OPTIMIZING PAPI FOR LOW-OVERHEAD COUNTER MEASUREMENT

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A THESIS

Submitted in Partial Fulfillment of the

Requirements for the Degree of

Master of Science

(in Computer Engineering)

The Graduate School

The University of Maine

December 2017

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An Abstract of the Thesis Presented
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December/2017

Performance analysis is an essential step for better software optimization, which is critical for embedded systems, desktop applications and scientific computing. Most modern microprocessors contain hardware performance counters that can help with performance analysis. The PAPI library is a widely used self-monitoring performance measurement interface that supports the performance counter hardware found in most major microprocessors. PAPI supports self-monitoring: letting programs instrument chunks of code and gather detailed performance values.

A key aspect of self-monitoring is reading hardware performance counters with minimum possible overhead. Any overhead in the measurements can affect the accuracy of the results. In perf_event, the Linux interface to performance counters, the values are read via the read system call. This involves a large overhead when entering and exiting the operating system kernel.

In this work, we modify PAPI to use the rdpmc instruction that allows userspace measurement of counters on x86 systems. This replaces the use of the high-overhead read() system call. We tested the result across 14 modern systems and 4 benchmarks. We find that the performance measurement latency is improved by at least a factor of three (and often a factor of six or more) in our test cases.
The greatest gratitude is sent to my advisor, Dr. Vincent M. Weaver, for his complete support on this dissertation. Dr. Weaver has always been very encouraging, patient, knowledgeable, inspiring and supportive. The door to Dr. Weaver’s office was always open whenever I had a question about my research and thesis writing. Without the help of him, this thesis would have never been written or completed. It is hard to imaging having a better advisor and mentor for my research and study on performance measurement.

Also, acknowledged are my committee members: Dr. Bruce Segee, Dr. Yifeng Zhu for their comments, suggestions and revisions provided to my research work. It has been a good experience working and studying at the Department of Electrical & Computer Engineering. I want to express my gratefulness to the professors that have taught me professional knowledge during these two years. I thank Dr. Hummels, Dr. Segee, Dr. Zhu, Dr. Abedi and Dr. Weaver for teaching such wonderful classes and providing countless help whenever it is needed. I am also grateful to Ms. Cindy Plourde and Lynn Hathaway for taking care of my administrative-related business.

Being a foreign student, I want to thank the staff from the Office of International Program, especially Ms. Mireille Le Gal and Ms. Sarah Joughin. Without them, my study in Maine was not possible.

I acknowledge the financial support from teaching assistance program of the department and the National Science Foundation under Grant No. SSI-1450122.
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1 INTRODUCTION AND MOTIVATION

The number of transistors that can be fit on a silicon chip doubles about every 18 months. However, despite the remarkable development in CPUs, software performance improvement based on these ever-faster machines is not in the same step. One of the reasons for this phenomenon could be that DRAM bandwidth increases quite slowly compared with the dramatic growing speed of CPU performance [1], while the performance of most applications depends on both core speed of the processor and bandwidth of the memory system.

Software optimization is quite critical no matter the application type: embedded application, desktop application or science computing. For better application optimization, performance measurement is an essential step. Reading data from the performance counters contained in most modern microprocessors can help with performance measurement. However, gathering this kind of data requires understanding the interaction of computer architecture, operating system, compiler and the running application [2]. The information about accessing these counters is usually poorly documented or unavailable to application developers and performance tool designers.

However, there are various tools available that can read the values of these hardware counters, such as PAPI [4], LIKWID [5] and perf [6]. Usually there are 3 ways for these tools to get hardware counter values: aggregate measurement, statistical sampling and self-monitoring [7]. Aggregate measurement is the kind of method that gathers total counts of specific events occurrences from the start to the end of the workload. This is the easiest and lowest overhead method to get hardware counter values. Statistical sampling obtains profiling data via counter overflows on timer interrupts. Using this method usually can get an imprecise result with low overhead, or fine-grained resolution values with high operating system overhead because of the increased
interrupts. Self-monitoring, on the other hand, allows developers to gather exact hardware performance readings for any specific blocks of code, rather than the entire program.

Though all the performance measurement tools can get performance data either by aggregate measurement or statistical sampling, Performance Application Programming Interface (PAPI) is one of the only tools that support self-monitoring. PAPI allows users to instrument a simple routine including start, read event, and stop to any block of code, that helps gather fine-grain and exact “caliper” measurement solely around the code of interest. Instrumenting PAPI into user’s code involves adding extra code to the program. This extra code will perturb the program’s execution and cause overhead. A goal with measurement software is to make this perturbation as small as possible.

1.1 Motivation

An overhead refers to a benchmark invariant difference between reported and actual count for a given event such as cache misses, branch instructions, total cycles and so on. [9]. Mytkowicz et al. [10] found that an overhead as low as a 2.5% increase in instruction count could interfere with properly correlating results. Mytkowicz et al. [11] also later shows that simply adding an additional PAPI counter could be enough to cause noticeable perturbations. Low overhead is critical for accurate performance measurements.

There is a long list of application performance analysis third-party tools that use or incorporate support for PAPI to gather, display and analyze performance information [11]. For instance, TAU (Tuning and Analysis Utilities) developed at the University of Oregon uses PAPI to support hardware counter reading and maintain portability. HPCToolkit can collect measurements based on hardware performance counters with installation of PAPI; otherwise, it can only collect measurements based on the operating system timer. There are various other tools that have
combined with PAPI to enhance their performance analysis module, such as KOJAK, PerfSuite, Titanium, SCALEA, OpenSpeedshop, SvPablo and so on [12]. The wide use of PAPI as a performance tool illustrates the importance of reducing the PAPI overhead of collecting performance data, which is very important for application developers to tune and optimize the performance of their programs.

1.2 Background

1.2.1 Hardware counters

Hardware performance counters, or hardware counters, are a set of registers contained in most modern microprocessors. These counters can provide critical hardware event information for hardware verification/debugging and software related tasks such as performance monitoring, analysis or tuning. For most modern microprocessors, a small number of counter registers (4-7 for recent x86 processors) support measurement of a subset of hundreds of events. These events are usually about cycle count, instruction count, branch taken and prediction accuracy, TLB misses and invalidations, pipeline stalls, and memory access behaviors like miss rate at each memory hierarchy level.

There are usually two types of performance counter registers: configuration registers and counting registers. To monitor a performance event, the user has to access the configuration registers to select an event, start or stop counting, or enable interrupts. The operating system can then send low-level CPU calls to carry out the user’s request. The user can than read from the counting registers that holds the current counts. Extra permission may be needed for users to access the counting registers, although they can also read the event value directly on some processors by special instructions (like rdpmc on x86) [6].

3
1.2.2 PAPI Library

The information about accessing hardware counters is usually poorly documented or unavailable to application developers and performance tool designers [3]. PAPI [13], initiated at the University of Tennessee at Knoxville, is a consistent, portable, cross-platform easy-use interface to the hardware counters on a wide variety of machines, providing developers information for performance analysis and tuning.

PAPI has two interfaces for the users to get access to hardware counters: the high level interface provides users simple and straightforward start, stop and read routines so that they can get specified event information from hardware counters without changing code across different platforms; the low level interface is fully programmable, thread safe, and allow users to define their own event sets.

On Linux, PAPI uses the perf_event interface to get access to performance counters. The perf_event subsystem was added to the Linux kernel in version 2.6.31 with the name of "Performance Counters for Linux" and was renamed to perf_event in Linux 2.6.32 [14]. To enable/disable counters, the ioctl () system call is called. The read () system call is used to read counter values. When sampling, a ring buffer that contains results can be gained by calling mmap () and users can check to see if the result is available by a signal or the poll () call[14].

Before perf_event was standard, PAPI used the perfctr [15] and perfmon2 [16] Linux interface, but they needed extra custom patching of the Linux kernel. Perfctr reads the values by accessing the mmap page and using the x86 rdpmc instruction without calling the read () system call. Once perf_event was merged into the mainline Linux kernel, PAPI stopped the use of perfctr and perfmon2. However, after changing to perf_event, PAPI read met with a sharp increase of read overhead mainly because perf_event uses the read () instead of rdpmc instruction to read counter values.
2 RELATED WORK

Low-overhead counter access is important, and there are various previous works on the topic, such as PAPI overhead, low-level interface overhead, and other performance tool overhead. PAPI is widely used and is often the comparison point for such studies.

2.1 PAPI Overhead

As mentioned in the last chapter, PAPI is now implemented via the *perf_event* interface. However, most previous PAPI comparisons use *perfctr* or *perfmon2* because they predate the introduction of *perf_event*. This makes direct comparison to our work difficult.

The overhead of PAPI including *PAPI_start()* / *PAPI_stop()* and *PAPI_read()* was measured by Moore et al. [18] [19] on several architectures and it seems that Linux / x86 had the least overhead. But the Linux version and x86 machine information is not given.

Weaver [20] instruments several PAPI overhead measurements [3] on various kernel interfaces for multiple PAPI versions (PAPI 4.0.0-4.1.2). The results show that the Linux 2.6.32 kernel version with perfctr generated the least overhead, while perf_events has the most overhead. His work gives a clue that the use of the *read()* system call introduces many extra clock cycles.

