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A PORTABLE PROGRAMMING INTERFACE FOR PERFORMANCE EVALUATION ON MODERN PROCESSORS

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Summary

The purpose of the PAPI project is to specify a standard application programming interface (API) for accessing hardware performance counters available on most modern microprocessors. These counters exist as a small set of registers that count events, which are occurrences of specific signals and states related to the processor's function. Monitoring these events facilitates correlation between the structure of source/object code and the efficiency of the mapping of that code to the underlying architecture. This correlation has a variety of uses in performance analysis, including hand tuning, compiler optimization, debugging, benchmarking, monitoring, and performance modeling. In addition, it is hoped that this information will prove useful in the development of new compilation technology as well as in steering architectural development toward alleviating commonly occurring bottlenecks in high performance computing.

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1 Introduction

For years, collecting performance data on applications programs has been an imprecise art. The user has had to rely on timers with poor resolution or granularity, imprecise empirical information on the number of operations performed in the program in question, vague information on the effects of the memory hierarchy, and so on. Today, hardware counters exist on every major processor platform. These counters can provide application developers valuable information about the performance of critical parts of the application and point to ways for improving the performance. Performance tool developers can use these hardware counters to develop tools and interfaces that users can insert into their applications. The current problem facing tool developers is that access to these counters is poorly documented, unstable, or unavailable to the user-level program. The focus of PAPI is to provide an easy-to-use, common set of interfaces that will gain access to these performance counters on all major processor platforms, thereby providing application developers the information they may need to tune their software on different platforms. Our goals are to make it easy for users to gain access to the counters to aid in performance analysis, modeling, and tuning.

PAPI provides two interfaces to the underlying counter hardware: a simple, high-level interface for the acquisition of simple measurements and a fully programmable, thread-safe, low-level interface directed toward users with more sophisticated needs. The low-level interface manages hardware events in user-defined groups called EventSet. The high-level interface simply provides the ability to start, stop, and read the counters for a specified list of events. PAPI attempts to provide portability across operating systems and architectures wherever possible and whenever reasonable to do so. PAPI includes a predefined set of events meant to represent a lowest common denominator of a "good" counter implementation, the intent being that the same tool would count similar and possibly comparable events when run on different platforms. If the programmer chooses to use this set of standardized events, then the source code need not be changed, and only a recompile is necessary. However, should the developer wish to access machine-specific events, the low-level application programming interface (API) provides access to all available native events and counting modes.

In addition to raw counter access, PAPI provides the more sophisticated functionality of user callbacks on counter overflow and hardware-based SVR4 compatible profiling, regardless of whether the operating system sup-

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ports it. These features provide the necessary basis for any source-level performance analysis software. Thus, for any architecture with even the most rudimentary access to hardware performance counters, PAPI provides the foundation for truly portable, source-level performance analysis tools based on real processor statistics.

2 Discussion of PAPI Metrics

Through interaction with the high performance computing community, including vendors and users, the PAPI developers have chosen a set of hardware events deemed relevant and useful in tuning application performance. This section provides justification for the choice of the PAPI predefined events and discusses how performance data collected about these events can be used to optimize the performance of applications. The complete list of PAPI predefined events can be found in the appendix. These events may differ in their actual semantics on different platforms, and all events may not be present on all platforms. However, it is hoped that most of these events will be made available in the future on all major HPC platforms to improve the capability for tuning applications across multiple platforms. The predefined events include access to the memory hierarchy, cache coherence protocol events, cycle and instruction counts, and functional unit and pipeline status. Each of these areas is discussed in greater detail below, along with a discussion of how the metrics in each area relate to application performance tuning. Background on architectural issues discussed in this section can be found in Brehob et al. (1996) and Hennessy and Patterson (1996).

Because modern microprocessors have multiple levels in the memory hierarchy, optimizations that improve memory use can have major effects on performance. Levels of the memory hierarchy range from small, fast register memory to larger, slower levels of cache memory to still larger and slower main memory. Different levels of cache memory may have separate instruction and data caches or may consist of a unified cache that buffers both instructions and data in the same cache. Most modern microprocessors have two levels of cache, although some now have three levels (e.g., three levels are optional with the Compaq EV5 and EV6 architectures). A load or store instruction generates a memory-addressing process that first attempts to locate the addressed memory item in the L1 cache. If the item is present in the L1 cache, the result is an L1 cache hit. If the item is not present, the result is an L1 cache miss, and an attempt is next made to locate the item in the L2 cache, with the result being an L2 cache hit or

miss. The operating system uses main memory as a cache for a larger virtual address space for each process and translates between virtual addresses used by a program and the physical addresses required by the hardware. Memory is divided into blocks called pages. To keep the overhead of address translation low, the most recently used page addresses are cached in a translation lookaside buffer (TLB). When a program references a virtual address that is not cached in the TLB, a TLB miss occurs. If, in addition, the referenced page is not present in main memory, a page fault occurs. The latency of data access becomes greater with each level of the memory hierarchy, with a miss at each level multiplying the latency by an order of magnitude or more. For example, the latencies to different levels of the memory hierarchy for the MIPS R10000 process in the SGI/Cray Origin 2000 are shown in Table 1 (Cortesi, 1998).

The L1 and L2 cache hit rates indicate how cache-friendly a program is, and these rates can be derived from PAPI metrics. The L1 data cache hit rate is calculated as

$$1.0 - (\text{PAPI_L1_DCM} / (\text{PAPI_LD_INS} + \text{PAPI_SR_INS})).$$

The L2 data cache hit rate is calculated as

$$1.0 - (\text{PAPI_L2_DCM} / \text{PAPI_L1_DCM}).$$

Values of 0.95 or better for these hit rates indicate good cache performance.

The PAPI metrics for level 1 and level 2 load-and-store misses (PAPI_L1_LDM, PAPI_L1_STM, PAPI_L2_LDM, PAPI_L2_STM) can provide information on the relative read-and-write cache performance.

A large number of data TLB misses (PAPI_TLB_DM) indicates TLB thrashing, which occurs when data being accessed are spread over too many pages and TLB cache reuse is poor. TLB thrashing can be fixed by using cache blocking or data copying or, when supported by the operating system, telling the operating system to use larger page sizes.

