HP Caliper – An Architecture for Performance Analysis Tools

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Abstract

HP Caliper is an architecture for software developer tools that deal with executable (binary) programs. It provides a common framework that allows building of a wide variety of tools for doing performance analysis, profiling, coverage analysis, correctness checking, and testing. HP Caliper uses a technology known as dynamic instrumentation, which allows program instructions to be changed on-the-fly with instrumentation probes. Dynamic instrumentation makes HP Caliper easy to use: It requires no special preparation of an application, supports shared libraries, collects data for multiple threads, and has low intrusion and overhead. This paper describes HP Caliper for HP-UX, running on the IA-64 (Itanium) processor. It describes Caliper's architecture, dynamic instrumentation algorithm, and the experiences gathered during its implementation.

1. Introduction

The IA-64 processor's instruction set architecture (ISA) offers an impressive set of architectural features which explicitly create synergy between compilers and the processor [10]. The IA-64 groups up to three instructions in bundles for execution in parallel and can issue multiple bundles per clock. The architecture provides 128 integer registers, 128 floating point registers, 64 1-bit predicate registers, and 8 branch registers. Both control and data speculation are supported, as well as predication to eliminate branches, software pipelining of loops, and branch prediction.

These processor features enable powerful program optimizations. However, their efficiency depends on the dynamic run-time behavior of a given program, which can only be guessed by a static compiler. Additionally, modern software paradigms emphasize distributed systems, component-based modularization and object-oriented designs. This further prevents compilers from optimization and analysis on a global scope.

Over the last years, the computing community has developed a strong set of tools and methods used to analyze and monitor run-time behavior of a program. Statistical sampling and binary instrumentation are two of the major techniques.

Statistical sampling is typically performed by taking periodic snapshots of the program state, e.g., its instruction pointer (IP). Sampling is considered to be light-weight, non-intrusive, and imprecise. It imposes low overhead on a program's run-time performance and can be used for time-critical experiments. However, measurements are statistical samples and have errors. Without special hardware support, due to super-scalar issues, deep pipelining, and out-of-order instruction completion, a sampled IP may not be related to the instruction address that caused a particular sampling event. Some architectures introduce a varying offset to the IP at a particular sampling event [2, 10].

The IA-64's performance measurement unit (PMU) offers programmable CPU event counters, event address registers (EAR), and a branch trace buffer (BTB). The PMU supports a set of over 150 event types, allowing a wide range of system analysis tasks [10], such as analysis of cache misses, translation look-aside buffer (TLB) misses, or instruction cycles. When such a hardware counter overflows, it is possible to precisely link events to an instruction address with help of the event address registers (EAR).

Dynamic binary instrumentation allows program instructions to be changed on-the-fly and leads to a whole class of more precise results. Measurements such as basic-block coverage and function invocation counting are accurate. Since the binary code of a program is modified, all interactions with the processor and operating system may change significantly, for example a program's cache and paging behavior. Instrumentation is therefore considered to be intrusive. Due to additional instructions, execution time can slow down anywhere from some percent to factors like 2x or 4x. Dynamic instrumentation, as opposed to static instrumentation, is performed at run-time of a program and only instruments those parts of an executable that are actually executed. This minimizes the overhead imposed by the instrumentation process itself.

Tools based on dynamic instrumentation require no special preparation of an executable, like many other tools for performance analysis and tuning do. Such treatment could be recompilation with a special compiler flag, or a modified link process before or during program start. A good example is profile-based optimization (PBO). There, a program must be recompiled with a special flag to insert counting code in the program and to output a trace profile at the end of the program run. Feeding this profile back into the compiler allows combining of static analysis and runtime information and to generate a highly optimized application for a representative set of input data. This data combination also requires another compiler flag to be used. PBO generates efficient code, but is complicated to use, especially for large-scale software systems. It has not been widely accepted by the software industry.

HP Caliper (or *Caliper* for short) integrates PMU supported sampling and fast dynamic instrumentation. It offers a framework for performance analysis tools for binary executables and requires no special preparation or recompilation of these binaries. It supports shared libraries, collects data for multiple threads and processes, and has low intrusion and overhead. This paper describes HP Caliper for HP-UX, running on the IA-64 (Itanium) processor. It describes HP Caliper's architecture and public interfaces, presents the dynamic instrumentation algorithm and details experiences gathered and lessons learned during its implementation.

