reflection (or returned by native methods), whose exact types thus can not be determined by static analysis of Java code. Also, in our opinion, these techniques are unlikely to scale well with the growth of the analysed code (the tests used for evaluation in [17] seem to us unrealistically small).

Thus, if we can instrument methods in any class only once, before it has been loaded by the VM (which is the only option in most of the contemporary industrial Java VMs), precise (and exhaustive) call graph revelation for an arbitrary root method done in acceptable time seems highly problematic. That is probably why call subgraph instrumentation and profiling is not used in conventional profiling tools for Java.

However, as we show here, if a VM (or, generally, a runtime system) provides a way to instrument code at run time, a novel technique for call graph revelation and instrumentation can be implemented. In the following two subsections we briefly describe the two variants (schemes) of this technique. Both of them use simple conservative class hierarchy analysis (which simplifies the implementation a lot), and yet — at least the second scheme — demonstrate quite acceptable precision (see Section 7) on even highly-polymorphic tests.

6.1 Scheme A

In this scheme, we establish the following conditions under which a method `m()` is instrumented:

1. Class `C` to which `m()` belongs has been loaded by the VM.
2. Using class hierarchy analysis, `m()` is determined to be reachable directly or transitively from the root method.

The actual procedure works as follows:

1. The procedure starts when the subgraph root method's class is loaded (we can intercept this event using the standard class load hook mechanism of the JVM). Blocking further class loads temporarily, obtain the list of all classes currently loaded by the VM. For each class a special “mirror” data structure is created that will hold certain information relevant to our analysis. To speed up further analysis, for each class we can also determine and record in the mirror the names of all of its subclasses. Thus, for any given loaded class, all of its subclasses can be obtained instantly. After determining all loaded classes, install our own class load hook that performs operations described in step 3, and resume the TA.

Then, for the root method `m()`, perform step 2.

```

public static void methodEntry(char methodId) {
    ThreadInfo ti = getThreadInfo();           // Get record for current thread
    if (ti != null && ti.inCallGraph) {
        if (ti.inProfilerRuntimeMethod) return; // Avoid recursive instrumentation invocation
        ti.inProfilerRuntimeMethod = true;
        ti.stackDepth++;                       // Increase the simulated stack depth

        // ... Obtain current timestamp and record the "method entry" event

        ti.inProfilingRuntimeMethod = false;
    } else if (methodId == rootMethodId) {      // Entered root method from outside call graph
        if (ti == null) { // This thread never entered our call graph before
            ti = ThreadInfo.newThreadInfo();
            // ... Record the new profiled thread creation event
        }
        ti.inProfilerRuntimeMethod = true;
        ti.inCallGraph = true;

        // ... Obtain the current timestamp and record the "root method entry" event

        ti.inProfilerRuntimeMethod = false;
    }
}

```

Figure 3: General structure of `methodEntry()` instrumentation method

2. Scan the bytecodes of method `m()`, examining each call instruction. If a call instruction is for a static method `SC.s()`, mark this method as “reachable unscanned static” in the SC class mirror. Then check if class `SC` is currently loaded by the VM. If it is, mark method `s()` as scanned and perform step 2 for it in turn.

If a call instruction is for a virtual method `VC.v()`, mark this method as “reachable unscanned virtual”. Then check if class `VC` is currently loaded by the VM. If it is, mark the method as scanned and perform step 2 for it. Next, check all of the subclasses of `VC` that are currently loaded by the VM. If in any of them `v()` is overridden, perform the same procedure for this method, i.e. mark it as scanned and repeat step 2 for it.

When this step exhausts, we have a number of methods in loaded classes marked as “reachable scanned” and a number of methods in the mirrors for not yet loaded classes that are marked “reachable unscanned”. Now, instrument each scanned method using method hotswapping mechanism, and mark them accordingly.

The next step 3 is performed every time a new class is loaded by the VM.