2.2 Lower-Level Interface Overhead

Weaver [7] investigates the overhead of *perf_event* in terms of start/stop/read/overall on various x86_64 machines with a full range of Linux kernels. The measurements are at the raw system call level, one level lower than the PAPI interface we investigate. He also conducts the comparison against perfctr and perfmon2, and shows that perf_event has larger overhead in some implementations. Several methods, including using *rdpmc* to reduce overhead of
userspace to kernel space, are used to minimize the overhead and results are comparable with the perfctr and perfmon2 interfaces after the use of rdpmc.

Zaparanuks, Jovic and Hauswirth [28] investigate measurement overhead of both user and user+kernel counters using PAPI on top of perfmon2 and perfctr, as well as using perfmon2 and perfctr directly. It is a detailed investigation into obtaining minimum overhead on these interfaces, but predates the introduction of perf_event.

### 2.3 Other Performance Counter Tools

Roehl et al. [20] study the performance of likwid-perfctr and the LIKWID Marker API under the Linux OS on Intel IvyBridge-EP, Intel Haswell and AMD Interlagos. With the support of Marker API, likwid-perfctr can provide self-monitoring for an application. The Marker API is designed to measure code region performance by inserting API calls into user’s code and do self-monitoring. However, comparing with PAPI, Marker API has to specify the events that need to be measured on the command line rather than in user’s code. LIKWID relies on the MSRs using the Linux /dev/msr interface, causing high overhead because every time it reads or writes to counters it must context switch into the kernel. They mention the idea of using the rdpmc instruction to reduce overhead caused by system calls, but since the kernel disables rdpmc by default if not using perf_event, they cannot use it without patching the kernel. They also instrument the same STREAM test code with PAPI and compare with the LIKWID start/stop routine, however the result is not valuable and hard to know how much overhead read operations cost since they did not use a separate read routine.

Demme and Sethumadhaven propose LiMiT [21], a Linux interface to provide fast, userspace access to performance counters. Compared with PAPI, it is relatively complicated to install since it requires a user land API and a kernel patch, and a note on the project’s website notes that the
patch is unstable and can cause system crashes. They claim LiMiT is 90x faster than PAPI and 23x faster than perf_event, but the results are somewhat unclear since there is no detailed description about the test or the kernel versions.

AMD proposed an advanced Lightweight Profiling [22] interface providing userspace-only access to all aspects of controlling performance counters, not just reads. This could potentially speed up much more than reads, however the Linux kernel developers have refused to add support for the interface unless it moderated by the kernel, which would defeat the entire purpose [23].

DeRose [24] describes the HPM Toolkit, which contains components such as the hpmcount utility that can measure application overall wall clock time as well as hardware performance counter information. The HPM library supports the measurement of program sections. HPM Toolkit uses the PAPI interface, so it supports the measurement of programs that run on the Intel platform under Linux in addition to IBM Power 3 with AIX. The majority of the overhead of this tool is caused by gettimeofday(), which is used to measure time cost. The reason why they do not chose cycles for time measurement is recording cycles could occupy an extra hardware counter and it is not accurate for PAPI since it measures total user mode time.

2.4 Non-Temporal Overhead

Our work, and much of the previous work, is mainly about the overhead in terms of extra cycles introduced by the measurement. Performance can also affect other metrics.

Lehr [25] implements performance measurement on a subset of the SPEC CPU 2006 benchmark suite [33] and found that even with as low as 10% of running time overhead, performance event counts (including stores, branch misprediction and cache related events) can be perturbed significantly.
Huang et al. [26] studied the power and energy consumption as well as PAPI power overhead when doing the measurement on the Intel Haswell processors. They found that power monitoring by PAPI could induce large power overhead (32% more than idle). The measurement itself is using processor resources (memory, cache, cpu and so on) that can lead to a certain amount of power and energy overhead.

Babka and Tuma [27] investigate the overhead of PAPI in both cycle count and cache behavior on an AMD and Intel machine. Although the results were high, the PAPI version they were using was based on a Perfctr interface that is out of date and benchmarks they used in the experiment were not described in detail.

Maxwell et al. [17] test the PAPI overhead in terms of event counts (for example load/store counts). The overhead is decided to be significant or not by comparing with the event counts that PAPI read. If the expected value is very large then the overhead is insignificant, otherwise, calibration is needed. By reducing the instruction overhead, event counts obtained by PAPI are more accurate.
3 SPEEDING UP PAPI WITH THE RDPMC INSTRUCTION

3.1 Proposal for using \textit{rdpmc} in PAPI code

In order to get hardware event values for any block of code of an application, one has to go through several steps. Figure 3.1 presents example code instrumented with PAPI. The first step is initialization where users have to initialize the PAPI library, create an event set, check event availability and add events. These parts may have relative higher overhead than read calls, but are of much less significance since users can separate this part of code from the object code to avoid overhead influence. \textit{PAPI\_start()} and \textit{PAPI\_stop()} can be put in the startup/shutdown part of the program as well to limit perturbation of the measurement. This leaves the \textit{PAPI\_read()} routine as the most important routine that needs to be low-overhead. To get counter values on Linux, \textit{PAPI\_read()} calls the \textit{read()} system call, which takes a relatively long time (hundreds to thousands of cycles) to enter into the Linux kernel and executes a lot of code before returning to the user. This overhead can be avoided by using the \textit{rdpmc} instruction, which can read the counters directly from userspace, without involving the operating system. In the following work, we will extend PAPI to use this low-overhead \textit{rdpmc} instruction instead of using the default \textit{read()} system call.

3.2 RDPMC instruction

RDPMC (Read Performance Monitor Counter) is a native instruction from the x86 instruction set. Performance counters were first introduced with the Pentium MMX and \textit{rdpmc} was introduced at the same time. While at first only two counters were available, now all of the core CPU counters support them (up to 8 general purpose plus three fixed on Intel processors).
Figure 3.1 illustrates rdpmc operation on the Pentium MMX processor. Two 40-bit performance-monitoring counters (0 and 1) are specified in the ECX register. By calling the `rdpmc` instruction, the value contained in performance-monitoring counter will be loaded into EDX: EAX, with the high-order 8 bits going to EDX register and low-order 32 bits going to EAX register.

The purpose of the instruction is to allow application code to access performance counters directly to avoid the overhead of calling into the operating system. The application code can read the performance-monitoring counters at a privilege level of 1, 2, or 3 with the instruction enabled (setting the PEC flag in the CR4 register). The instruction itself only takes a short amount of time to run, on the order of a few tens of cycles [29].

### 3.3 PAPI rdpmc code

Before `perf_event` was merged into Linux, users could set performance counters to be free-running and access them using an assembly-language `rdpmc` call. However, with `perf_event` using `rdpmc` is not that simple any more, since Linux is a multi-tasking operating system and there might be multiple users of `perf_event`. The kernel may rearrange event counters at any point, which could happen due to context switching or multiplexing (when the number of events that the kernel is measuring is more than the number of available counters). The counter value might have changed since the last read because of multiplexing. Also, due to context switching or counter overflowing, the kernel may have read and restarted the counters.

Extra PAPI code (show in Figure 3.3) is needed to ensure that the kernel has not changed the event configuration since last time the event was read. The overhead of the code is on the order of a few hundred cycles, which is double the read overhead. However, it is still much faster than using the `read()` system call, which is slow, disturbs to the CPU, and involves running an unpredictable amount of kernel code.
To conduct a rdpmc read, first the pc->lock variable is read in the beginning of the code and checked at the end to ensure it stays the same since it may been be incremented by the kernel any time the perf_event_update_userpage () is called. The calling of barrier () ensures that the pc->lock value is synchronized with the kernel. To check whether or not multiplexing is happening, pc->time_running and pc->time enabled is checked. There is multiplexing if those values are not equal to each other, and more accurate multiplex calculation follows (The results need to be scaled appropriately to account for the time where the event was not running). The count value stores the most recent value read by the kernel. Then the rdpmc instruction is called and the sign extended result returned from it is added to the count value. Variable pc->lock is read again in the end and if it is not the same as the beginning, the whole process will run again until the value is not changed.

The code listed in Figure 3.3 is based on sample code provided by the kernel developers. It works in PAPI but may need some additional error handling. If the kernel is busy updating the page, the sequence checking could never make progress and a livelock may happen, but we have not met this problem in practice. Extra code is needed to help break out the loop and go back to a read () if this happens.