2. Related Work

This section describes related work as characterized by Cmelik and Keppel [5]. They present a list of over 45 hardware emulators, "decode-and-dispatch" interpreters, "pre-decode" interpreters working on intermediate representations, static cross compilers, and dynamic cross compilers. These tools differ in support for kernel code, time of instrumentation, requirements for debug information, and support for signals and multithreaded programs.

Many tools try to generalize static or dynamic instrumentation and create abstractions of machines, file formats, compiler code layouts and optimization strategies. These tools often come with additional generators for machine abstractions.

Paradyn [9] is a performance measurement tool for parallel and distributed programs. It includes an abstract, machine independent, dynamic instrumentation API (DynInst), and provides precise performance data down to the procedure level.

The Parallel Tools Consortium sponsors two related projects, the Performance API (PAPI) project and the Dynamic Probe Class Library (DPCL), the latter being based on Paradyn.

Spike [6] is a profile-directed optimization system. It uses code-layout to improve cache behavior and hot-cold optimization to minimize the number of instructions executed on frequent paths through a program. Atom (Analysis Tools with OM) is a tool based on Om [14]. Atom NT is a set of tools built with the Spike library, including profilers, arc counters, and simulators for cache and branch prediction units.

Some tools and libraries allow static instrumentation of binary executables. EEL [11] is a machine-independent library for editing executables and provides abstractions which allow tools to analyze and modify binary executables. Etch [13] is a tool which allows instrumentation of Win32/Intel executables. Tools based on Etch include call graph profilers and instruction execution analyzers. UQBT [4] is a retargetable and "resourceable" binary translator. Resourceable means that it accepts a binary from one of several platforms as input, which is then transformed to an intermediate representation and finally retargeted to several target machines.

Rational's Purify, Quantify, and PureCoverage [12] are systems which perform static instrumentation for error detection, run-time performance analysis, and coverage analysis. Intel's Vtune is a low-level CPU sampler which allows detection of CPU bottlenecks and cache behavior.

HP's Aries [18] combines fast code interpretation with dynamic translation in order to execute PA-RISC applications transparently and accurately on IA-64 systems running HP-UX.

Previous work at HP's dynamic instrumentation lab includes a callback driven dynamic instrumentation environment and dynamic optimizers for x86, PA-RISC, and IA64. A transparent dynamic optimizer named Dynamo is under development at the HP Laboratory in Cambridge.

3. HP Caliper Architecture

HP Caliper is physically organized as a shared object library with the Caliper API as its interface. A tool built with HP Caliper runs as a *Developer Tool Process*, controlling an *Application Process* via the operating system's debug interface (e.g., ttrace on HP-UX or /proc on Linux).

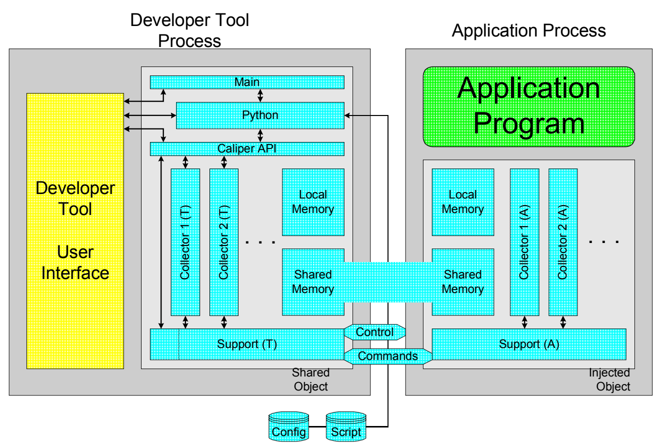


Fig 1: HP Caliper Architecture

Developer tools based on HP Caliper are physically split into two parts, the user interface and the HP Caliper shared object (libcaliper.so). User interfaces can be stand-alone scripts or integrated development environments (IDE). HP Caliper allows to inject an optional run-time library into the application process to record information, react on application events, and communicate with the developer tool.

The shared object is HP Caliper's main component. It contains support code, collectors, the Caliper API, and memory management routines. It integrates a Python interpreter and provides a default C main function.