For SMP environments, PAPI assumes a four-state MESI cache coherence protocol (possible states: modified, exclusive, shared, and invalid). In a cache-coherent SMP, the system signals to a CPU when the CPU needs to maintain the coherence of cache data. An intervention is a signal stating that some other CPU wants to use data from a cache line that the CPU receiving the signal has a copy of. The other CPU requests the status of the cache line and requests a copy of the line if it is not the same as memory. An invalidation is a signal that another CPU has modified a cache line that this CPU has in its cache and that this CPU needs to discard its copy. A high number of cache line in-

Table 1
Latencies to Different Levels of the
Memory Hierarchy for the MIPS R10000
Processor in the SGI/Cray Origin 2000

CPU register	0 cycles
L1 cache hit	2 or 3 cycles
L1 cache miss satisfied by L2 cache hit	8 to 10 cycles
L2 cache miss satisfied from main memory, no translation lookaside buffer (TLB) miss	75 to 250 cycles
TLB miss requiring only reload of TLB	2000 cycles
TLB miss requiring virtual page to be loaded from backing store	Hundreds of millions of cycles

validations (PAPI_CA_INV) is an indicator of cache contention. The CPU that produces the high count is being slowed because it is using data being updated by a different CPU. The CPU doing the updating will be generating a high number of PAPI_CA_SHR events. Thus, a large number of PAPI_CA_SHR events also indicates that the program is being slowed by memory contention for shared cache lines. In an SMP, each processor has its own TLB, but page tables may be shared. If a processor changes a page table entry that another processor may be using, the first processor must force the second processor to flush its TLB. This notification that a page table entry has changed is called a translation lookaside buffer shutdown (PAPI_TLB_SD). A large number of PAPI_TLB_SD events indicates memory contention for the same page table entries.

PAPI metrics include counts of the various types of instructions completed, including integer, floating point, load, and store instructions. Because floating-point operations may be undercounted due to counting a floating-point multiply add (FMA) as a single instruction, a separate count of FMA instructions completed (PAPI_FMA_INS) has been included so that the floating-point operation count can be adjusted accordingly if necessary.

The store-conditional instruction is used to implement various kinds of mutual exclusion, such as locks and semaphores. Store conditionals (PAPI_CSR_TOT) should never be a significant portion of program execution time. A small proportion of failed store-conditional instructions (PAPI_CSR_FAL) is to be expected when asynchronous threads use mutual exclusion. However, more than a small proportion indicates some kind of contention or false sharing involving mutual exclusion between asynchronous threads. Other types of synchronization instructions, such as fetch and increment, are included under the count for synchronization instructions completed (PAPI_SYC_INS).

A high number of synchronization instructions may indicate an inefficient algorithm.

Pipelining is used to make CPUs faster by overlapping the execution of multiple instructions, thus reducing the number of clock cycles per instruction. The overlap among instructions is called instruction-level parallelism. Superscalar processors can issue multiple instructions per clock cycle and thus depend on a variety of static and dynamic instruction scheduling techniques to maximize processor throughput. These techniques include software optimizations such as software pipelining, loop unrolling, and intraprocedural analysis in addition to post-RISC architectural changes such as speculative execution, branch

prediction, and VLIW with predication. The net result is that while pipelining is implemented in hardware, its full benefit can only be realized through appropriately designed software. A stall occurs when an instruction in the pipeline is prevented from executing during its designated clock cycle. Stalls cause the pipeline performance to degrade from the ideal performance. Stalls may occur because of resource conflicts when the hardware cannot support all possible combinations of instructions in the overlapped execution, because of data or control dependencies, or because of waiting for access to memory.

PAPI includes events for measuring how heavily the different functional units are being used (PAPI_BRU_IDL, PAPI_FXU_IDL, PAPI_FPU_IDL, PAPI_LSU_IDL). A functional unit is idle if it has no work to do, as opposed to being stalled if it has work to do but cannot because of any variety of reasons. Data for these events provide information about the “mix” of operations in the code. Several of the PAPI metrics allow detection of when and why pipeline stalls are occurring (PAPI_MEM_SCY, PAPI_STL_CYC, PAPI_STL_CCY, PAPI_FP_STAL). Because pipelining is, for the most part, beyond the control of the application programmer, the PAPI metrics relevant to pipelining are mainly intended to provide performance data relevant to compiler writers (e.g., for use in compiler feedback loops). However, the application programmer may be able to use pipeline performance data, together with compiler output files, to restructure code application code so as to allow the compiler to do a better job of software pipelining. The application programmer may also find it useful to look at pipelining performance data when experimenting with different compiler options.

Letting an instruction move from the instruction decode stage of the pipeline into the execution stage is called instruction issue. An instruction is completed once all logically previous instructions have completed, and only then is its result added to the visible state of the CPU. Because of speculative execution, a mispredicted branch can cause instructions that have been executed, but not completed, to be discarded. Resource contention can cause instructions to be issued more than once before being completed. Normally, branch mispredictions and reissues are rare, and the number of issued instructions (PAPI_TOT_IIS) should correspond fairly closely to the number completed (PAPI_TOT_INS). A high number of mispredicted branches (PAPI_BR_MSP) indicates that something is wrong with the compiler options or that something is unusual about the algorithm. If the number of issued instructions greatly exceeds the number completed, and the count of mispredicted branches remains low, then the

load/store pipeline is likely experiencing resource contention, causing load-and-store instructions to be issued repeatedly.

Ratios derived from a combination of hardware events can sometimes provide more useful information than raw metrics. Two ratios, defined as PAPI metrics, are floating-point operations completed per second (PAPI_FLOPS) and total instructions completed per second (PAPI_IPS). Another useful ratio is completed operations per cycle (PAPI_TOT_INS/PAPI_TOT_CYC). A low value for this ratio indicates that the processor is stalling frequently. The typical value for this ratio will depend on the underlying processor architecture. The ratio of completed loads and stores per cycle (PAPI_LST_INS/PAPI_TOT_CYC) indicates the relative density of memory access in the program. The ratio of floating operations completed per cycle (PAPI_FP_INS/PAPI_TOT_CYC) indicates the relative density of floating-point operations.