One should set --enable-perfevent-rdpmc = yes in configure when building and installing since it currently is not enabled by default in PAPI. This feature will be enabled by default in the soon to be released PAPI 5.6.
Figure 3.2 Instrument user code with PAPI

```c
/* user start up code */
retval = PAPI_library_init( PAPI_VER_CURRENT ); //initialize PAPI library
if (retval != PAPI_VER_CURRENT ) {
  fprintf(stderr,"PAPI_library_init\n");
  exit(retval);
}
retval = PAPI_create_eventset( &EventSet ); // create eventset
if (retval != PAPI_OK ) {
  fprintf(stderr,"PAPI_create_eventset\n");
  exit(retval);
}
retval = PAPI_add_event( EventSet, PAPI_TOT_CYC ); // add PAPI_TOT_CYC(total cycle count) event
if (retval != PAPI_OK ) {
  fprintf(stderr,"PAPI_add_event\n");
  exit(retval);
}
retval = PAPI_add_event( EventSet, PAPI_TOT_INS ); // add PAPI_TOT_INS(total instruction count) event
if (retval != PAPI_OK ) {
  fprintf(stderr,"PAPI_add_event\n");
  exit(retval);
}
}
/* user code*/
if ( ( retval = PAPI_start( EventSet ) ) != PAPI_OK ) { // start event measurement
  fprintf(stderr,"PAPI_start\n");
  exit(retval);
}
/* user code */
PAPI_read(EventSet,values); // read current event value and store into values array
/* user code */
if ( ( retval = PAPI_stop( EventSet, NULL ) ) != PAPI_OK ) { // stop event measurement
  fprintf(stderr,"PAPI_stop\n");
  exit(retval);
}
/* user clean up code*/
PAPI_shutdown();
```

Figure 3.3 RDPMC operation on Pentium MMX processor.
Figure 3.4 Code required for a perf_event rdpmc read

```c
/* The kernel increments pc->lock any time */
/* perf_event_update_userpage() is called */
/* so by checking now, and the end, we */
/* can see if an update happened while we */
/* were trying to read things, and re-try */
/* if something changed */
/* The barrier ensures we get the most up to date */
/* version of the pc->lock variable */
seqpc->lock;
barrier();

/* For multiplexing */
/* time_enabled is time the event was enabled */
/* time_running is time the event was actually running */
/* running = pc->time_running; */

/* if cap_user_time is set, we can use rdtsc */
/* to calculate more exact enabled/running time */
if ((pc->cap_user_time) && (enabled || running)) {
    cyc = rdtsc();
    time_offset = pc->time_offset;
    time_mult = pc->time_mult;
    time_shift = pc->time_shift;
    quot=(cyc>>time_shift);
    rem = cyc & ((1<<time_shift)-1);
    delta = time_offset + (quot * time_mult) +
    (rem * time_mult) >> time_shift)
    enabled=delta;
```
4 EXPERIMENTAL SETUP

We test on fourteen different machines as shown in Table 4.1. These machines cover multiple generations of Intel and AMD processors, from a 20-year-old Pentium II machine up to and including more modern machines.

Most of the machines tested ran the Linux 4.9 kernel provided with the Sid release of Debian Linux. A few of the machines are running the 3.16 kernel provided with Jessie Debian Linux.

We first compare the overhead of `PAPI_read()` and `PAPI_start() / PAPI_stop()` routines in the `papi_cost` tool before and after being enhanced with `rdpmc` instructions across the 14 machines mentioned above. On the Haswell machine we also test and compare the before and after overhead by instrumenting PAPI code into several benchmarks like Sobel Edge Detector, HPL and STREAM. Next, we run several benchmarks at the same time to create a situation of context switching and multiplexing, aiming to catch event counter rearrangement. STREAM is a heavy memory utilizing benchmark. Each event you want to read via `rdpmc` must have an associated mmap page. This could potentially have overhead issues. We ran experiments on STREAM with PAPI instrumented in to see if there are any page faults or significant numbers of extra TLB accesses or misses.

Most of our experiments are against a development git snapshot a21e3da5096bb410eaf6 from March 2017, as at the time of this writing no full PAPI release contains the `rdpmc` code. For comparison we also look at the 5.4.0, 5.4.1, 5.4.3, 5.5.0, and 5.5.1 official PAPI releases.
Table 4.1 Machines used in this study

<table>
<thead>
<tr>
<th>Processor</th>
<th>Counters Available</th>
<th>Processor</th>
<th>Counters Available</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intel Pentium II</td>
<td>2 general</td>
<td>Intel Broadwell i7-5557U</td>
<td>4 general 3 fixed</td>
</tr>
<tr>
<td>Intel Pentium 4</td>
<td>18 general</td>
<td>Intel Broadwell-EP E5-2620</td>
<td>4 general 3 fixed</td>
</tr>
<tr>
<td>Intel Core2 P8700</td>
<td>2 general 3 fixed</td>
<td>Intel Skylake i7-6700</td>
<td>4 general 3 fixed</td>
</tr>
<tr>
<td>Intel Atom Cedarview D2550</td>
<td>2 general 3 fixed</td>
<td>AMD fam10h Phenom II</td>
<td>4 general</td>
</tr>
<tr>
<td>Intel IvyBridge i5-3210M</td>
<td>4 general 3 fixed</td>
<td>AMD fam15h A10-6800B</td>
<td>6 general</td>
</tr>
<tr>
<td>Intel Haswell i7-4770</td>
<td>4 general 3 fixed</td>
<td>AMD fam15h Opteron 6376</td>
<td>6 general</td>
</tr>
<tr>
<td>Intel Haswell-EP E5-2640</td>
<td>4 general 3 fixed</td>
<td>AMD fam16h A8-6410</td>
<td>4 general</td>
</tr>
</tbody>
</table>

4.1 PAPI_Cost Benchmark

We use the `papi_cost` utility provided by PAPI as the reference benchmark to measure `PAPI_read()` overhead. A segment of code in this utility for read testing is shown in Figure 4.1.

The code is wrapped with `PAPI_start()` and `PAPI_stop()` with the EventSet as parameter that was defined in the set up part of the `papi_cost`. After one call to `PAPI_read()`, it loops `num_iters` (initially 1 million) times calling the `PAPI_read()` function, and the value of events is saved in array parameter `values`. To measure cycle cost for each `PAPI_read()` run, it calls the PAPI library function `PAPI_get_real_cyc()` that uses `rdtsc` read timestamp instruction on x86 systems.

We extend `papi_cost` code to return the median, 25th and 75th percentile values so that we can use those to make boxplots. The patch of the modified code is contained in Appendix A. A sample of output about how many cycles `PAPI_read()` cost after running `papi_cost` utility is shown in Figure 4.2. The 99th percentile value is used to show that the max cycles value is an
outlier. We also modified \texttt{papi\_cost} further to log in which loop cycle the outliers happen to help with outlier analysis.

Figure 4.5 \textit{PAPI\_read()} test code from \texttt{papi\_cost} utility

/** Start the read eval */
printf("\nPerforming read test...\n"");
if ( retval = PAPI\_start\(\text{EventSet}\) ) != PAPI\_OK ) {
    printf(stderr,"PAPI\_start\);}
exit(retval);
}
PAPI\_read\(\text{EventSet}, values\); 
for ( i = 0; i < num\_iters; i++ ) {
totcyc = PAPI\_get\_real\_cyc\(\text{Counter}\); 
PAPI\_read\(\text{EventSet}, values\);
totcyc = PAPI\_get\_real\_cyc\(\text{Counter}\) - totcyc;
array[i] = totcyc;
}
if ( retval = PAPI\_stop\(\text{EventSet}, values\) ) != PAPI\_OK ) {
    printf(stderr,"PAPI\_stop\); 
exit(retval);
}
do\_output\(\text{2, array, bins, show\_std\_dev, show\_dist}\);

Figure 4.6 Sample for \texttt{papi\_cost} output

\begin{verbatim}
Total cost for PAPI\_read (2 counters) over 1000000 iterations
min cycles : 139
max cycles : 13382
mean cycles : 143.275044
std deviation: 23.831947
25\% cycles : 142
50\% cycles : 142
75\% cycles : 142
99\% cycles : 161
\end{verbatim}

4.1.1 PAPI benchmark setup

To measure \textit{PAPI\_read()} overhead with the \texttt{papi\_cost} utility, one needs to go through the following steps to download PAPI, configure it properly and run the \texttt{papi\_cost} program found in the \texttt{src\/utils} directory.

(1) Get the latest version of the PAPI repository.

If it is the first time, clone it with the following command:
git clone https://bitbucket.org/icl/papi.git

The command above creates a papi folder on the local computer that contains a complete copy of the PAPI git repository. If one is using an existing checkout of PAPI, be sure it is a version from April 2017 or newer. One can update the current git tree via the git pull command.

(2) Configure papi with rdpmc enabled

cd src

./configure --enable-perfevent-rdpmc=yes

(3) Run make.

When make is running, among the options passed there should be something like:
-DUSEPERFEVENTRDPMDM=1 in the command line options scrolling by just before the always there message:
-DPEINCLUDE = libpfm4/include/perfmon/perfevent

(4) Once things are compiled, one can check if perf_event rdpmc is enabled by running

./papi_component_avail -d

and it should list Fast counter read: 1

(5) Run papi_cost

utils/papi_cost

(6) A subset of the results looks something like this:

Total cost for PAPI_read (2 counters) over 1000000 iterations

min cycles : 139
max cycles : 34190
mean cycles : 148.594704
std deviation: 67.128018

(7) Modify PAPI code to get percentile values. Patch the papi_cost with code in Appendix A. This will report the boxplot information similar to the following:
Total cost for PAPI_read (2 counters)
over 1000000 iterations
min cycles : 139
max cycles : 34190
mean cycles : 148.594704
std deviation: 67.128018
25th percentile :145
50th percentile : 148
75th percentile : 148
99th percentile: 167

(8) Run through different number of event set from 1 event to 4 events. The default number of
events is 2, with PAPI_TOT_CYC and PAPI_TOT_INS. To delete or add events, modify the
papi/src/utils/cost.c file by the use of the PAPI_add_event () function. Be sure to change the
length of the value [] array appropriately.