3. Upon loading of a class `C`, check if a mirror data structure has already been created for this class, and if not, create one. Check if there are any reachable methods in the mirror. If yes, mark each of these methods scanned and perform step 2 for each of them.

Next, determine all of `C`’s superclasses. For each superclass, check if it contains any reachable virtual methods. If so, check if any of these methods are overridden in `C`. Mark each such method as “reachable scanned virtual” and perform step 2 for it.

In our implementation, all bytecode scanning and other code analysis operations are performed at the tool side. The code at the

target VM (server) side sends to the tool messages such as “class loaded”, “initial list of classes loaded by the VM”, etc., and receives messages containing lists of methods to instrument. It is worth noting that once any code has been instrumented and thus profiling started, further code analysis and instrumentation upon class loading, which may be relatively time-consuming, could have affected profiling results quite significantly. To prevent this, every time a class load event occurs, our server-side code records a special “thread suspend” profiling event. The “thread resume” event is recorded just before returning from the class load hook to the TA code. This compensates for the time spent in code analysis and instrumentation.

Note further that, although the VM may perform concurrent class loads, all class load, analysis and instrumentation operations in the JFluid back end are made serial. This is done by making the class load hook method, which effectively initiates these operations, synchronized on a lock. In this way, we guarantee that at any point our analysis operates on a fixed set of classes, and therefore no classes can get missed or instrumented twice.

This scheme works much better than static Class Hierarchy Analysis, since only the classes actually loaded by the VM are analysed, and their number is usually significantly smaller than the number of all classes on the class path. Furthermore, we can easily cope with method invocations via reflection, by instrumenting the code of the `java.lang.reflect.Method.invoke()` method itself. Every time `Method.invoke()` is called, we check to see if its argument method has already been instrumented. If not, we dynamically process and instrument it as yet another reachable method.

However, quite often this scheme may result in a large number of methods instrumented but never called (see Section 7). Thus, we eventually came up with another scheme, which uses a more lazy approach, presented in the next section.

6.2 Scheme B

To overcome the shortcomings of the previous scheme, we extend the set of conditions necessary for method `m()` to be instru-

mented. Two new conditions, in addition to the first two presented in the previous subsection, are added:

1. Method `m1()` which calls `m()` directly has been instrumented;
2. Method `m1()` is about to be executed for the first time.

The fact that a method is instrumented only when its chances to be called are good, since its direct caller has been called, is likely to reduce the number of unnecessarily instrumented methods quite significantly. However, to make this algorithm work, the instrumentation in every target application method that has callees, should check, every time it is invoked, whether this is the first invocation of the given method. If so, it triggers the procedure of instrumentation of its direct callees. Fortunately, for the most time-sensitive profiling kind, CPU profiling, this check can be implemented within the same injected `metodEntry()` method that performs CPU time measurements operations. The additional check takes very little time compared to the rest of the instrumentation code. Before instrumentation starts, we allocate a global array of booleans, called `methodInvoked[]`, where each element corresponds to a method in the profiled subgraph. During instrumentation, methods that are found reachable are assigned integer identifiers that grow monotonically. Thus each method is associated with an element of the above array, and to check if an invocation of the given method is the first one, it is sufficient to check if `methodInvoked[methodId] == false`.

The above array can grow over time, but the space that it occupies is generally not an issue, since it is at most one byte per instrumented method. And as our measurements (see Section 7), even for large real-life applications this number is usually on the order of at most a few tens of thousand.

The algorithm itself works as follows:

1. The procedure starts when the root method's class is loaded (we can intercept this event using a standard JVM class load hook). Obtain the list of all classes currently loaded by the VM and create mirror data structures in the same way as in Scheme A. Also create a growable global boolean array `methodInvoked[]` that indicates whether any instrumented method has been invoked at least once.
2. Instrument the root method `m()`, and mark it as instrumented in the C's mirror.
3. This step is performed every time any instrumented method `m()` is entered. Check if this method is being executed for the first time. If this is true, perform step 4 for this method.
4. Scan the bytecodes of method `m()`, examining each "call" instruction. If a call is for a static method `SC:s()`, and method `s()` is not marked as instrumented, mark it as "reachable uninstrumented static" in the SC class mirror.