3 Design

3.1 LAYERED ARCHITECTURE

The PAPI architecture uses a layered approach, as shown in Figure 1. Internally, the PAPI implementation is split into portable and machine-dependent layers. The topmost portable layer consists of the high- and low-level PAPI interfaces. This layer is completely machine independent and requires little porting effort. It contains all of the API functions as well as numerous utility functions that perform state handling, memory management, data structure manipulation, and thread safety. In addition, this layer provides advanced functionality not always provided by the operating system—namely, event profiling and overflow handling. On the other hand, the high-level interface provides a very simple and primitive interface to control and access the hardware counters. The target audience for the high-level interface is application engineers and benchmarking teams looking to quickly and simply acquire some rudimentary application metrics. The tool designer will likely find the high-level interface too restrictive. The portable layer calls the substrate, the internal PAPI layer that handles the machine-dependent portions of accessing the counters. The substrate is free to use whatever methods deemed appropriate to facilitate counter access, whether that be register-level operations (T3E), customized system calls (Linux/x86), or calls to another library (AIX 4.3). The substrate interface and functionality are well defined, leaving most of the code free from conditional compilation directives. For each architecture/operating system pair, only

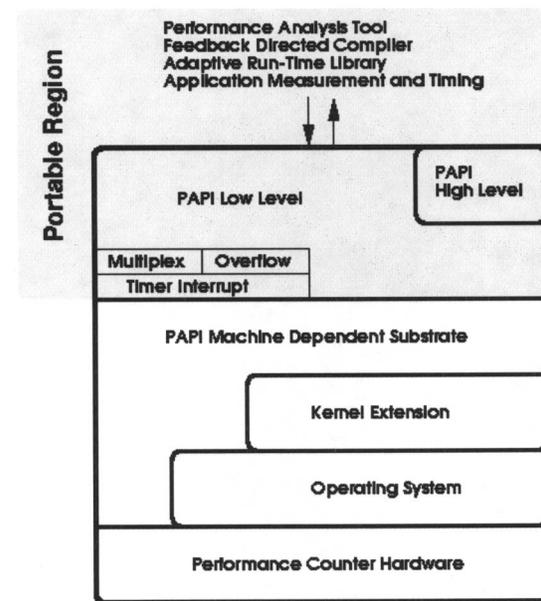


Fig. 1 PAPI architecture

“PAPI implements as many presets as possible on a given platform without providing misleading or erroneous results. Providing such a classification can cause problems for the naive user, especially when results for the same event are compared between systems.”

a new substrate layer needs to be written. Experience indicates that no more than a week is required to generate a fully functional substrate for a new platform, if the operating system provides the necessary support for accessing the hardware counters.

3.2 PORTABILITY

While the API addresses source code portability through an interface, it does nothing to address the difficulty in decoding the machine-specific settings for the performance monitor control hardware. As a proposed solution, PAPI includes 64 predefined events, called presets, that are representative of most major RISC-like events. The complete list of presets can be found in the appendix. PAPI implements as many presets as possible on a given platform without providing misleading or erroneous results. Providing such a classification can cause problems for the naive user, especially when results for the same event are compared between systems. Direct comparison between systems is not the intention of the PAPI presets. Rather, the intention is to standardize the names for the metrics, not the semantics of those names. Thus, the user must still have a working knowledge about the processor under study to make sense of the performance data.

3.3 EVENTSETS

PAPI provides an abstraction from particular hardware events called EventSets. An EventSet consists of events that the user wishes to count as a group. There are two reasons for this abstraction. The first reason is efficiency in accessing the counters through the operating system. Most operating systems allow the programmer to move the counter values in bulk without having to make a separate system call for each counter. By exposing this grouping to the user, the PAPI library can greatly reduce its overhead when accessing the counters. This efficiency is especially important when PAPI is used to measure small regions of code inside loops with large iteration counts. The second reason for EventSets is that users can evolve their own specialized counter groupings specific to their application areas. In practice, most users have an understandably difficult time relating a single counter value to the performance of the region of code under study. More often than not, the relevant performance information is obtained by relating different metrics to one another. For example, the ratio of loads to level 1 cache misses is often the dominant performance indicator in dense numerical kernels.

EventSets are managed by the user through the use of integer handles, which helps simplify interlanguage-calling

interfaces. The use of EventSets has been freed from as many programming restrictions as possible. The user is free to allocate and use any number of them as long as the substrate can provide the required resources. Multiple EventSets may be used simultaneously and may share counters. If the user tries to add more events to an EventSet than are simultaneously countable on the underlying platform, PAPI returns an appropriate error code, unless the user has explicitly enabled software multiplexing. PAPI also returns an error code if the user attempts to use an EventSet that is not in the proper state.

3.4 MULTIPLEXING

Most modern microprocessors have a very limited number of events that can be counted simultaneously. This limitation severely restricts the amount of performance information that the user can gather during a single run. As a result, large applications with many hours of runtime may require days or weeks of profiling to gather enough information on which to base a performance analysis. This limitation can be overcome by multiplexing the counter hardware. By subdividing the usage of the counter hardware over time, multiplexing presents the user with the view that many more hardware events are countable simultaneously. This unavoidably incurs a small amount of overhead and can adversely affect the accuracy of reported counter values. Nevertheless, multiplexing has proven useful in commercial kernel-level performance counter interfaces, such as SGI's IRIX 6.x. Hence, on platforms in which the operating system or kernel-level counter interface does not support multiplexing, PAPI plans to provide the capability to multiplex through the use of a high-resolution interval timer. To prevent naive use of multiplexing by the novice user, the high-level API can only access those events countable simultaneously by the underlying hardware, unless a low-level call has been used to explicitly enable multiplexing.

3.5 USER CALLBACKS ON THRESHOLD

One of the most significant features of PAPI for the tool writer is its ability to call user-defined handlers when a particular hardware event exceeds a specified threshold.

This is accomplished by setting up a high-resolution interval timer and installing a timer interrupt handler. For systems that do not support counter overflow at the operating system level, PAPI uses SIGPROF and ITIMER_PROF. PAPI handles the signal by comparing the current counter value against the threshold. If the current value

exceeds the threshold, then the user's handler is called from within the signal context with some additional arguments. These arguments allow the user to determine which event overflowed, how much it overflowed, and at what location in the source code.