(9) We run the comparative test on the latest PAPI git repository and released versions from 5.4
to 5.5.

One can use the wget command to download a specific released version, for example, if you
want to download papi 5.5.1, run the following command:

wget http://icl.utk.edu/projects/papi/downloads/papi-5.5.1.tar.gz

Configure PAPI as before, though it is not possible to enable rdpmc support as it does not exist in
older versions.

(10) The test to generate the outlier plots modified papi_cost to print out all 1-million timing
results and counter results to disk, which is a minor change to papi_cost

(11) The historical PAPI versions are trickier, as they run on old versions of Linux that are not
necessarily easy to obtain or set up.

To get perfctr running, it is necessary to get a 2.6.32 Linux kernel source, and patch with the
most recent (confusingly named) 2.6.40 perfctr patch. Then boot into a version of Linux that can
handle old kernels (something newer like Debian Jessie might have problems, but booting with
When configuring and building PAPI should automatically detect you are using rdpmc. If it does not, it may be necessary to manually make the permissions on /dev/perfctr be 666. Be sure to use a current git snapshot of PAPI as there was a long-standing bug breaking older perfctr and perfmon2 support that was not fixed as of 5.5.1.

_Perfmon2_ is more difficult because the newest supported version is 2.6.30. Checkout the perfmon2 git tree and build the kernel, and boot into it. It is necessary to have an older version of Linux, such as Debian Squeeze (most newer Linux distributions require 2.6.32 kernels at least). It is necessary to be running on an older processor supported. For our measurements we created a Debian squeeze chroot, booted with `init=/bin/sh`, and manually switched to and entered the chroot. This worked, but can be a bit of a complex task if unless one is a Linux expert. Again building PAPI is the same as it is on other platforms and should auto detect you are on perfmon2.

### 4.2 Sobel Edge Detector benchmark

The Sobel edge detector, also called Sobel operator, usually is used to perform a 2-D gradient measurement on an image and create an image emphasizing edges. The operator contains two $3 \times 3$ kernels that are convolved with the original image to get the approximate value of the image derivatives. The kernels are applied to the image separately, producing $G_x$ and $G_y$, which are the horizontal and vertical magnitude. Combining the above two images together, can get the gradient magnitude, using:

$$G = \sqrt{G_x^2 + G_y^2}$$
4.2.1 Sobel Edge Detector benchmark setup

As shown in 4.3, we instrumented the `PAPI_read()` function in the convolution section of the sobel code (code is listed in Appendix B). The center of the matrix (3*3 kernel) is applied to the pixel of interest from the input matrix and the surrounding pixels are added together and used to calculate the value for the pixel in the output matrix. For example, with a convolution matrix

\[
\begin{bmatrix}
0 & -1 & 0 \\
-1 & 5 & -1 \\
0 & -1 & 0 \\
\end{bmatrix}
\]

and pixel values 
\[
\begin{bmatrix}
a & b & c \\
d & e & f \\
g & h & i \\
\end{bmatrix}
\]

if we want to apply the convolution to pixel f, the resulting output pixel would end up being

\[
\text{out}_{1,1} = (0 \times a) + (-1 \times b) + (0 \times c) + (-1 \times d) + (5 \times e) + (-1 \times f) + (0 \times g) + (-1 \times h) + (0 \times i).
\]

After each iteration of the convolution, the `PAPI_read(Eventset,values)` function is called and the number of cycles is read by `PAPI_get_real_cyc()` function. Events `PAPI_TOT_CYC` and `PAPI_TOT_INS` are added in the `Eventset`. By running command `./sobel test.jpg`, we can get output similar with Figure 4.4. Test.jpg is a jpg format image with the size of 1920*1200.
4.3 High-Performance Linpack (HPL) Benchmark

HPL is a software package that solves a dense linear equation $Ax=b$, where $A$ is an $N \times N$ matrix in double precision (64 bits). The main aim of the benchmark is to measure the floating point
computing power of a large distributed-memory computer, the result of which can be submitted to the TOP500 supercomputer list [34].

The first step of solving the order-n linear system is computing LU factorization with row partial pivoting of the n-by-n+1 coefficient matrix that will be partitioned into nb-by-nb blocks. The data is distributed onto a P-by-Q grid of processes for cluster computing, however, in this experiment, we only measure \texttt{PAPI\_read()} in one process.

4.3.1 HPL benchmark installation and setup [30]

(1) Install dependencies

To successfully install and use HPL, a few software dependencies must be met. They are:

- Gfortran (Fortran compiler)
- MPICH2 (an implementation of MPI)
- mpich2 (dev - development tools)
- and BLAS (Basic Linear Algebra Subprograms) [30].

(2) Download HPL and set it up

Download the HPL package, extract the tar file and create a makefile based on the given one.

Run the following commands one by another.

```
tar xf hpl-2.1.tar.gz
cd hpl-2.1/setup
sh make\_generic
cd..
cp setup/Make\_UNKNOWN Make\_OpenBLAS
```

The last command makes a copy of Make\_UNKNOWN to Make\_OpenBLAS. The make file contains the details of system configuration, libraries like mpich2, atlas/blas package, home directory and so on. Next we will adjust the Make\_OpenBLAS file and compile HPL with the support of BLAS.

(1) Modify make file

The changes in makefile are shown in Figure 4.5
Figure 4.9 Part of Makefile for HPL benchmark

```c
# Message Passing Library (MPI) ------------------------------------------
# MPIcc tells the C compiler where to find the Message Passing Library
# header files, MPIlib is defined to be the name of the library to be
# used. The variable MPlib is only used for defining MPIinc and MPIlib.
#
# MPlib = /usr/
# MPIinc = -I$(MPdir)/include
# MPIlib = -lmpi
# $(MPdir)/lib/x86_64-linux-gnu/libmpi.a
#
# # Linear Algebra Library (BLAS or VSIMPL) --------------------------------
# LINcc tells the C compiler where to find the Linear Algebra Library
# header files, LAlib is defined to be the name of the library to be
# used. The variable LAinc is only used for defining LAinc and LAlib.
#
# LAinc =
# LAlib = /home/yamliu/research/blas/openblas-0.2.19/libopenblas.a -lpthread
#
# # HPL includes / libraries / specifics -------------------------------
#
# PAPIlib = /home/yamliu/research/papi_overhead/papi/papi/src/libpapi.a -lp
# HPL_INCLUDES = -I$(INCl) -I$(INCl)/$(ARCH) $(LAinc) $(MPIinc)
# HPL_LIBS = $(MPIlib) $(LAlib) $(MPIlib) $(PAPIlib)
```

In the last row shown in Figure 4.5, the path of PAPI library is added in the HPL_LIBS variable, so that we can instrument PAPI code into HPL benchmark.

(2) Compiling and running the HPL benchmark

Before making any changes to the code, we compiled the HPL benchmark using the following command to make sure that the makefile was working properly.

```
make arch=OpenBLAS
```

After make finished successfully, the file “xhpl” will show up in the “bin/OpenBLAS” folder. Next, it is necessary to create a “HPL.dat” input file in the same folder as shown in Figure 4.6 and run the ./xhpl command. The output is shown in Figure 4.7.

(3) HPL parameter tuning

HPL.data is the input file for HPL. N is the problem size, which is the size of the coefficient matrix. Normally, using the largest problem size fitting in memory can help give a best performance result of the system. As shown in Figure 4.8, the free memory for this Haswell machine we are
working on is 3245M which is 405M double precision (8 bytes) elements. The size of the coefficient matrix is the square root of that number and equals 20607. Since the OS and other things need memory as well, 80%*20607=16000 should be a good setting for N.

NB is the block size and is used for data distribution and computational granularity. According to [32], a good block sizes falls in [32..256] interval. We test the performance when NB is set to 32, 64, 128, 256 respectively, and find that when NB is set to 128, it gets the best performance (Gflop). We set NB to 128 for our runs.

We are only studying the case of single processors, so we set Qs and Ps to 1.

(4) Instrument HPL with PAPI

We set Ps and Qs to 1 (we only use 1 process) and chose HPL_pdgev0 code as the host code (Shown in Figure 4.9) of the PAPI_read() measurement since it takes the most time during the whole calculation and iterates the main calculation code including LU factorization, panel broadcast and update for Ns/NBs times. In this way, we can get the results of the total cycles used for the PAPI_read(). The patch for the code instrumented with PAPI is listed in Appendix C.