The HP Caliper API consists of a set of C function interfaces to the main architectural blocks of HP Caliper. The interfaces, although written in ANSI C, follow object-oriented design principles and form a simple object model consisting of Measurement sets, Events, Processes, Configuration, Context and Collectors. These classes are described in the following paragraphs.

Measurement sets enable measurement specification and combination. Instrumentation-based measurements include function coverage and counting, basic block coverage and counting, arc counts, and call graphs. PMU-based global performance metrics include control speculation miss ratio, data speculation miss ratio, ALAT capacity miss ratio, data and instruction cache miss ratios, TLB miss ratios, and more. Statistics of branch mispredictions and branch taken ratios can be obtained.

Event objects deal with application and user events and handle event queues. Typical program events include process creation and destruction, shared object loading and unloading, timer expiration, PMU counter overflow, and process termination.

Process is a set of interfaces allowing creation of or attachment to a process as well as handling of process related events, such as signals. It allows controlling processes via the OS's debug interface (e.g., ttrace or /proc).

Configuration permits to parameterize HP Caliper and to set parameters such as initial size of shared memory blocks.

Context allows HP Caliper to scale to large applications by narrowing down measurements in both time and space. A context's three dimensions are:

- *Address* - to include or exclude modules (DLLs), functions and address ranges
- *Time* - to schedule measurements
- *Event* - to specify program actions for specific program events (e.g., fork / exec).

A *Collector* is a tool built into HP Caliper that performs a special kind of measurement, for example, PMU sampling or instrumentation-based function counting. Collectors use the infrastructure offered by HP Caliper. Each collector adds an individual API to the HP Caliper API to interact with the developer tool. On the application side, support code for the instrumentation may be injected and each individual collector may inject additional private code. Data and control transfers between HP Caliper and an application use shared memory.

The *Caliper Support Library* offers a framework of services and tools for dynamic instrumentation and sampling. These services include:

- encoding and decoding of machine instructions to an intermediate representation (IR) with automatic fix-up of IP-relative branches.
- handling of an executable's ELF file, code and data segments, debug and unwind information, and function tables.
- managing data exchange between HP Caliper and its monitored processes (e.g., for counters, events, or control instructions).
- controlling a process with the debug and performance measurement interfaces (perfmon()).

A developer tool communicates with HP Caliper via the Caliper API or via the integrated Python interpreter. This Python interpreter performs multiple tasks. It contains wrappers for all API functions and is used to interpret initialization and configuration scripts. The interpreter acts as the main interface for all command line tools and as the main shell for the integrated debugger cdb (described later). It can also be directly accessed from the graphical user interface and from the C main function. Currently, Python can not be used to describe probe code sequences at a high level.

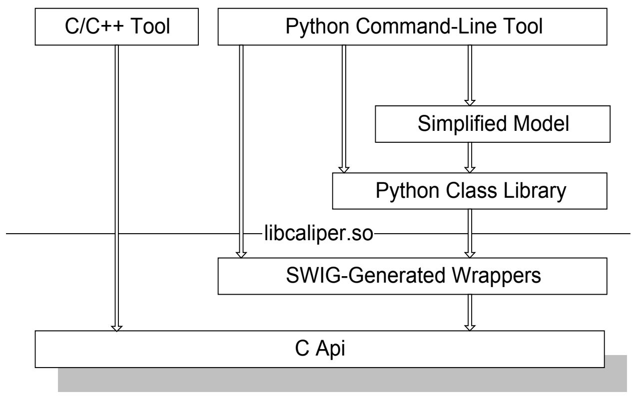
The API resides in a set of C header files, which are processed by SWIG [16] to generate Python wrapper code. The interpreter and the wrappers are included in the HP Caliper shared object. SWIG uses text templates to generate code and some templates had to be changed to make SWIG usable on a 64-bit processor with "new" data types like uint64_t.

The generated wrapper code is very complex to use. Therefore, a Python class library was developed based on the SWIG-generated interfaces. These classes are more intuitive and serve as the main scripting interface to HP Caliper.

This programming model was also felt to be too complex for simple and standardized tasks. This was especially true for novice users, since knowledge of the Caliper API and its object model was required. A further simplified model was developed which only considers the most basic user control requirements. In this model, only a few variables can be assigned before a measurement starts, and all other details are hidden. For example, these variables include the name of the application to be monitored and the type of measurement to be performed.