Using the same mechanism as for user-programmable overflow handling, PAPI also guards against register overflow of counter values. Each counter can potentially be incremented multiple times during a single clock cycle. This fact, combined with increasing clock speeds and the small precision of some physical counters, means that counter overflow is likely to occur on platforms in which 64-bit counters are not supported in hardware or by the operating system. For such cases, PAPI implements 64-bit counters in software using the same mechanism as for user-specified overflow dispatch.

3.6 STATISTICAL PROFILING

Statistical profiling is built on the above method of installing and emulating arbitrary callbacks on overflow. Profiling works as follows: when an event exceeds a threshold, a signal is delivered with a number of arguments. Among those arguments is the interrupted thread's stack pointer and register set. The register set contains the program counter, the address at which the process was interrupted when the signal was delivered. Performance tools such as UNIX `prof` extract this address and hash the value into a histogram. At program completion, the histogram is analyzed and associated with symbolic information contained in the executable. What results is a line-by-line account of where counter overflow occurred in the program. GNU `prof`, in conjunction with the `-p` option of the GCC compiler, performs exactly this analysis using process time as the overflow trigger. PAPI aims to generalize this functionality so that a histogram can be generated using any countable event as the basis for analysis.

PAPI provides support for execution profiling based on any counter event. The `PAPI_profil()` call creates a histogram of overflow counts for a specified region of the application code. In the exact manner of UNIX `profil()`, the identified region is logically broken up into equal-size subdivisions. Each time the counter reaches the specified threshold, the current subdivision is identified, and its corresponding hash bucket is incremented.

Because the overflow process is emulated at a relatively coarse grain, PAPI runs the risk of falsely identifying regions of code as the cause of large numbers of overflows. To alleviate some of these problems, the developers of PAPI are experimenting with a variety of

statistical methods to recover additional useful data, including range compression of the histogram, randomization of the timer interval, and weighting of the increments.

3.7 THREAD SUPPORT

As very large SMPs become ever more popular in the HPC community, fully thread-aware performance tools are becoming a necessity. This necessity presents a significant challenge to the PAPI development team, due largely to the variety of thread packages. As with any API, the interface must be reentrant because any number of threads may simultaneously call the same PAPI function. This means that any globally writeable structures must be locked while in use. This requirement has the potential of increasing overhead and introducing large sections of machine-dependent code to the top layer. PAPI has only one global data structure, which keeps track of processwide PAPI options and thread-specific pointer maps. Fortunately, this structure is only written by two API calls that are almost exclusively used during the initialization and termination of threads and the PAPI library.

A second problem is the accuracy of event counts as returned by threads calling the API. To support threaded operation, the operating system must save and restore the counter hardware on context switches among different threads or processes. The PAPI library must keep thread-specific copies of the counter data structures and values. In addition, the PAPI library detects existing or new threads when they call a PAPI function and initializes the necessary thread-specific data structures at that time. There are some threading APIs that hide the concept of user- and kernel-level threads from the user. Pthreads and OpenMP are the most striking examples. As a result, unless the user explicitly binds his or her thread to a kernel thread (sometimes called a lightweight process, or LWP), the counts returned by PAPI may not necessarily be accurate. Pthreads permit any "Pthread" to run on any LWP unless previously bound. Unbound user-level threads that call PAPI will most likely return unreliable or inaccurate event counts. Fortunately, in the batch environments of the HPC community, there is no significant advantage to user-level threads, and thus kernel-level threads are the default. For situations in which this is not the case, PAPI developers have plans to incorporate simple routines to facilitate binding by the user.

3.8 ACCURACY OF PERFORMANCE COUNTER DATA

Although PAPI attempts to introduce as little overhead as possible and thus perturb application performance to only

a minor degree, some perturbation is inevitable and has yet to be measured. Counts produced for various PAPI metrics may vary from one run to another of the same program on the same inputs on some architectures, due to contention for resources with other applications or the operating system. The vendor-provided counter interfaces may occasionally have bugs that cause inaccurate reporting of hardware counter data. More study is needed to determine the accuracy of performance counter data measured by PAPI. With its portable interface to hardware counters, PAPI actually provides a good framework for conducting statistical studies of the reliability and consistency of these data.

4 Performance Counter Implementations

4.1 PENTIUM PRO/II/III ON LINUX v2.0, v2.2

This platform was the first one targeted for a variety of reasons, including access to the kernel source code and the simplicity of the counters. The counters on the Pentium Pro and Pentium II/III are one 64-bit cycle counter and two 40-bit general-purpose counters. The Pentium Pro and Pentium II/III have identical counter sizes and event codes.

Erik Hendriks had written a performance counter kernel extension for *Beowulf* that provided an excellent framework on which to hang additional functionality. Some of the features added to the kernel patch include the ability to reset the cycle counter, faster configuration and access, process/thread inheritance, and support for Linux kernel versions outside the main tree.

4.2 SGI/MIPS R10000/R12000 ON IRIX 6.x

This platform has one of the best vendor-provided counter interfaces, and the counter interface is well documented. PAPI chose to implement the IRIX substrate using the `ioctl()` interface to the `/proc` file system. There are several advantages to the SGI platform that made some aspects of PAPI easier to implement, such as kernel-level multiplexing and internally supported overflow handling. The MIPS R10000 and R12000 have two 32-bit counters that support a total of 31 different events. For PAPI, there were two main problems with this platform. The first problem was that there is no way to write to the counters, which means that PAPI cannot reset the counters by zeroing them. This API routine was therefore implemented in the substrate by emulating zeroing of the counters through bookkeeping. The second problem is that a pro-

cess may have access to the counters taken from it by the kernel. Once a process has acquired the counters, the same process may not reacquire them. When access to the counters has been given to another process, the values cannot be trusted, and the process should be restarted. PAPI will detect a change in counter ownership and will exit with an error message.