As shown in Figure 4.10, we insert the code of PAPI_read() and calculate the cost of it after each HPL function in every iteration. The functions are HPL_pdpanel_init (re-initializes panel data structure), HPLpdfact (factors current panel), HPL_binit (initializes the row broadcast), HPL_bcast (performs the row broadcast), HPL_bwait (finalizes row broadcast, waits for the row broadcast of current panel to terminate), HPL_pdupdate (broadcasts a panel and update the trailing submatrix) and MNxtMgid (updates message id for next factorization). The value array [i][num_iters] (i=0,1..6) saves the cost of PAPI_read() after the (i+1)th fuction, num_iters is the index of the current iteration. For instance, if i=0, array [0][num_iters] saves the total cycle cost of PAPI_read() after the calling of the first function HPL_pdpanel_init(). Similarly, the value eventVal[i][num_iters] (i=0,1..6) saves the value of the event that being measured for the (i+1)th
function. The event value eventVal[1][num_iters], for example, stores event values for the second function (HPL_pdfact). We first add events PAPI_TOT_CYC (total cycle) and PAPI_TOT_INS (total instruction completed) to eventset so that we can keep consistent with papi_cost. To analyze the cost of each PAPI_read, we then respectively set the event to PAPI_L1_DCM (level 1 data cache miss), PAPI_L1_ICM (level 1 instruction cache miss), PAPI_BR_INS (branch instruction), PAPI_BR_MSP (conditional branch instructions mispredicted), PAPI_TLB_DM (translation buffer data miss) and PAPI_TLB_IM (translation buffer instruction miss).

(5) Measuring user and kernel space event cost by PAPI_read()

Our result shows that, for different subroutines where we instrumented PAPI_read() function, the cycles that the PAPI_read() cost vary considerably. So we use the rdpmc instruction to measure the user and kernel events that PAPI_read() costs for each subroutine. Figure 4.11 demonstrates how we measure the events value for PAPI_read() in HPL_pdfact section. Total user events can be calculated by rawAfter-rawBefore1 and kernel event can be obtained by rawAfter2-rawBefore2. USER_EVENT and KERNEL_EVENT are used as variables for rdpmc() and they are the macro definitions for the counter index that rdpmc() requires. Usually they are 0 and 1 since we are measuring two events. To make sure the counters are getting desired event data, we use the PAPI_add_named_event() function to help us setup counters. For example, if we add the following two lines of code before using rdpmc(counter_index), the counter with index 0 would measure userspace PAPI_TOT_CYC value and the counter with index 1 would measure kernel space PAPI_TOT_CYC value.

PAPI_add_named_event(eventset," L1D:REPLACEMENT:u=1");
PAPI_add_named_event(eventset," L1D:REPLACEMENT:u=0:k=1");

We did this measurement on the Haswell machine, so the event name can be looked up from the Haswell machine section in papi/src/papi_events_table.h file.
Figure 4.10 HPL.dat file

HPLinepack benchmark input file
Innovative Computing Laboratory, University of Tennessee
HPL.out output file name (if any)
6    device out (6=stdout, 7=stderr, file)
1    # of problems sizes (N)
16000   Ns
1    # of NDs
128   Nd
0    PMAP process mapping (0=Row-, 1=Column-major)
1    # of process grids (P x Q)
1    Ps
1    Qs
16.0    threshold
1    # of panel fact
0    PFACTs (0=left, 1=Crout, 2=Right)
1    # of recursive stopping criterium
2    NBMINs (>= 1)
1    # of panels in recursion
2    NDVVs
1    # of recursive panel fact.
2    RFACVs (0=left, 1=Crout, 2=Right)
1    # of broadcast
2    BCASTs (0=1rg, 1=1rM, 2=2rg, 3=2rM, 4=Lng, 5=LnM)
1    # of lookahead depth
0    DEPTHs (>=0)
2    SWAP (0=bin-exch, 1=long, 2=mix)
64    swapping threshold
0    L1 in (0=transposed, 1=no-transposed) form
0    U in (0=transposed, 1=no-transposed) form
1    Equilibration (0=no, 1=yes)
8    memory alignment in double (> 0)
Figure 4.11 HPL output

An explanation of the input/output parameters follows:

T/V : Wall time / encoded variant.
N : The order of the coefficient matrix A.
NB : The partitioning blocking factor.
P : The number of process rows.
Q : The number of process columns.
Time : Time in seconds to solve the linear system.
Gflops : Rate of execution for solving the linear system.

The following parameter values will be used:

N : 16000
NB : 128
PMAP : Row-major process mapping
P : 1
Q : 1
PFAC T : Left
NUMIN : 2
NDIV : 2
RFAC T : Right
BCAST : Ring
DEPTH : 0
SWAP : Mix (threshold = 64)
L1 : transposed form
U : transposed form
EQUIL : yes
ALIGN : B double precision words

- The matrix A is randomly generated for each test.
- The following scaled residual check will be computed:
  $\frac{|Ax-b|_\infty}{(\text{eps} \times (\|A\|_\infty + \|b\|_\infty)) \times N}$
- The relative machine precision (eps) is taken to be $1.110223e-16$
- Computational tests pass if scaled residuals are less than $16.0$

<table>
<thead>
<tr>
<th>T/V</th>
<th>N</th>
<th>NB</th>
<th>P</th>
<th>Q</th>
<th>Time</th>
<th>Gflops</th>
</tr>
</thead>
<tbody>
<tr>
<td>WR02R2L2</td>
<td>16000</td>
<td>128</td>
<td>1</td>
<td>1</td>
<td>24.47</td>
<td>1.116e+02</td>
</tr>
</tbody>
</table>

HPL_cpgesv() start time Wed Sep 6 15:21:30 2017
HPL_endgesv() end time Wed Sep 6 15:21:55 2017

$\frac{|Ax-b|_\infty/(\text{eps} \times (\|A\|_\infty + \|b\|_\infty)) \times N)$ - $0.0026383$ .... PASSED

Finished 1 tests with the following results:
1 tests completed and passed residual checks,
0 tests completed and failed residual checks,
0 tests skipped because of illegal input values.

End of Tests.
Figure 4.12 Free memory for Haswell machine

```
yanliu@haswell:~/research/benchmarks/hpl-2.1/bin/OpenBLAS$ free -m
    total    used    free    shared    buff/cache   available
Mem: 3758  139  3245    25        367       3326
Swap: 0 0 0
```

Figure 4.13 Main calculation code of HPL_pdgesv0

```
/*
 * Loop over the columns of A
 */
    for( j = 0; j < N; j += nb )
    {
        n = N - j; jb = Min( n, nb );
        /* Release panel resources - re-initialize panel data structure */
        (void) HPL_pdpanel_free( panel[0] );
        HPL_pdpanel_init( GRID, ALGO, n, n+1, jb, A, j, tag, panel[0] );
        /* Factor and broadcast current panel - update */
        HPL_pdfact( panel[0] );
        (void) HPL_binit( panel[0] );
        do
        {
            (void) HPL_bcast( panel[0], &test );
            while( test != HPL_SUCCESS );
            (void) HPL_bwait( panel[0] );
            HPL_pupdate( NULL, NULL, panel[0], -1 );
        }
        /* Update message id for next factorization */
        tag = MPxtMsgid( tag, MSGID_BEGIN_FACT, MSGID_END_FACT );
    }
    /* Release panel resources and panel list */
    (void) HPL_pdpanel_disp( &panel[0] );
```

if( panel ) free( panel );
```
Figure 4.14 Part of HPL code with PAPI_read()

    /*
    * Release panel resources - re-initialize panel data structure
    */
    {void} HPL_pdpanel_free (panel[0]);
    HPL_pdpanel_init (GRID, ALGO, n, n+1, jb, A, j, tag, panel[0]);
    /*
    *start papi read*/
    if(num_iters==max_iters)
    {
        totcyc=PAPI_get_real_cyc();
        PAPI_read(eventset,values);
        totcyc=PAPI_get_real_cyc()-totcyc;
        array[0][num_iters]=totcyc;
        eventVal[0][num_iters]=values[0]-lastVal;
        lastVal=values[0];
    }
    /*end papi read*/

    /* Factor and broadcast current panel - update */
    HPL_odfact (panel[0]);
    /*start papi read*/
    if(num_iters==max_iters)
    {
        totcyc=PAPI_get_real_cyc();
        PAPI_read(eventset,values);
        totcyc=PAPI_get_real_cyc()-totcyc;
        array[1][num_iters]=totcyc;
        eventVal[1][num_iters]=values[0]-lastVal;
        lastVal=values[0];
    }
    /*end papi read*/

    {void} HPL_binit (panel[0]);
    /*start papi read*/
    if(num_iters==max_iters)
    {
        totcyc=PAPI_get_real_cyc();
        PAPI_read(eventset,values);
        totcyc=PAPI_get_real_cyc()-totcyc;
        array[2][num_iters]=totcyc;
        eventVal[2][num_iters]=values[0]-lastVal;
        lastVal=values[0];
    }
    /*end papi read*/

    do
        {void} HPL_bcost (panel[0], &test );
    while (test != HPL_SUCCESS);
    /*start papi read*/
    if(num_iters==max_iters)
    {
        totcyc=PAPI_get_real_cyc();
        PAPI_read(eventset,values);
        totcyc=PAPI_get_real_cyc()-totcyc;
        array[3][num_iters]=totcyc;
        eventVal[3][num_iters]=values[0]-lastVal;
        lastVal=values[0];
    }
    /*end papi read*/
4.4 STREAM benchmark

The STREAM benchmark [31] is used to test sustainable memory bandwidth (in MB/s) by measuring the performance of four long vector operations including COPY \((a(i) = b(i))\), SCALE \((a(i) = q \times b(i))\), SUM \((a(i) = b(i) + c(i))\) and TRIAD \((a(i) = b(i) + q \times c(i))\). The array size can be set to a size that is larger than the machine cache size.

4.4.1 STREAM benchmark setup

The STREAM benchmark is quite easy to setup since we run it on a uniprocessor. The first thing to do is to get the C code and the external timer code from the STREAM website [31]. Next, it is necessary to run the following compiling command to compile a standard-conforming version of STREAM.

\[
\text{gcc -O stream.c -o stream}
\]

After running the ./stream command, the output will be similar to Figure 4.12.
With STREAM working properly, the `PAPI_read()` function is added after each long vector operation in the stream code as shown in Figure 4.13. The vector operations are copy, scale, add and triad separately. We also add the `PAPI_read()` function inside the operation of copy to create a better comparison with the `papi_cost` benchmark as shown in Figure 4.14. The patch of tuned STREAM code is listed in Appendix D. To compile the code instrumented with PAPI, run the following commands one after another:

```
gcc -O -c stream.c

gcc -o stream stream.o PAPIPATH/src/libpapi.a
```

Figure 4.16 STREAM output

```
STREAM version $Revision: 5.10 $  
This system uses 8 bytes per array element.
Array size = 10000000 (elements), Offset = 0 (elements)
Memory per array = 76.3 MiB (= 0.1 GiB).
Total memory required = 228.0 MiB (= 0.2 GiB).
Each kernel will be executed 10 times.
The *best* time for each kernel (excluding the first iteration) will be used to compute the reported bandwidth.
Your clock granularity/precision appears to be 1 microseconds. Each test below will take on the order of 13787 microseconds. (= 13787 clock ticks)
Increase the size of the arrays if this shows that you are not getting at least 20 clock ticks per test.
WARNING -- The above is only a rough guideline.
For best results, please be sure you know the precision of your system timer.

<table>
<thead>
<tr>
<th>Function</th>
<th>Best Rate MB/s</th>
<th>Avg time</th>
<th>Min time</th>
<th>Max time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copy</td>
<td>7938.1</td>
<td>0.020170</td>
<td>0.020156</td>
<td>0.020189</td>
</tr>
<tr>
<td>Scale</td>
<td>7888.4</td>
<td>0.020298</td>
<td>0.020283</td>
<td>0.020336</td>
</tr>
<tr>
<td>Add</td>
<td>8944.9</td>
<td>0.026848</td>
<td>0.026831</td>
<td>0.026878</td>
</tr>
<tr>
<td>Triad</td>
<td>8979.0</td>
<td>0.026778</td>
<td>0.026729</td>
<td>0.026809</td>
</tr>
</tbody>
</table>

Solution Validates: avg error less than 1.000000e-13 on all three arrays
```
Figure 4.17 STREAM code with PAPI instrumented \((PAPI\textunderscore read())\) after long vector operation

```c
/*start papi read*/
if(num\_iters<=max\_iters)
{
    totcyc=PAPI\_get\_real\_cyc();
PAPI\_read(eventset,values);
totcyc=PAPI\_get\_real\_cyc()-totcyc;
array[num\_iters]=totcyc;
num\_iters++;
}

/*end papi read*/

times[0][k] = mysecond();
#endif TUNED
    tuned\_STREAM\_Copy();
#else
    #pragma omp parallel for
    for (j=0; j<STREAM\_ARRAY\_SIZE; j++)
        c[j] = a[j];
#endif
    times[0][k] = mysecond() - times[0][k];
    times[1][k] = mysecond();

/*start papi read*/
if(num\_iters<=max\_iters)
{
    totcyc=PAPI\_get\_real\_cyc();
PAPI\_read(eventset,values);
totcyc=PAPI\_get\_real\_cyc()-totcyc;
array[num\_iters]=totcyc;
num\_iters++;
}

/*end papi read*/
```

Figure 4.18 STREAM code with PAPI instrumented \((PAPI\_read())\) inside long vector operation