Tools using HP Caliper can access the C API, the Python SWIG-generated functions, the Python class library, the simplified layer or operate HP Caliper from an IDE. Other language interfaces, such as C++ or Java, can be added on top of the C API.

A small and simple driver is sufficient in order to perform useful work with the HP Caliper shared object. All such a command-line driver does is analyzing its parameters in order to find arguments specifying a script file and finally running this script.



An arc counter standalone tool is written in roughly 20 lines of Python code. (The following code snippet is simplified for clarity):

```
#!./caliper
import caliper, os, sys
try:
# Create process and load executable
    test_exec = os.path.abspath(sys.argv[1])
    proc      = caliper.process()

    proc.load(test_exec,
              sys.argv[1:],
              ["PATH=."])

# Create context
    context = caliper.context(proc)

# Create collector: arc_counter
    arc_count = caliper.arc_count(context)

# Run the measurement
    establish_measurement()

# Retrieve counters and generate report
    fout = open(test_exec + ".pbo", "w");
    arc_count.report(fout)
    fout.close()
except:
     ...
```

A control file in the simplified model looks like:

```
# specify applicatioin
application = "a.out"

# specify output file
pbo_out     = "flow.dat"

# run collector
collect(pbo)
```

4. Dynamic Instrumentation

This section explains HP Caliper's dynamic instrumentation algorithm. It briefly discusses, why it can be characterized as a lazy algorithm before it finally outlines the experiences gathered during its implementation and testing.

One of the major benefits of dynamic instrumentation, as opposed to static instrumentation, is scalability. According to the 80:20 rule (in a typical program, 80 percent of the runtime is spent in 20 percent of the code), only a small fraction of an executable system has to be instrumented in order to detect the most significant parts of a program.

Dynamic instrumentation can be performed in a variety of ways. The two strategies we considered for generating probe code were to either make use of trampolines (out-of-line), or inline and relocate probe code (in-line).

As an example, an out-of-line instrumentation strategy may perform code transformations like the following in order to perform function counting. A given function foo's entry point may look like this in IA-64 assembly:

```
foo::
  alloc         r33=ar.pfs,0,11,1,0
  addl          r9=-2944,r1
  addl          r8=-2936,r1
foo'::
  . . .
```

The out-of-line strategy will instrument foo's entry point with a long branch to a trampoline that executes the original instruction, plus some additional code to update an invocation counter.

```
foo::
  nop.m
  brl   trampoline
foo'::
  . . .

trampoline::
// save state, create free register rx
  . . .

// execute original instructions
  alloc         r33=ar.pfs,0,11,1,0
  addl          r9=-2944,r1
  addl          r8=-2936,r1


// perform additional tasks
// update a counter for this function

  movl rx, addr-of-counter
  fetchadd [rx], 1

// restore state
  . . .

// return to original code.
  brl  foo'
```

There are, of course, many possibilities for encoding, reaching, and returning from the actual trampoline code. Care must be taken for code with branch instructions in the first bundle of a function. Trampoline code and original code may be farther apart than the 25-bit encoded relative address offsets of the IA-64 allow. Therefore, long branches have to be used.

This strategy has several advantages. If all of the probe code is placed out-of-line and the instrumented instructions branch to it and back, then the counting code will not cause any wrinkles in the address space of the original application. Thus, all branches would continue to reach their designated targets. It is also easy to combine multiple instrumentations simply by cascading trampolines.

The other major strategy for probe code generation is to inline and relocate code. The above code snippet for function foo would then be transformed into the following:

```
foo_instrumented::

// modified alloc instruction to
// generate free register
  alloc         r33=ar.pfs,0,12,1,0

// perform additional tasks,
// update a counter for this function

  movl r45, addr-of-counter
  fetchadd [r45], 1

  addl          r9=-2944,r1
  addl          r8=-2936,r1
```

This strategy leads to more compact code, less intrusion, and better performance. It does, however, come at a price.

Insertion of probe code changes the relative offsets in a code stream and requires lookup of indirect branches (in a translation table) whose target cannot be determined by the instrumenter. Combining different instrumentations and probe code is not as easy as it is in the well-defined, sand-box style trampoline approach.