4.3 IBM POWER 604/604e/630 ON AIX 4.3

The IBM 604/604e/630 substrate is built over the *pmtoolkit*, which is a proprietary kernel extension for AIX 4.3 that supports a system and kernel thread performance monitor API (Smolders, 1999). *pmtoolkit* adds support to AIX for optional performance monitor (PM) contexts that are extensions of the regular processor and thread contexts and include one 64-bit counter per hardware counter and a set of control words. The control words define what events get counted and when counting is on or off. The November 1999 release of the *pmtoolkit* includes event tables for the 604, 604e, 630, and 630+. The 604 has two counters, the 604e has four counters, and the 630 and 630+ processors both have eight counters. Architectural issues for the IBM POWER3, which uses the 630 processor, may be found in Andersson et al. (1998).

4.4 COMPAQ ALPHA EV4/5/6 ON TRU64 UNIX

The pfm pseudo-device is the interface to the Alpha on-chip performance counters under Tru64 Unix. The interface consists of a set of `ioctl()` calls. The Tru64 kernel must be rebuilt to configure the pfm pseudo-device into it. The EV4 CPU (21064, 21064A, 21066, and 21068 processors) has two counters. The EV5 (21164, 21164A, 21164PC) has three counters. The EV6 (21164) has two counters. The EV4, EV5, and EV6 counters can be independently programmed. The EV67 counters are not completely independent. Any one statistic may be selected, or one of the following pairs may be selected: (cycles0, replay), (retinst, cycles1), or (retinst, bcachemisses).

4.5 CRAY T3E, EV5 ON UNICOS/MK

The T3E contains a large number of modified EV5 processors arranged in a three-dimensional torus. Each processor in the system runs a slimmed-down version of the operating system Unicos/mk, a derivative of the Mach microkernel. Access to the EV5's three performance counters is achieved through customized assembly routines provided by SGI/Cray. These routines make calls to the PAL code, microcode set up by the manufacturer to

handle low-level operations. While this interface is very small, it is programmable enough to support the necessary functionality in PAPI. The main problem on the T3E is that the performance registers are not accumulated by the PAL code into 64-bit quantities, and thus this accumulation must be performed by PAPI. Furthermore, the Unicos/mk scheduler may migrate a job to another CPU. In that case, PAPI's only valid course of action is to detect the fault and inform the user.

5 Tools

5.1 DISPLAY OF PAPI PERFORMANCE DATA

The PAPI project has developed two tools that demonstrate graphical display of PAPI performance data in a manner useful to the application developer. These tools are meant to demonstrate the capabilities of PAPI rather than as production quality tools. The tool front ends are written in Java and can be run on a separate machine from the program being monitored. All that is required for real-time monitoring and display of application performance is a socket connection between the machines.

The first tool, called the *perfometer*, provides a runtime trace of a chosen PAPI metric, as shown in Figure 2 for floating operations per second (PAPI_FLOPS). This particular example illustrates how calls to PAPI routines at the beginnings and ends of procedures can provide information about the relative floating-point performance of those procedures. The same display can be generated for any of the PAPI metrics. For example, Figure 3 shows a display of the L1 cache hit rate.

The second tool, called the *profometer*, provides a histogram that relates the occurrences of a chosen PAPI event to text addresses in the program, as shown in Figure 4 for L1 data cache misses. Again, the same display can be generated for any of the PAPI metrics. Future plans are to develop the capability of relating the frequency of events to source code locations, allowing the application developer to quickly locate portions of the program that are the source of performance problems.

5.2 INTEGRATION WITH OTHER TOOLS

Visual Profiler, or *vprof*, is a tool developed at Sandia National Laboratory for collecting statistical program counter data and graphically viewing the results on Linux Intel machines (Janssen, 1999). *vprof* uses statistical event sampling to provide line-by-line execution profiling of source code. *vprof* can sample clock ticks using the `profil` system call. The *vprof* developer has added support for

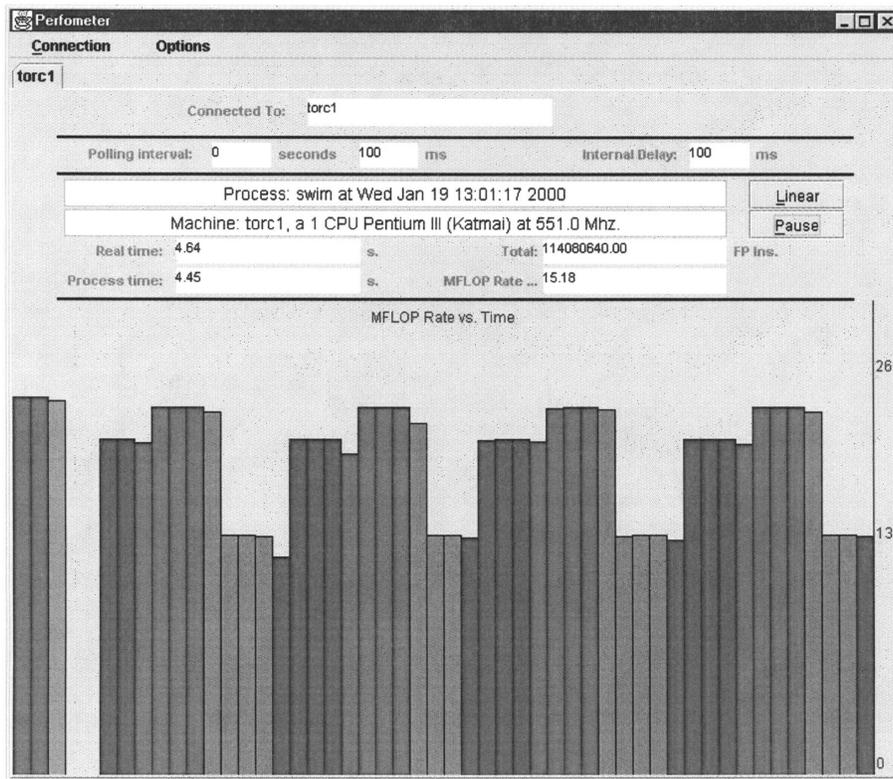


Fig. 2 Perfometer displaying Mflops

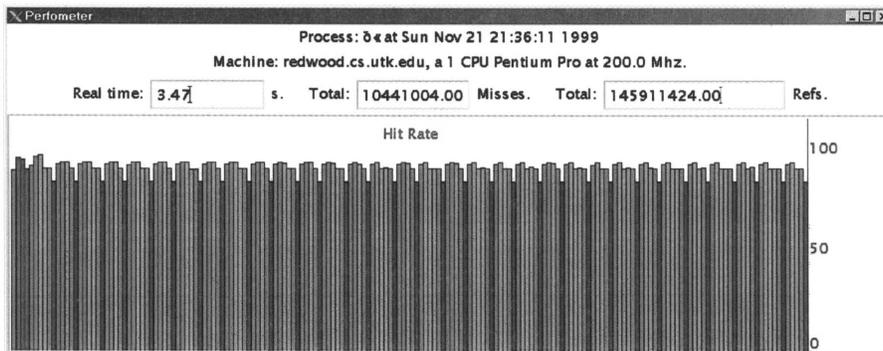


Fig. 3 Perfometer displaying the L1 cache hit rate

PAPI so that vprof can also sample the wide range of system events supported by PAPI. A screenshot showing vprof examination of both profil and PAPI_TOT_CYC data is shown in Figure 5.