If a call is for a virtual method `VC:v()`, and this method is not marked as instrumented, mark it as "reachable uninstrumented virtual" in the VC class mirror. Next, check all subclasses of VC that are currently loaded by the VM. If in any of them `v()` is overridden and not marked as instrumented, also mark it as "reachable uninstrumented virtual".

When this step is exhausted, we have reached the end of `m()` and marked a number of methods directly reachable from it as "reachable uninstrumented". Now, using the hotswapping mechanism, instrument those of the above methods that belong to classes which by this time have already been loaded by the VM.

5. This step is performed by the class load hook, upon loading of any class C. Check if a mirror has already been created for class C, and if not, create one. Next, determine all of the C's superclasses. For each superclass, check if its mirror contains any reachable virtual methods. If so, check if any of these methods are overridden in C. Mark each such method in C as "reachable uninstrumented virtual".

Finally, instrument all methods in C marked as "reachable uninstrumented" and mark them as instrumented.

In our tests, this scheme generally works much better, resulting in a close match between the number of instrumented and actually executed methods (see the next section). As an only drawback, for short-running applications it may result in a higher overhead due to a large number of `RedefineMethods()` calls, each of which carries just one or two instrumented methods.

7. EVALUATION

This section presents experimental results obtained from our VM and tool executing several benchmarks. Our goal was to evaluate the efficiency and accuracy of our system, and to compare the two instrumentation schemes described in the previous section. As the first set of benchmarks (the "small" ones), we used the standard SPECjvm98 [19] suite, executed with 100%-sized inputs. To these, we added one non-standard benchmark, Notepad, which is a demonstration GUI program distributed with Sun's JDKTM.

As the second, "large" benchmark set, we used the Sun PetStore [21] sample application running on top of SunTM ONE Application Server 7, Standard Edition. J2EE [20] and Web applications, together with the code of application servers on top of which they run, are probably the largest Java applications, that can be easily obtained at present. PetStore was chosen as representing a (hopefully) typical J2EE application that manages an on line shop and supports all the usual customer activities. With this application, we exercised two scenarios, resulting in two benchmarks, "PetStore 1" and "PetStore 2". In the first scenario the "user" (our workload emulation tool) would just browse through the store, add a few items to the shopping cart, buy them and leave. In the second scenario, the user would retrieve, edit and update their persistent account details.

In all tests except Notepad we did not profile Java core class methods to avoid results dependency on the JDK (core class internal code can change between JDK versions). For Notepad, core classes were included (they are mostly AWT/Swing graphics classes in this case) to demonstrate the spectacular difference between two profiling schemes in a "real life" situation.

All experiments were performed on the Sun E420ER server with four 450MHz UltraSPARCTM II processors, with 4GB of main memory, running the SolarisTM Operating Environment, version 2.8. We executed each small benchmark once to "warm up", and then three more times to gather results. The recorded results were calculated as an average for these three runs. In case of PetStore, we generated the workload using the OpenSTA tool [2]. Each testing sequence consisted of 10,000 consecutive interactions, preceded by two warm-up sessions of 100 and 1000 interactions respectively.

All measurement results are grouped into two identically structured tables. The results in Table 1 are for the whole program profiling: each benchmark was instrumented transitively starting from its main method (the run methods of all threads in PetStore). The second table contains the results for partial instrumentation of each of the benchmarks, performed in the following way. For each of the SPECjvm98 benchmarks, we picked up an (essentially arbitrary) method `m()`, that, together with its callees, takes about 10%

of the total charged execution time of the fully profiled benchmark. `m()` would then be used as a call subgraph root for partial profiling. In Notepad a root method was one called in response to a user action (“New File”). As a developer profiling their program would normally do, we discarded the results of the first invocation, when most or all of the method hotswapping operations are performed, and the overhead is high and randomly distributed. Finally, in PetStore we profiled the call graph originating from the business method `processEvent()` of the `ShoppingClientControllerEJB` class, which, as we observed, is effectively the single entrypoint into the business code of PetStore.