```c
for (j=0; j<STREAM\_ARRAY\_SIZE; j++)
{
    c[j] = a[j];
    /*start papi read*/
    if(num\_iters1<=max\_iters1)
    {
        totcyc=PAPI\_get\_real\_cyc();
PAPI\_read(eventset,values);
totcyc=PAPI\_get\_real\_cyc()-totcyc;
array1[num\_iters1++]=totcyc;
    }
    /*end papi read*/
}
```
5 RESULTS

We first compare the overhead results between existing PAPI and PAPI enhanced with our `rdpmc` changes across the fourteen x86 machines. Next we will show the results when several real world benchmarks are instrumented with PAPI, and read overhead with additional events is also described. Finally, there are the result of read overhead across several past PAPI versions and historical performance interfaces.

The results show that we can reduce overhead by at least three times (and more typically around six times) on a wide variety of x86 hardware. We instrumented the PAPI library code into several benchmarks and found that the more computer resources that the host code takes, the more overhead `PAPI_read()` costs.

5.1 read() vs rdpmc overhead

We test `read()` vs `rdpmc` overhead on several benchmarks, including `papi_cost`, Sobel Edge Detector, HPL and STREAM. The results are reported in tables from Table 5.1 to Table 5.7.

Table 5.1 summarizes the `read()` system call vs `rdpmc` instruction speedup found on the fourteen x86 machines when running `papi_cost` util. The values are cycles that are measured by the `PAPI_get_real_cyc()` calls wrapping around the target code. In `papi_cost`, `PAPI_read()` is called 1 million times and we report the median value instead of the average as extremely large outliers may show up occasionally and skew the average and standard deviation. Among all the fourteen machines we test, the speedup is at least 2.5x, and is typically around 6x on recent Intel machines. This varies a bit more on AMD machines, and also on low-end machines such as the ATOM processors.
Table 5.2 Median read vs rdpmc speedup from papi_cost running the PAPI_read 1 million times

<table>
<thead>
<tr>
<th>Vendor</th>
<th>Machine</th>
<th>read () cycles</th>
<th>rdpmc cycles</th>
<th>Speedup</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intel</td>
<td>Pentium II</td>
<td>2533</td>
<td>384</td>
<td>6.6x</td>
</tr>
<tr>
<td>Intel</td>
<td>Pentium 4</td>
<td>3728</td>
<td>704</td>
<td>5.3x</td>
</tr>
<tr>
<td>Intel</td>
<td>Core 2</td>
<td>1634</td>
<td>199</td>
<td>8.2x</td>
</tr>
<tr>
<td>Intel</td>
<td>Atom</td>
<td>3906</td>
<td>392</td>
<td>10.0x</td>
</tr>
<tr>
<td>Intel</td>
<td>Ivybridge</td>
<td>885</td>
<td>149</td>
<td>5.9x</td>
</tr>
<tr>
<td>Intel</td>
<td>Haswell</td>
<td>1118</td>
<td>142</td>
<td>7.8x</td>
</tr>
<tr>
<td>Intel</td>
<td>Haswell-EP</td>
<td>820</td>
<td>125</td>
<td>6.6x</td>
</tr>
<tr>
<td>Intel</td>
<td>Broadwell</td>
<td>1030</td>
<td>145</td>
<td>7.1x</td>
</tr>
<tr>
<td>Intel</td>
<td>Broadwell-EP</td>
<td>750</td>
<td>118</td>
<td>6.4x</td>
</tr>
<tr>
<td>Intel</td>
<td>Skylake</td>
<td>942</td>
<td>144</td>
<td>6.5x</td>
</tr>
<tr>
<td>AMD</td>
<td>fam10h Phenom II</td>
<td>1252</td>
<td>205</td>
<td>6.1x</td>
</tr>
<tr>
<td>AMD</td>
<td>fam15h A10</td>
<td>2457</td>
<td>951</td>
<td>2.6x</td>
</tr>
<tr>
<td>AMD</td>
<td>fam15h Opteron</td>
<td>2186</td>
<td>644</td>
<td>3.4x</td>
</tr>
<tr>
<td>AMD</td>
<td>fam16h A8</td>
<td>1632</td>
<td>205</td>
<td>8.0x</td>
</tr>
</tbody>
</table>

Table 5.2 shows the comparison of PAPI_read () cost supported by read () system call and rdpmc instruction between papi_cost and Sobel-convolution. We run PAPI_read () after each iteration of sobel convolution operation (Figure 6) and calculate the total cost for PAPI_read () for 1 million iterations. All cycles values are median value from the 1 million results. In the Sobel-convolution code, PAPI_read () costs a bit more cycles than the plain papi_cost benchmark when using the rdpmc instruction, while the results are quite close to each other when PAPI_read () is supported by the read () system call. For the Sobel-convolution code, the rdpmc instruction shows a significant speedup (6.7x) compared to the read () system call.
Table 5.3 Sobel compared with papi_cost on Haswell machine

<table>
<thead>
<tr>
<th>Benchmark</th>
<th>rdpmc cycles</th>
<th>read () cycles</th>
<th>speedup</th>
</tr>
</thead>
<tbody>
<tr>
<td>papi_cost</td>
<td>142</td>
<td>1118</td>
<td>7.8x</td>
</tr>
<tr>
<td>Sobel-convolution</td>
<td>169</td>
<td>1139</td>
<td>6.7x</td>
</tr>
</tbody>
</table>

Table 5.4 HPL compared with papi_cost on Haswell machine

<table>
<thead>
<tr>
<th>Benchmark</th>
<th>rdpmc cycles</th>
<th>read () cycles</th>
<th>speedup</th>
</tr>
</thead>
<tbody>
<tr>
<td>papi_cost(1million)</td>
<td>142</td>
<td>1118</td>
<td>7.8x</td>
</tr>
<tr>
<td>HPL_pdpanel_init</td>
<td>346</td>
<td>2277</td>
<td>6.6x</td>
</tr>
<tr>
<td>HPL_pdfact</td>
<td>3504</td>
<td>18076</td>
<td>5.2x</td>
</tr>
<tr>
<td>HPL_binit</td>
<td>371</td>
<td>2423</td>
<td>6.5x</td>
</tr>
<tr>
<td>HPL_bcact</td>
<td>383</td>
<td>2370</td>
<td>6.2x</td>
</tr>
<tr>
<td>HPL_bwait</td>
<td>453</td>
<td>2377</td>
<td>5.2x</td>
</tr>
<tr>
<td>HPL_pdupdate</td>
<td>4790</td>
<td>22309</td>
<td>4.6x</td>
</tr>
<tr>
<td>MNxtMgid</td>
<td>346</td>
<td>2603</td>
<td>7.5x</td>
</tr>
</tbody>
</table>

Table 5.3 summarizes the PAPI_read () cost with the support of rdpmc instruction and the read() system call among the papi_cost and several HPL functions in the HPL_pdgv0.c file. As explained in the HPL parameter tuning section, we set the problem size N to 16000 and the block to 128 so each function is called for 125 (16000/128) times. Table 4 shows the average values from 125 times, excluding papi_cost (1 million). For most HPL calls, PAPI_read () is higher than in papi_cost but still in the same order (300-500 cycles). However, if one calls PAPI_read () after HPL_pdfact () and HPL_pdupdate (), the cost is considerably higher than the plain PAPI_read () call. It is likely this is due to cache misses caused by the intense workload. Table 5.4 gives average event value read by the PAPI_read () for those HPL functions. We can see that for most events listed in Table 5.4, HPL_pdfact () and HPL_pdupdate () give much higher values than the others.

Table 5.5 shows userspace and kernel space event values for PAPI_read () after each HPL function when the PAPI_read () is instrumented with the rdpmc instruction and the read () system call separately. We can see from Table 5.5 that for all three userspace events (total cycle,
L1 data cache misses and TLB data cache misses) caused by the \texttt{PAPI\_read()} function that instrumented after \texttt{HPL\_pdfact} and \texttt{HPL\_pdupdate} is a relatively higher value than the others. Kernel space values are all 0. Table 5.6 shows similar values as in Table 5.5 for userspace events. However, kernel event values are not 0 anymore, which is reasonable since \texttt{PAPI\_read()} is instrumented by read system call when measuring data in Table 5.6.

Table 5.5 Event value for each HPL function

<table>
<thead>
<tr>
<th>PAPI event</th>
<th>HPL_pdfpanel_init</th>
<th>HPL_pdfact</th>
<th>HPL_binit</th>
<th>HPL_bcast</th>
<th>HPL_bwait</th>
<th>HPL_pdupdate</th>
<th>MNxtMgid</th>
</tr>
</thead>
<tbody>
<tr>
<td>PAPI_L1_ICM</td>
<td>65</td>
<td>10721</td>
<td>11</td>
<td>8</td>
<td>2</td>
<td>17832</td>
<td>7</td>
</tr>
<tr>
<td>PAPI_L1_DCM</td>
<td>15</td>
<td>1753095</td>
<td>14</td>
<td>5</td>
<td>4</td>
<td>38874364</td>
<td>13</td>
</tr>
<tr>
<td>PAPI_TLB_IM</td>
<td>3</td>
<td>30</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>12</td>
<td>0</td>
</tr>
<tr>
<td>PAPI_TLB_DM</td>
<td>2</td>
<td>10590</td>
<td>7</td>
<td>3</td>
<td>3</td>
<td>299735</td>
<td>7</td>
</tr>
<tr>
<td>PAPI_BR_INS</td>
<td>162</td>
<td>1405652</td>
<td>68</td>
<td>71</td>
<td>67</td>
<td>5149713</td>
<td>65</td>
</tr>
<tr>
<td>PAPI_BR_MSP</td>
<td>3</td>
<td>5532</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>13987</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 5.6 User and kernel space event cost by \texttt{PAPI\_read()} with \texttt{rdpmc} instruction

<table>
<thead>
<tr>
<th>PAPI event</th>
<th>HPL_pdfpanel_init</th>
<th>HPL_pdfact</th>
<th>HPL_binit</th>
<th>HPL_bcast</th>
<th>HPL_bwait</th>
<th>HPL_pdupdate</th>
<th>MNxtMgid</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOT_CYC(user)</td>
<td>512</td>
<td>4019</td>
<td>464</td>
<td>408</td>
<td>426</td>
<td>4813</td>
<td>420</td>
</tr>
<tr>
<td>TOT_CYC(kernel)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>L1_DCM(user)</td>
<td>5</td>
<td>39</td>
<td>6</td>
<td>2</td>
<td>2</td>
<td>38</td>
<td>5</td>
</tr>
<tr>
<td>L1_DCM(kernel)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>TLB_DM(user)</td>
<td>0</td>
<td>11</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>13</td>
<td>0</td>
</tr>
<tr>
<td>TLB_DM(kernel)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Table 5.7 User and kernel space event value cost by PAPI_read() with read() system call

<table>
<thead>
<tr>
<th>PAPI event</th>
<th>HPL_pdppanel_init</th>
<th>HPL_pdfact</th>
<th>HPL_binit</th>
<th>HPL_bcast</th>
<th>HPL_bwait</th>
<th>HPL_pupdate</th>
<th>MNxtMgid</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOT_CYC(user)</td>
<td>461</td>
<td>4551</td>
<td>383</td>
<td>379</td>
<td>396</td>
<td>4925</td>
<td>398</td>
</tr>
<tr>
<td>TOT_CYC(kernel)</td>
<td>1755</td>
<td>13545</td>
<td>1752</td>
<td>1741</td>
<td>1740</td>
<td>16024</td>
<td>1753</td>
</tr>
<tr>
<td>L1_DCM(user)</td>
<td>7</td>
<td>43</td>
<td>8</td>
<td>3</td>
<td>3</td>
<td>43</td>
<td>7</td>
</tr>
<tr>
<td>L1_DCM(kernel)</td>
<td>20</td>
<td>123</td>
<td>18</td>
<td>13</td>
<td>12</td>
<td>98</td>
<td>17</td>
</tr>
<tr>
<td>TLB_DM(user)</td>
<td>0</td>
<td>16</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>16</td>
<td>0</td>
</tr>
<tr>
<td>TLB_DM(kernel)</td>
<td>0</td>
<td>18</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>17</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 5.8 STREAM comparing with papi_cost

<table>
<thead>
<tr>
<th>Benchmark</th>
<th>rdpmc cycles</th>
<th>read() cycles</th>
<th>speedup</th>
</tr>
</thead>
<tbody>
<tr>
<td>papi_cost(1 million)</td>
<td>142</td>
<td>1118</td>
<td>7.8x</td>
</tr>
<tr>
<td>element copy</td>
<td>142</td>
<td>1085</td>
<td>7.6x</td>
</tr>
<tr>
<td>vector copy</td>
<td>3974</td>
<td>19233</td>
<td>4.8x</td>
</tr>
<tr>
<td>vector scale</td>
<td>4191</td>
<td>19100</td>
<td>4.6x</td>
</tr>
<tr>
<td>vector add</td>
<td>3932</td>
<td>18855</td>
<td>4.8x</td>
</tr>
<tr>
<td>vector triad</td>
<td>4524</td>
<td>19281</td>
<td>4.3x</td>
</tr>
</tbody>
</table>

Table 5.7 describes PAPI_read() cost in papi_cost and STREAM code. We insert a PAPI_read() after each element copy operation for 1 million times as shown in Figure 4.14 and after each long vector (10M) operation for 1000 iterations as well. We can see from the table that the read() system call and the rdpmc instructions give very similar result for both papi_cost and element copy. However, for vector operations, the result is much higher, but still shows significant speedup (around 4.5x). We assume there should be lots of cache misses and TLB misses for those operations and the results from Table 5.8 confirm our assumptions. Table 5.9 shows total Level 1 cache misses and TLB misses for STREAM when PAPI_read() is supported by
rdpmc and read () system call respectively. Though the values are quite large, there is not much difference between using the rdpmc instruction and read () system call in this case.

Table 5.9 Level 1 cache miss and TLB misses for each vector operation in STREAM

<table>
<thead>
<tr>
<th>PAPI event</th>
<th>vector copy</th>
<th>vector scale</th>
<th>vector add</th>
<th>vector triad</th>
</tr>
</thead>
<tbody>
<tr>
<td>PAPI_L1_DCM</td>
<td>2505104</td>
<td>2505348</td>
<td>3757675</td>
<td>3757657</td>
</tr>
<tr>
<td>PAPI_TLB_DM</td>
<td>25651</td>
<td>39855</td>
<td>27620</td>
<td>24158</td>
</tr>
</tbody>
</table>

Table 5.10 Total Level 1 cache miss and TLB miss for STREAM when PAPI_read() supported by rdpmc and read() separately

<table>
<thead>
<tr>
<th>PAPI event</th>
<th>rdpmc</th>
<th>read</th>
</tr>
</thead>
<tbody>
<tr>
<td>PAPI_L1_DCM</td>
<td>12534134630</td>
<td>12534099690</td>
</tr>
<tr>
<td>PAPI_TLB_DM</td>
<td>110624743</td>
<td>110819195</td>
</tr>
</tbody>
</table>

5.2 Additional Event Overhead

By default the papi_cost benchmark measures two events, PAPI_TOT_INS(total instructions) and PAPI_TOT_CYC(total cycles). They are typical events to measure, especially if you are interested in metrics such as Instruction per Cycle (IPC).

We slightly modify papi_cost to measure from one to four events and test the result on the Haswell machine. Figure 5.1 and Figure 5.2 show how the overhead increases with event number increases for both situations. Each event to be read via rdpmc must have an associated mmap page that can be mapped by the process. So, with rdpmc, each event needs to be read individually and it is reasonable to take more cycles for more events. The read () interface can group multiple events that can be read with one single call. However, the kernel code still has to read the counters out one by one, so the time grows less linearly.
Figure 5.19 PAPI read() cost with rdpmc instruction varies with event number

Figure 5.20 PAPI_read() cost with read() system call varies with event number
5.3 Read overhead by PAPI version

Figure 5.3 shows the `PAPI_read()` overhead gathered for the past few PAPI releases. It can be seen that the overhead has not changed much in the recent past few version as they all use the `perf_event` interface. The figure reports how `PAPI_cost` varies with PAPI on Haswell machine, and results are similar on other machines.

5.4 Kernel update influence

To check if kernel changes pc->lock in rdpmc read code (see Figure 3.3 PAPI rdpmc code) when `per_event_update_userpage()` is called, we add an index (`loopCount`) in the rdpmc code and increment it every time pc->lock changes and print a message to screen if it increases (Figure 5.4). When we run stream benchmark with the setting of `STREAM_ARRAY_SIZE=10M, NTIMS=1000`, the message of “pc->lock changes, loopCount is 2” happens occasionally.

5.5 PAPI_start/stop overhead

The `PAPI_stop()` function reads the current event value once to get a total result between the `PAPI_start()` and the `PAPI_stop()` section. We assume the change from the `read()` system call to the `rdpmc` instruction could also speedup the `PAPI_start()` / `PAPI_stop()` routines. Table 5.10 shows the speed up on the Haswell machine for the `papi_cost` benchmark, and results are similar. We slightly change the `papi_cost` code and make it to only perform start/stop test. By using the `strace` command, we find that the `ioctl()` call dominates the overhead (Figure 5.5). That could be why `rdpmc` doesn’t speed up the `PAPI_start()` / `PAPI_stop()` routine.
Table 5.11 *PAPI_start ()*/PAPI_stop ()* speedup on Haswell machine

<table>
<thead>
<tr>
<th>PAPI function</th>
<th>rdpmc cycles</th>
<th>read() cycles</th>
<th>speedup</th>
</tr>
</thead>
<tbody>
<tr>
<td>PAPI_start/stop</td>
<td>7318</td>
<td>7604</td>
<td>1.03x</td>
</tr>
</tbody>
</table>

Figure 5.21 *papi_cost* varies with PAPI version
Figure 5.22 rdpmc read code with loopCount checking