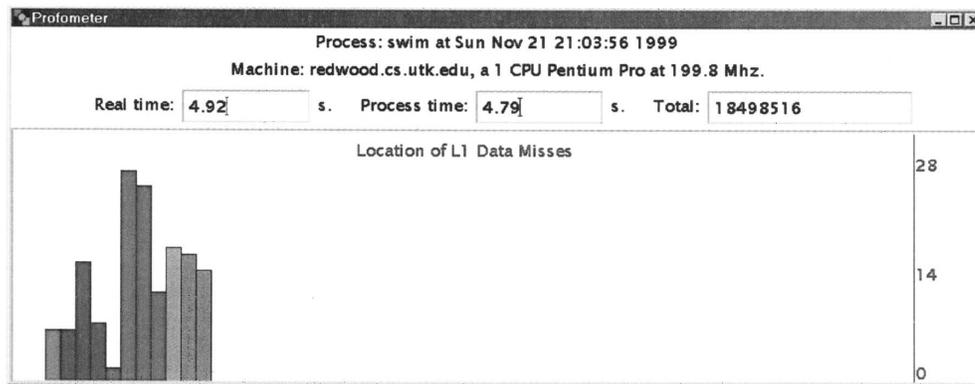


Fig. 4 Profometer display L1 data cache misses

SvPablo is a graphical source code browser and performance visualizer that has been developed as part of the University of Illinois's Pablo project (DeRose and Reed, 1999; DeRose, Zhang, and Reed, 1998). SvPablo supports automatic instrumentation of HPF codes with Portland Group's HPF compiler and interactive instrumentation of C and Fortran programs. During execution of an instrumented code, the SvPablo library maintains statistics on the execution of each instrumented event on each processor and maps these statistics to constructs in the original source code. The current version of SvPablo includes support for the MIPS R10000 hardware performance counters. The next version of SvPablo, being developed at the IBM Advanced Computing Technology Center, has integrated support for PAPI. Screenshots of SvPablo displays of PAPI metrics are shown in Figures 6 and 7.

DEEP, from Pacific-Sierra Research, stands for development environment for parallel programs. DEEP provides an integrated interactive GUI interface that binds performance, analysis, and debugging tools back to the original parallel source code. DEEP supports Fortran 77/90/95, C, and mixed Fortran and C in Unix and Windows 95/98/NT environments. DEEP supports both shared-memory (automatic parallelization, OpenMP) and distributed-memory (MPI, HPF, Data Parallel C) parallel program development. A special version of DEEP, called DEEP/MPI, is aimed at support of MPI programs. DEEP provides a graphical user interface for program structure browsing, profiling analysis, and relating profiling results to source code. DEEP developers are incorporating sup-

“During execution of an instrumented code, the SvPablo library maintains statistics on the execution of each instrumented event on each processor and maps these statistics to constructs in the original source code.”