In each table, there are two lines for each benchmark: they correspond to results obtained using instrumentation scheme A and B (see previous section), respectively. The columns in the tables have the following meaning:

- *Calls* is the total number of calls to instrumented methods.
- *Bare time* refers to the time taken by the benchmark running without instrumentation. *Root time* in Table 2 is the time, measured using our lightweight code fragment profiling mechanism, for the method that is used as a call subgraph root in the partially profiled run.
- *Total time* is the total execution time for the instrumented benchmark.
- *Overhead* is the percentage increase of the total time with respect to the bare time.
- *Instrumentation, Hotswapping, Tool 1, Tool 2* are the relative (to the total execution time) times spent, respectively, in the injected instrumentation code (i.e. `methodEntry()` and `methodExit()` methods); in the VM performing method hotswapping operations; in the tool performing bytecode analysis and rewriting; and in the tool performing profiling data processing. The last two values also include time spent exchanging data between the system components. For Notepad in partial profiling mode, and PetStore, Hotswapping and Tool 1 times are not given, since the respective operations were performed during the warm-up execution(s).
- *Total instrumented methods* and *called instrumented methods* are the total number of methods that were instrumented, and the number of instrumented methods that were actually called at least once during execution.

When profiled fully, most of the benchmarks make a large number of calls, which results in instrumentation consuming very significant time and the resulting high overhead (the maximum value of nearly 50 times is observed in `compress`). The cost of transferring the rough profiling data to the tool and processing it (“Tool 2”) is 2-3 times lower than the cost of the instrumentation, and, by coincidence or some deeper reason, is 18-19% for the majority of the benchmarks. Method analysing and hotswapping time is negligibly small in all of the tests except for Notepad (discussed a few paragraphs below).

Running benchmarks with partial profiling leads to a very considerable reduction in the overhead. However, the absolute values of overhead (more than 100 per cent for more than half of the benchmarks) are still high. We conclude that measuring exact execution time using total, or even partial (in our case, 10-50% of the total number of methods) instrumentation-based profiling is not suitable for small computationally-intensive applications running on modern highly optimized VMs and processors. Apparently,

relatively heavyweight instrumentation that we employ breaks too many optimizations on various levels when it is injected into methods that, in the compiled form, consist of just a handful of instructions. On the other hand, lightweight instrumentation that we also have in our tool produces much more realistic results.

The situation is quite different for large benchmarks, for which JFluid imposes not very high overhead even when full profiling is performed. In case of partial profiling, the overhead (on the order of 2 per cent in one case, and 12 per cent in the other) is probably acceptable even for in-the-field usage. Clearly, using instrumentation and partial profiling really pays off in large applications, where “call intensity” is generally not very high, and where it really makes sense for developers to instrument a small (maybe just a few per cent) proportion of application code, because even this amount of code may, in absolute terms, be quite large (a few hundred methods in our case) and worth optimizing. Furthermore, J2EE and Web applications may interact with the underlying Application Servers in complex ways, so it makes a lot of sense to profile code that belongs to different “code layers” together in such cases. Our technique, which automatically instruments methods based on the logical task that they perform, rather than, say, on their affiliation with one or another package (layer), directly addresses this issue.

Now consider the number of methods that our system instruments. In benchmarks that do not include many polymorphic calls, such as `compress` or `db`, the total number of instrumented methods and the number of called methods are equal or very close, and is the same or close for both call graph revelation schemes. This changes dramatically in `javac`, `Notepad`, and `PetStore`, where scheme A causes instrumentation of many more methods². To our surprise, for PetStore even the “lazy” instrumentation scheme B results in a large number of methods instrumented but not called.