Susan L. Graham, et. al. [8] investigated the relative overhead associated with the inline and out-of-line instrumentation strategies and found the overhead to be 34% for inline and 112% for out-of-line strategies. The transformation overhead is computed as the run-time of all code that is added to the application in order to support the primary probe code, without including the probe code itself. The benchmark included spec programs such as compress, gcc, li, sc, espresso, and more.

The use of long branches had to be minimized for another reason. The first versions of the IA-64 only emulate the long branch, which causes additional run-time performance impacts. A trampoline-based instrumentation approach with out-of-line branches made heavy use of long branches and was therefore disregarded in favor of the current in-line approach.

Preliminary measurements on HP-UX showed that the overhead of a long call branch, compared to a short call branch, is approximately 100 to 300 cycles. This number was considered to be small for an emulated instruction and permitted us to use the long branch instruction "occasionally" in the algorithm.

The inlining relocation method is faster even without considering the extra cost of an emulated long branch instruction. This justified our algorithmic decision in the light of an upcoming, hardware-supported long branch instruction.

4.1 Algorithm

HP Caliper's approach works at the granularity level of functions, which are always instrumented as a whole. Probes are inlined into functions and instrumented functions are relocated.

The dynamic instrumentation algorithm performs the following five steps, which are encapsulated in the Caliper API:

1. *Attach and Inject*: HP Caliper identifies an executable or an already running process. It attaches to a process using the HP-UX ttrace system call. The process stops and transfers control to HP Caliper, which injects code into the process which allocates shared memory and optionally adds run-time libraries for dynamic instrumentation.

2. *Function Discovery*: Function entry points are identified by analysis of the unwind information tables (sometimes called exception tables), the procedure lookup tables, and the symbol table. Unlike a debugger, HP Caliper does not depend on debug information in order to perform this step. The analysis may still miss some function entry points because of a lack of unwind information and symbolic information. However, these functions are discovered dynamically. Whenever a call target cannot be found in the internal function dictionary during instrumentation, a break is inserted at the target address of a call branch, assuming it to be a function entry point.

3. *Static Break Insertion*: Every function's entry point is patched with a break instruction.

4. *Run under Dynamic Instrumentation:* Control is transferred back to the process. The process runs until it hits one of the inserted break instructions at the entry point of a function. Since the process is controlled by ttrace, control transfers to HP Caliper and the instrumentation process begins at the current function.

The function is analyzed for instrumentability, probe codes are inlined into the function, IP-relative references are updated, counters are created, and an instrumented version of the function is moved to shared memory. The original function's entry point is patched with a long branch instruction to its instrumented version. Break instructions are inserted at function external IP-relative branches, whose targets have not yet been instrumented or have not been identified by function discovery.

After instrumentation, control transfers to the instrumented function, which continues to run until it hits the next break instruction. Control will again transfer to HP Caliper and the dynamic instrumentation process is resumed.

5. *Output*: Upon process termination or user request, control again transfers to HP Caliper. Statistics, counters, and other measurement results are now retrieved and

output into one of the integrated, collector-specific formats or via user-defined, script-based output routines.

This dynamic instrumentation algorithm could rightfully be characterized as a lazy instrumentation algorithm. If a program were to consist of only one, presumably huge, function *F*, the algorithm would instrument the whole program at once after reaching *F*'s entry point. No code transformations that depend on information only available at run-time are performed.

Programs consisting of only one function, however, are not a standard case in today's computing environments, right the opposite is true! The instrumentation sequence also depends on the dynamic control flow of a program and can be changed interactively or via the definition of context. We, therefore, continue to use the term "dynamic instrumentation" to describe this algorithm.

Without further explanation we would like to mention another property of this algorithm, the possibility to mix instrumented and non-instrumented code without hurting program correctness.

4.2 Experiences

This section describes the most important experiences gathered and lessons learned during implementation and debugging of this algorithm for HP-UX.

The IA-64 contains a high performance register stack engine (RSE) which helps to minimize the cost of creating a call frame and a function call by maintaining a separate register stack. If a programming model requires consistent unwinding of the stack, e.g. during a C++ exception, both program stack and register stack have to be unwound.