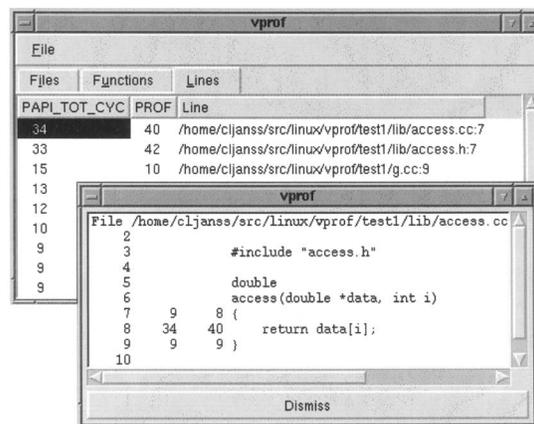


Fig. 5 vprof displaying profil and PAPI_TOT_CYC data

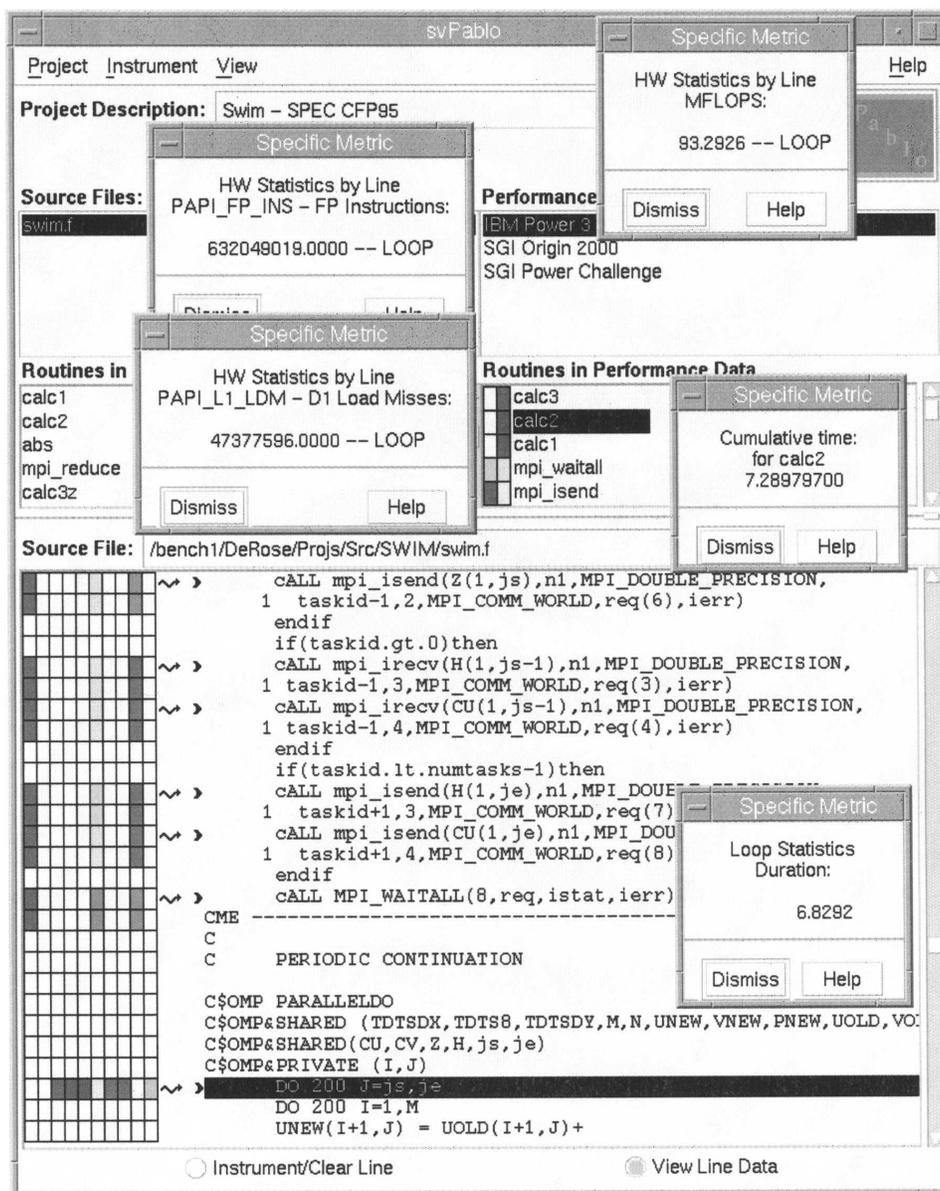


Fig. 6 SvPablo source code browser displaying PAPI metrics

port for PAPI so that statistics for the standard PAPI metrics can be viewed and analyzed from the DEEP interface. A screenshot of the DEEP/MPI interface displaying PAPI data for L2 cache misses is shown in Figure 8.

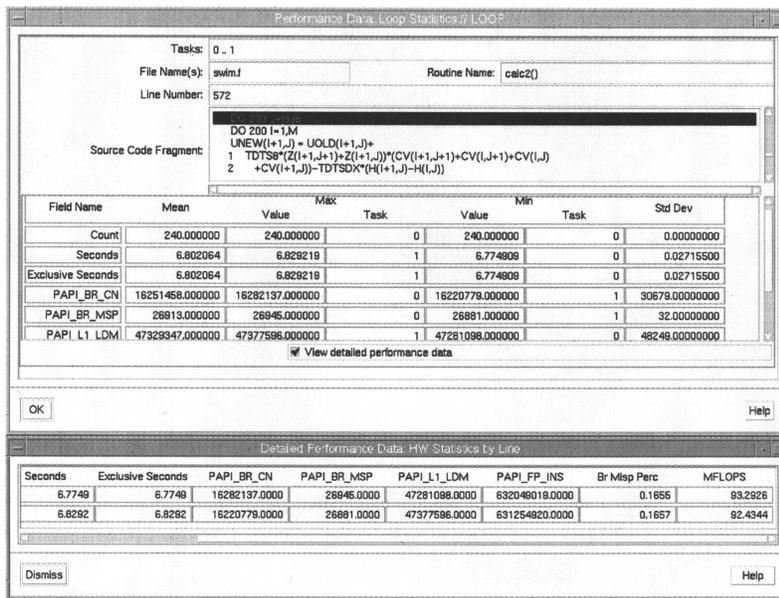


Fig. 7 SvPablo statistics displays showing PAPI data

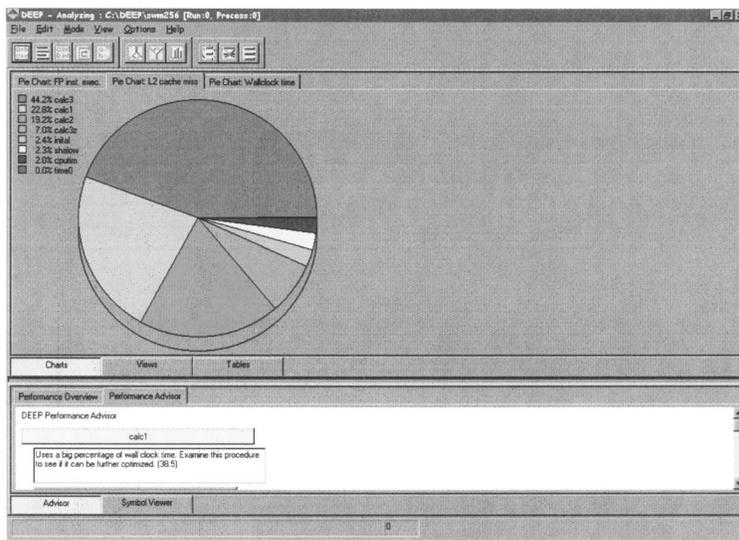


Fig. 8 DEEP/MPI displaying PAPI data for L2 cache misses

6 Related Work

6.1 PERFORMANCE COUNTER LIBRARY

The Performance Counter Library (PCL) is a common interface for accessing performance counters built into mod-

ern microprocessors in a portable way (Berrendorf and Ziegler). PCL supports query for functionality, start and stop of counters, and reading the current values of counters. Performance counter values are returned as 64-bit integers on all supported platforms. Performance counting can be down in user mode, system mode, or user-or-system mode. PCL supports nested calls to PCL functions to allow hierarchical performance measurements. However, nested calls must use exactly the same list of events. PCL functions are callable from C, C++, Fortran, and Java. Similar to PAPI, PCL defines a common set of events across platforms for access to the memory hierarchy, cycle and instruction counts, and the status of functional units, and it translates these into native events on a given platform when possible. In addition, PAPI defines events related to SMP cache coherence protocols and to cycles stalled waiting for memory access. Unlike PAPI, PCL does not support software multiplexing or user-defined overflow handling. The PCL API is very similar to the PAPI high-level API and consists of calls to start a list of counters and to read or stop the counter most recently started. PCL is available for Tru64 Unix on Alpha 21164 and Alpha 21264 processors, for CRAY Unicos/mk on Alpha 21164, for SGI IRI 6.x on R10000 and R12000 processors, for Solaris 2.x on UltraSPARC I/II, and for Linux 2.0.36 on Pentium/ PPro/Pentium II/Pentium III. In the PCL Solaris and Linux implementations, the counters are not saved on context switches. PCL does not support native events.