Instrumenting more methods than necessary should generally be avoided, since, firstly, methods instrumented unnecessarily can be called by the TA (in the wrong context). The instrumentation code in that case returns quickly, but still consumes some time. Another issue is that instrumenting more methods means that more time is spent in hotswapping, and more methods get deoptimized, run interpreted, then recompiled, etc. In the long term these effects get amortised, but in the short time period they may make a big difference. We thus conclude that the “lazy” scheme B is generally much more suitable for applications that we consider appropriate for instrumentation-based profiling.

8. RELATED WORK

In a recent paper [5] Brear et al. describe a profiling tool called JBolt, that uses an equivalent of dynamic bytecode instrumentation, and, furthermore, can search for performance bottlenecks in the profiled program by progressive refinement. That is, this tool adaptively inserts and removes code probes into methods of the running program in order to find method(s) that contribute most to the total execution time. Reliable identification of bottlenecks may require more than one run of the target application. The system uses

²The difference in the number of calls and called methods for Notepad and PetStore with different schemes is explained by the fact that in these benchmarks we instrument Java core and Application Server classes, respectively, which call native methods, which, in turn, can call Java code. Our code analysis schemes cannot follow the latter kind of calls; however if a method that has been instrumented for other reasons is called by a native method, JFluid registers this call. Since scheme A causes a very large number of methods to be instrumented, some of them may, by coincidence, be called by the native code. This is a shortcoming of our technique, which is not yet addressed.

Table 1: Results for whole program instrumentation

Benchmark/ scheme	Calls	Bare time, ms	Instr. time, ms		Instr., %	H/S, %	Tool 1, %	Tool 2, %	Instr. methods	
			total	ovhd,%					total	called
compress	225.93M	23241	1199465	5061	75	< 0.1	< 0.1	18	55	53
			1199498	5061	75	< 0.1	< 0.1	18	55	53
db	70320	24714	25838	4.5	1.1	< 0.1	< 0.1	< 0.1	52	46
			25912	4.8	1.1	< 0.1	< 0.1	< 0.1	52	46
jack	1.86M	7756	20630	165	36	3.3	4.2	9.2	274	264
			20718	166	36	3.8	4.2	9.2	274	264
javac	46.7M	19575	275625	1308	67	1	0.9	19	992	730
			277399	1317	67	1.8	0.8	19	936	730
jess	77.62M	8965	416021	4640	72	< 0.1	0.2	19	478	327
			415044	4530	72	< 0.1	0.4	19	442	327
mpegaudio	91.7M	18204	504528	2672	73	< 0.1	0.2	19	241	213
			503576	2666	73	< 0.1	0.2	19	230	213
Notepad	144256	1373	18589	1254	3.1	58	44	2.4	7486	2874
	126067		24775	1704	2.0	55	36	1.8	3853	2706
PetStore 1	6.01M	3921025	4395469	12.1	1.2	N/A	N/A	1.5	5345	287
			4364105	11.3	1.0	N/A	N/A	1.5	979	213
PetStore 2	178M	9630732	12635520	31.2	8.7	N/A	N/A	5.3	8734	1124
			12568103	30.5	8.5	N/A	N/A	5.2	2691	1073

an equivalent of a dynamic bytecode instrumentation mechanism, that is available in a special “virtual JVM”. The latter is effectively a JVM written in Java and running on top of a standard JVM. To reduce the performance impact, this virtual JVM is designed in such a way that it takes control of the target Java application only at some points, and between them the target application runs at full speed, its bytecodes being executed by the base JVM. The work is in progress, and initial results that are reported in the above paper are probably insufficient to make definite conclusions about the value of this approach.

BEA Systems’ JRockit JVM [6] is probably the closest equivalent of our modified Java VM. JRockit supports dynamic method instrumentation, and allows the user to select an arbitrary number of methods to instrument using the GUI tool called Management Console. Methods can only be picked up by hand, i.e. no equivalent of our call subgraph profiling is available.