For every region in a program, unwind information is generated and stored in the text segment for fast access. The presence of unwind information is a requirement by the IA-64 runtime software architecture [10]. If code motion happens during instrumentation, the unwind information must be dynamically updated. This is no easy task, since regions get modified by probe code inlining. Unwind information updating is not yet fully resolved and blocks HP Caliper from being used for analysis of C++ programs which make use of C++ exceptions.

Compilers frequently translate a C/C++ switch statement into an indirect branch based on a branch table located in the code segment. HP's compilers place branch tables in a read-only data section of the text segment. It is generally impossible for a binary code analyzer to decide whether a given address contains data (such as an entry of a branch table) or real code. Some algorithms exist to identify branch tables and, for some code generation schemes, this problem can always be solved [3,17].

HP Caliper uses compiler-generated annotations residing in an executable's ELF file to identify these tables. If a branch table has been identified, the table entries are patched so they point to their corresponding instrumented target addresses. Whenever an indirect branch is executed based on an unmodified branch table, it will go to a function's non-instrumented version. Although the program maintains correctness, the resulting counter values become imprecise.

Because of this, HP Caliper's precision depends on the presence of annotations. Annotations are linked to the unwind information for a given region and as long as the executable contains unwind information, the corresponding annotations can be found.

The foremost requirement for binary instrumentation is, of course, to preserve the program semantics at any given time. Probe code needs free registers and earlier approaches required the compiler to reserve registers for special use of a post link-time tools. This is again a topic of a recent discussions in the industry and certainly is a most convenient approach. However, the compiler group soon experienced register pressure and, consequently, this approach was skipped.

HP Caliper now uses a staged method to find free registers. Free registers are first identified with the assistance of compiler generated annotations. If no annotations are found, free registers are created by increasing the number of stacked output registers of a function by modifying a function's dominating alloc instruction. This will fail if the function doesn't have an alloc instruction, has multiple alloc instructions or because the alloc instruction already allocates all the stacked registers. In such a case, explicitly spilling/filling to the program stack is necessary.

Multithreaded applications presented a new kind of challenge for HP Caliper. Insertion of an instruction (e.g., a long branch instruction), turned out to be more complicated than expected. The IA-64 bundle size is 16 bytes, but load and store instructions only operate on a maximum of 8 bytes. This means that two store instructions are necessary to update a bundle. In multithreaded applications, there are two potentially hazardous scenarios. It is possible that a thread could hit a bundle while being in the middle of it's update process, thus executing a half-deployed instruction with an invalid instruction template field, which will result in a signal. Or, a thread could have been stalled on slot 1 or slot 2 of a bundle, waking up on a changed instruction, again resulting in incorrect program behavior.

The latter scenario has been solved in HP Caliper using a sequence of update steps. The first problem requires the installation of a signal handler for invalid template exceptions. This has not been implemented yet.

To date, HP Caliper simply halts all threads in the target application while performing an instruction update. While guaranteeing correct program behavior, this method slows down execution speed, especially on multi-processor systems. For this reason it will later be changed to a method with full support for multithreading.

The IA-64 supports call shadows where two branches are located in one bundle as in this example:

```
     nop.m      0
(p6) br.call.dptk.few  .-0x150
     br.call.sptk.few  .-0x410;; // shadowed
```

If the predicate register p6 is set to 1 then the first branch instruction is executed. Since branch targets and return address are always full bundle addresses on the IA-64, the second branch will never be executed.

If this instruction sequence is instrumented and counting code is inserted, then the original instructions get dispersed across multiple bundles, changing the implicit logic of the call shadow that supressed the second branch. Thus, HP Caliper performs an additional search for call shadows and alters the instrumentation sequences accordingly.

Break instructions are used in a similar, but conflicting way by both HP Caliper and debuggers, making it impossible to debug a HP Caliper-controlled application. Therefore we integrated debugging functionality into HP Caliper and named the driver for this functionality cdb (Caliper Debugger). This feature became invaluable for identifying program flaws, invalid probe code sequences, kernel bugs and forgotten stop bits all over the instrumented code.

Cdb makes use of the integrated Python interpreter to display a prompt, to parse commands, and to perform actions accordingly. It supports insertion of break points, single stepping, disassembly of original and instrumented code, dumping of data and registers, and more. HP Caliper allows falling back to a cdb prompt whenever an unexpected situation or signal occurs.