7 Conclusions

PAPI aims to provide the tool designer and application engineer with a consistent interface and methodology for use of the performance counter hardware found in most major microprocessor lines. The main motivation for this interface is the increasing divergence of application performance from near peak performance of most machines in the HPC marketplace. This performance gap is largely due to the disparity in memory and communication bandwidth at different levels of the memory hierarchy. With no viable hardware solution in sight, users requiring the optimal performance must expend significant effort on single-processor and shared-memory optimization techniques. To address this problem, users need a compact set of robust and useful tools to quickly diagnose and analyze processor-specific performance metrics. To that end, many design efforts have wastefully reinvented the soft-

ware infrastructure necessary for a suite of program analysis tools. PAPI directly challenges this model by focusing on a reusable, portable, and functionality-oriented infrastructure for performance tool design. It is hoped that through additional collaborative efforts, PAPI will become one of a number of modular components for advanced tool design and program analysis.

The PAPI specification and software, as well as documentation and additional supporting information, are available from the PAPI Web site at <http://icl.cs.utk.edu/parjects/papi>.

APPENDIX PAPI Standard Event Definitions

Memory hierarchy access events

PAPI_L1_DCM	Level 1 data cache misses
PAPI_L1_ICM	Level 1 instruction cache misses
PAPI_L2_DCM	Level 2 data cache misses
PAPI_L2_ICM	Level 2 instruction cache misses
PAPI_L3_DCM	Level 3 data cache misses
PAPI_L3_ICM	Level 3 instruction cache misses
PAPI_L1_TCM	Level 1 total cache misses
PAPI_L2_TCM	Level 2 total cache misses
PAPI_L3_TCM	Level 3 total cache misses
PAPI_TLB_DM	Data translation lookaside buffer misses
PAPI_TLB_IM	Instruction translation lookaside buffer misses
PAPI_TLB_TL	Total translation lookaside buffer misses
PAPI_L1_LDM	Level 1 load misses
PAPI_L1_STM	Level 1 store misses
PAPI_L2_LDM	Level 2 load misses
PAPI_L2_STM	Level 2 store misses

Cache coherence events

PAPI_CA_SNP	Snoops
PAPI_CA_SHR	Request for access to shared cache line
PAPI_CA_CLN	Request for access to clean cache line
PAPI_CA_INV	Cache line invalidation
PAPI_CA_ITV	Cache line intervention
PAPI_TLB_SD	Translation lookaside buffer shoot-downs

Cycle and instruction counts

PAPI_TOT_CYC	Total cycles
PAPI_TOT_IIS	Total instructions issued
PAPI_TOT_INS	Total instruction completed
PAPI_INT_INS	Integer instructions completed
PAPI_FP_INS	Floating-point instructions completed
PAPI_LD_INS	Load instructions completed
PAPI_SR_INS	Store instructions completed
PAPI_LST_INS	Total load/store instructions completed
PAPI_FMA_INS	Floating-point multiply add (FMA) instructions completed
PAPI_VEC_INS	Vector/SIMD instructions completed
PAPI_BR_UCN	Unconditional branch instructions completed
PAPI_BR_CN	Conditional branch instructions completed
PAPI_BR_TKN	Conditional branch instructions taken
PAPI_BR_NTK	Conditional branch instructions not taken
PAPI_BR_MSP	Conditional branch instructions mispredicted
PAPI_BR_PRC	Conditional branch instructions correctly predicted
PAPI_BR_INS	Total branch instructions completed
PAPI_CSR_FAL	Failed store conditional instructions
PAPI_CSR_SUC	Successful store conditional instructions
PAPI_CSR_TOT	Total store conditional instructions
PAPI_SYC_INS	Synchronization instructions completed
PAPI_FLOPS	Floating-point instructions completed per second
PAPI_IPS	Instructions completed per second

Functional unit and pipeline status events

PAPI_BRU_IDL	Cycles branch units are idle
PAPI_FXU_IDL	Cycles integer units are idle
PAPI_FPU_IDL	Cycles floating-point units are idle
PAPI_LSU_IDL	Cycles load/store units are idle
PAPI_MEM_SCY	Cycles stalled waiting for memory access
PAPI_MEM_RCY	Cycles stalled waiting for memory read
PAPI_MEM_WCY	Cycles stalled waiting for memory write
PAPI_STL_CYC	Cycles with no instruction issue

PAPI_FUL_ICY	Cycles with maximum instruction issue
PAPI_STL_CCY	Cycles with no instruction completion
PAPI_FUL_CCY	Cycles with maximum instruction completion

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BIOGRAPHIES

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Philip Mucci earned a B.A. in computer science from the Johns Hopkins University in 1993. During that period, he worked as a part-time software engineer for the MIT Laboratory for Computer Science and Thinking Machines Corporation in Cambridge, Massachusetts. The year following his B.A., he worked for Gradient Technologies, where he designed a multithreaded software licensing system. He then went to get his master's degree in computer science under the tutelage of Dr. Jack Dongarra, widely recognized as one of the leaders in Scientific Parallel Computing. During that time, he designed a high performance communication layer for PVM as a member of a development team, authored the LLCBench benchmark package, and served as a performance consultant to the Department of Defense Major Shared Resource Centers and Los Alamos National Laboratory. In 1998, he conceived PAPI and has been the chief technical architect ever since. Currently, he is a part-time research consultant for the University of Tennessee and a performance consultant for the Advanced Computation and Technology Center, a division of IBM Research in Yorktown, New York. He can be reached at mucci@cs.utk.edu.

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