In the SELF VM [12] an instrumentation-based profiling technique was once used, that featured eager injection of instrumentation code into the TA, done by the source-to-bytecode compiler. Initially, however, the instrumentation library routines would be deliberately made empty, allowing the dynamic compiler to optimize away the calls to them, thus eliminating any performance impact. Dynamic activation of the instrumentation was done by hotswapping the empty library routines with the “real” ones. At this point, all the TA code would be deoptimized, and then gradually recompiled again, now with calls to the instrumentation library.

ParaDyn/DynInst (see the [27] Web site, where documentation and published papers can be found), is a suite of tools and APIs that allow developers to profile and monitor running parallel and distributed programs using dynamic insertion and customization of measurement code. It operates on native machine code programs and supports a variety of platforms, including SPARC/Solaris, Windows and Linux on x86 processors, and AIX on RS6000. ParaDyn can insert and remove instrumentation adaptively, and has support for automatically locating bottlenecks in the program.

The IBM Jinsight tool [15, 18] follows some of the same principles as JFluid. Performance data in this tool is gathered in *bursts*, defined as “a set of trace execution information, gathered during

an interval of time, associated with a specific task in program”. A burst is triggered by a user-specified method. Jinsight filters the data based on the user-specified threads, methods and other criteria. The implementation is based on a special JVM which emits all events unconditionally, with the tool just filtering events that are relevant for the current task. The fact that the JVM always emits all events (or at least all events in one category) is likely to affect performance adversely.

The idea of accumulating and presenting data in the form of the calling context tree (CCT), which is both a very useful presentation format, and the data accumulation form that allows us to calculate and factor out the profiling overhead correctly for each method, was first introduced by Larus et al. in [3]. The same group has published a series of papers on different forms of profiling, but most of this work concerns measurements at a granularity finer than a single method, so that the path of control flow within subroutines is recorded.

9. CONCLUSIONS AND FUTURE WORK

Dynamic bytecode instrumentation mechanism that we implemented in the Java HotSpot VM, described in this paper, allows developers to instrument and profile a subset of a running application on-the-fly, and change this subset as many times as needed. Our VM-internal method hotswapping functionality should allow for any kind of instrumentation. However, in our profiling tool, called JFluid, we have so far concentrated mostly on a limited task — instrumenting and profiling a call subgraph in a running Java application. It appears that in presence of virtual method calls it is hard to identify all methods in a call subgraph using static code analysis with sufficient precision and in a reasonable time. Therefore we introduced a technique, where the tool reveals a call subgraph dynamically, while the application runs. We suggest two alternative schemes for doing that, and show experimentally that the second scheme, that makes decisions on what to instrument based on information available only at run time, generally gives better results.

We have shown that profiling a small part of the target application can significantly reduce the temporal overhead usually asso-

Table 2: Results for partial program instrumentation

Benchmark/ scheme	Calls	Root time, ms	Instr. time, ms		Instr., %	H/S, %	Tool 1, %	Tool 2, %	Instr. methods	
			total	ovhd,%					total	called
compress	104.3M	6579	574411	2285	73	< 0.1	0.1	18	7	7
			573393	2281	73	< 0.1	< 0.1	18	7	7
db	569	2612	25328	1.2	< 0.1	< 0.1	0.3	< 0.1	2	2
			25411	1.5	< 0.1	< 0.1	0.3	< 0.1	2	2
jack	242267	273	29140	271	3.3	0.1	2.6	1.8	66	55
			28785	267	3.4	0.3	1.2	2.0	65	55
javac	2.70M	850	44893	118	24	0.9	1.3	6.8	587	209
			38901	91	28	1.3	1.9	7.8	289	209
jess	5.67M	357	47471	403	48	0.2	0.5	12	33	4
			46056	388	49	< 0.1	0.5	12	8	4
mpegaudio	8.96M	612	80667	343	44	0.1	0.2	11	191	11
			70901	289	50	< 0.1	0.2	12	21	11
Notepad	660	49.7	62.1	25	4.2	N/A	N/A	< 0.1	7882	31
	380		56.0	12	2.7	N/A	N/A	< 0.1	76	27
PetStore 1	3.93M	12979	4012785	2.1	< 0.1	N/A	N/A	0.2	1231	128
			4010253	2.0	< 0.1	N/A	N/A	0.2	439	125
PetStore 2	170.4M	1313700	10799213	11.9	4.5	N/A	N/A	4.2	8606	976
			10771041	11.8	4.4	N/A	N/A	4.2	2546	891