Scripting languages such as Python typically have powerful support for socket communications of some kind. It was easy for us to offer a remote interface to cdb. This proved to be valuable during debugging of applications which expect input from stdin via redirection. The implementation of this remote functionality is concise and simple.

HP Caliper also has some limitations. Instrumentation does not work with dynamically generated code, with programs that internally change between little-endian and big-endian or with programs that use IP-aware signal handlers. It is also possible to create assembler code sequences where instrumentation will fail, for example code performing label arithmetic. However, such sequences are rarely used, if at all.

At the time of this writing, HP Caliper is able to successfully instrument the first ten Spec2000 benchmark programs (164.gzip, 175.vpr, 181.mcf, 197.parser, 168.wupwise and more) to perform function coverage analysis, function counting and arc counting on IP-relative call branches as well as hazard checking for predicates

4.3 Case Study: Predicate Hazard Checking

Predicate hazard checking is an interesting application of the HP Caliper framework and is presented here as a case study.

The HP compiler optimization group developed an algorithm where instructions are placed in the same issue group, although they may have a resource conflict, as in the following bundle with a read-after-write conflict:

```
      nop.m
(p35) addl  r14=0x40784634,r0  // write r14
(p36) ld4.s r15=[r14]          // read  r14
```

The instructions, however, are predicated. If it can be guaranteed that the predicates are never 1 at the same time, then this is a powerful optimization technique.

In order to verify the algorithm, the optimization group uses a static tool to read in ELF executables and to output potential hazards as tuples <hazard address, predicate register, predicate register>. Hundreds and thousands of potential hazards are indicated by the static tool. This information is then manually checked against disassembled code and run through other static analyzers.

Still, there had to be some form of dynamic verification. If one single occurring hazard was found, it was proven that the algorithm had a flaw for a given input stream.

In order to support our compiler optimization team, we wrote a collector which reads in the output of the static hazard analyzer and instruments functions containing potential hazards. The probe code sequences check whether or not two indicated predicate registers are both set to one at a questionable address and increase a counter for this hazardous case. If a single counter has a value of one or greater, an actual hazard has been found.

Implementing this collector was a straightforward operation, because all major building blocks like counter management, function discovery, probe code generation, insertion and handling of break instruction were already in place. The tasks to perform for hazard checking were more or less to define an input format and reader for the hazard file and the layout and implementation of the probe code sequences. We have been able to identify hazards and helped the optimizer group to improve their algorithms.

5. Future Work

HP Caliper will be ported to Linux on IA64 processors and to HP-UX on PA-RISC.

What are the IA-64 specific features used by HP Caliper that will complicate porting it to PA-RISC? The ISA of both processors is fairly similar and the success of HP's Aries emulator running PA-RISC applications on IA-64 demonstrates this. There are however two main problem areas:

- There is no PMU or equivalent hardware on PA-RISC. It is therefore expected that HP Caliper for PA-RISC will focus on binary code instrumentation.
- HP Caliper exploits two instructions unique to the IA-64, the long branch instruction `brl` and the memory access synchronizing `fetchadd` instruction for counter updates. For both instructions there is no equivalent on PA-RISC,

and workarounds for their usage must be developed.

No problems caused by operating system dependencies are expected. Although the debug and perfmon interfaces of HP-UX and Linux differ, their capabilities are both similar and powerful enough to allow HP Caliper to be ported

In order to fully support analysis of C++ programs making use of exceptions, the dynamic updating of unwind information will be developed soon.

An optional *Caliper Agent* above the Caliper API is under development. This agent routes API calls between the developer tool and the HP Caliper shared object, enabling a HP Caliper for distributed systems. The agent uses remote procedure calls (RPC) based on code generated from Caliper's API header files.

More tools will be developed on top of the instrumentation framework. In particular, these will include basic block related tools and API checkers such as a memory leak detection tool and a pthread correctness checker. Caliper's design will also change slightly to enable dynamic loading of collectors.

One of the more interesting challenges for the future is dynamic code transformation, e.g., optimization. Light-weight sampling will identify hot traces and dynamic instrumentation will optimize a program using this information. The optimizations may further adapt themselves as the characteristics of input data sets change.

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