ciated with instrumentation-based profiling. For small, computationally intensive benchmarks the absolute overhead of our technology may still remain quite high. However, for large programs, such as J2EE applications running on top of an Application Server, the situation is very different, and the benefits of our technique are much more apparent. For such applications, our technique can often reduce the profiling overhead very substantially (sometimes to as little as a few per cent), while still delivering enough useful information to the developer. Furthermore, instrumenting a limited, but interesting portion of the application code appears, somewhat unexpectedly, to be a quite efficient way of addressing “profiling scalability” problems in multithreaded applications. Some of our users have reported that for such applications under heavy load, standard overall instrumentation often results in excessive volumes of generated profiling data, that may cause an unproportional slowdown at best, and hang or crash the application in the worst case. By using JFluid to instrument the limited amount of code, they managed to successfully eliminate such problems.

CPU profiling is not the only useful thing that can be done using dynamic bytecode instrumentation. Presently our tool also supports object allocation profiling (not described in this paper), which is done by dynamically injecting calls to instrumentation at each allocation site. As a further continuation of this line of work, we consider object liveness analysis and, possibly, memory leak debugging, that can be done in relatively unobtrusive way, i.e. without interrupting the target application for noticeable time. We hope that adaptive instrumentation techniques similar to the one that we use for call graph revelation can help us in that. For example, once it is known that objects of some type(s) are not causing leaks, instrumentation for them can be removed, and instrumentation for suspicious types can be changed to generate more information, and so on.

In the more distant future, it may be worth thinking about how to further reduce the profiling overhead and/or make it more controllable, to ultimately enable in-the-field use of our technology. Such an “emergency servicing” capability in a VM may be very attractive for developers and system administrators, who currently suffer from bugs in deployed applications, that may be hard or impossible

to reproduce in the lab environment. We can imagine discovering a bottleneck or another problem in a running application, while keeping the overhead below some predefined (low) level at every moment, by gradually narrowing down the observation area and simultaneously increasing the level of detail in the generated tracing data.

10. ACKNOWLEDGEMENTS

The author is indebted to Adrian Mos for his help with measuring the performance of large Java applications, and to Mario Wolczko, for reading the early draft of the paper and giving very helpful comments. We are also grateful to numerous JFluid users who sent us their feedback and constructive suggestions.

11. TRADEMARKS

Sun, Sun Microsystems, Inc., Java, JVM, JDK, HotSpot, and Solaris are trademarks or registered trademarks of Sun Microsystems, Inc., in the United States and other countries. SPARC and UltraSPARC are trademarks or registered trademarks of SPARC International, Inc. in the United States and other countries. UNIX is a registered trademark in the United States and other countries, exclusively licensed through X/Open Company, Ltd.

12. REFERENCES

- [1] JSR 163 — Java™ Platform Profiling Architecture. <http://www.jcp.org/jsr/detail/163.jsp>.
- [2] Open System Testing Architecture (OpenSTA). <http://www.opensta.org>, 2003.
- [3] G. Ammons, T. Ball, and J. Larus. Exploiting hardware performance counters with flow and context sensitive profiling. In *Proceedings of the ACM SIGPLAN Conference on Programming Language Design and Implementation (PLDI-97)*. ACM Press, 1997.
- [4] T. Ball and J. Larus. Optimally profiling and tracing programs. In *ACM Transactions on Programming Languages and Systems*, volume 16, pages 1319–1360, 1994.

- [5] D. Brear, T. Weise, T. Wiffen, K. Yeung, S. Bennett, and P. Kelly. Search strategies for Java bottleneck location by dynamic instrumentation. UK Performance Engineering Workshop (UKPEW) 2003, Warwick, UK, July 2003.
- [6] BEA Systems. JRockit 8.1 SDK User Guide. <http://edocs.bea.com/wljrockit/docs81/userguide/index.html>.
- [7] B. Calder, P. Feller, and A. Eustace. Value profiling and optimization. *Journal of Instruction Level Parallelism*, 1, March 1999.
- [8] Borland Software Corporation. OptimizeIt Suite. <http://www.borland.com/optimizeit>, 2002.
- [9] M. Dmitriev. *Safe Evolution of Large and Long-Lived Java Applications*. PhD thesis, Department of Computing Science, University of Glasgow, Glasgow G12 8QQ, Scotland, 2001.
- [10] M. Dmitriev. Application of the HotSwap Technology to Advanced Profiling. In *Proceedings of the First Workshop on Unanticipated Software Evolution, held at ECOOP 2002 International Conference*, Malaga, Spain, 2002.
- [11] M. Dmitriev. Design of JFluid: a Profiling Technology and Tool Based on Dynamic Bytecode Instrumentation. Technical report, Sun Microsystems Laboratories, 2600 Casey Avenue, Mountain view, CA 94043, USA, 2004. Available at <http://research.sun.com>.
- [12] U. Hölzle. *Adaptive Optimization for Self: Reconciling High Performance with Exploratory Programming*. PhD thesis, Stanford University, March 1995. Also published as Sun Microsystems Laboratories Technical Report SMLI TR-95-35.
- [13] Intel Inc. Intel VTune Performance Analyzers. <http://www.intel.com/software/products/vtune/>.
- [14] T. Lindholm and F. Yellin. *The Java Virtual Machine Specification, Second Edition*. Addison-Wesley, 1999.
- [15] W. De Pauw, N. Mitchell, M. Robillard, G. Sevitsky, and H. Srinivasan. Drive-by Analysis of Running Programs. In *Proceedings for Workshop on Software Visualization, International Conference on Software Engineering*, May 2001.
- [16] Quest Software. JProbe Java Profiler. <http://java.quest.com/jprobe/jprobe.shtml>.
- [17] A. Rountev, A. Milanova, and B. Ryder. Fragment Class Analysis for Testing of Polymorphism in Java Software. In *Proceedings of the 25th International Conference on Software Engineering (ICSE'03)*. IEEE Computer Society Press, 2003.
- [18] G. Sevitsky, W. De Pauw, and R. Konuru. An Information Exploration Tool for Performance Analysis of Java Programs. In *Proceedings of TOOLS Europe 2001 Conference*, 2001.
- [19] Standard Performance Evaluation Corporation. SPEC Java Virtual Machine Benchmark Suite. <http://www.spec.org/osg/jvm98>, August 1998.
- [20] Sun Microsystems Inc. Java 2 Platform, Enterprise Edition - Documentation. <http://java.sun.com/j2ee/docs.html>.
- [21] Sun Microsystems Inc. Java Blueprints. <http://java.sun.com/blueprints/code>.
- [22] Sun Microsystems Inc. Java HotSpot™ Technology. <http://java.sun.com/products/hotspot>.
- [23] Sun Microsystems Inc. Java Virtual Machine Debug Interface Reference. <http://java.sun.com/products/jpda/doc/jvmdi-spec.html>, 2000.
- [24] Sun Microsystems Inc. Java Virtual Machine Wire Protocol Reference. <http://java.sun.com/products/jpda/doc/jdwp-spec.html>, 2000.
- [25] Sun Microsystems, Inc. Emerging technologies: jvmstat. <http://developers.sun.com/dev/coolstuff/jvmstat>, 2003.
- [26] Wily Technology. Introscope 3.0. http://wilytechnologies.com/solutions_introscope.html.
- [27] University of Wisconsin, Madison. ParaDyn Project. <http://www.cs.wisc.edu/paradyn/>.