```c
uint64_t loopCount=0;
do{
    /* The kernel increments pc->lock any time */
    /* perf_event_update_userpage() is called */
    /* So by checking now, and the end, we */
    /* can see if an update happened while we */
    /* were trying to read things, and re-try */
    /* if something changed */
    /* The barrier ensures we get the most up to date */
    /* version of the pc->lock variable */
    loopCount++;
    seq=pc->lock;
    barrier();

    /* For multiplexing */
    /* time_enabled is time the event was enabled */
    enabled = pc->time_enabled;
    /* time_running is time the event was actually running */
    /* running = pc->time_running; ]

    /* if cap_user_time is set, we can use retsc */
    /* to calculate more exact enabled/running time */
    /* for more accurate multiplex calculations */
    if (pc->cap_user_time) && enabled && running) {
        cyx = retsc();
        time_offset = pc->time_offset;
        time_mult = pc->time_mult;
        time_shift = pc->time_shift;

        quot = (cyx>>time_shift);
        rem = cyx & ([(uint64_t)1] << (time_shift - 1));
        delta = time_offset + (quot * time_mult) +
        (rem * time_mult) >> time_shift;
    }
    enabled=delta;

    /* actually do the measurement */
    /* Index of register to read */
    /* 0 means stopped/not-active */
    /* Need to subtract 1 to get actual index to rdpmc() */
    index = pc->index;

    /* count is the value of the counter the last time */
    /* the kernel read it */
    /* If we don’t sign extend it, we get large negative */
    /* numbers which break if an IDC_RESET is done */
    width = pc->rdpmc_width;
    count = pc->offset;
    count<<=(width); count>>=(64-width);

    /* hung. libpfsd perf_event.h has cap_usr_rdpmc */
    /* while actual perf_event.h has cap_user_rdpmc */

    /* Only read if rdpmc enabled and event index valid */
    /* Otherwise return the older (out of date) count value */
    if (pc->cap_usr_rdpmc && index) {
        /* Read counter value */
        pc = rdpmc(index);
        /* sign extend result */
        pc<<=(64-width);
        pc>>=(64-width);
        /* Add current count into the existing kernel count */
        count+=pc;

        /* Only adjust if index is valid */
        running+=delta;
    }
}
while(pc->lock != seq);
if (en) en=enabled;
if (run) run=running;
if (loopCount++) printf("pc->lock changes, loopCount is %lu", loopCount);
```
Figure 5.23 Output for `strace -c ./papi_cost`

```
yanliu@haswell:~/research/papioverhead/papi/papi/src/utils$ strace -c ./papi_cost
Cost of execution for PAPI start/stop, read and accum.
This test takes a while. Please be patient...

Performing loop latency test...
Total cost for loop latency over 1000000 iterations
min cycles : 18
max cycles : 32810
mean cycles : 27.507005
std deviation: 55.076678

Performing start/stop test...
Total cost for PAPI_start/stop (2 counters) over 1000000 iterations
min cycles : 145622
max cycles : 1945210
mean cycles : 17938.652270
std deviation: 7816.761506

<table>
<thead>
<tr>
<th>% time</th>
<th>seconds</th>
<th>usecs/call</th>
<th>calls</th>
<th>errors</th>
<th>syscall</th>
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<td>11.875804</td>
<td>3</td>
<td>4000011</td>
<td>ioctl</td>
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<tr>
<td>21.96</td>
<td>3.342422</td>
<td>3</td>
<td>1000036</td>
<td>read</td>
<td></td>
</tr>
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<td>0.000000</td>
<td>6</td>
<td>14</td>
<td>mmap</td>
<td></td>
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<td>0.000000</td>
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<td>6</td>
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<td>4</td>
<td>23</td>
<td>7 access</td>
<td></td>
</tr>
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<td>15</td>
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</tr>
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<td>4</td>
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<td>1</td>
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<td>0.000000</td>
<td>2</td>
<td>1</td>
<td>arch_prctl</td>
<td></td>
</tr>
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<td>0.000000</td>
<td>0</td>
<td>1</td>
<td>execve</td>
<td></td>
</tr>
</tbody>
</table>
```

---

100.00 15.218858 5000107 8 total
6 CONCLUSION AND FUTURE WORK

We have added userspace (rdpmc) performance counter read support to the PAPI library and found that we can reduce overhead by at least three times (and more typically around six times) on a wide variety of x86 hardware. We instrument several benchmarks and found that the more computer resources that the host code takes, the more overhead PAPI_read() costs. We also found that pc->lock value in rdpmc code may change occasionally.

We gained enough confidence that now PAPI enables the feature by default on all future versions of PAPI. PAPI will once again be able to gather low-overhead performance counter data, with overhead as low as the perfctr interface that was used for years before the introduction of the currently used Linux perf_event. We plan to investigate userspace read support on other architectures that support it, most notably the ARM and ARM64 architectures. Linux perf_event does not properly support this yet.

In addition to the PAPI_read() routine, we plan to investigate other parts of the PAPI library code with the aim to decrease the overhead. The ioctl() system call is one in particular intend to investigate.
REFERENCES


[27] Babka, V. and Tuma, P., Effects of Memory Sharing on Contemporary Processor Architectures. MEMICS 2007, p.3.


[34] Top500 Supercomputer Sites. https://www.top500.org/
Appendix A: Code patch for papi_cost benchmark

--- papi_cost.c 2017-10-26 15:39:50.247793044 -0400
+++ cost1.c 2017-10-26 15:37:50.910831915 -0400
@@ -1,44 +1,39 @@
-/** file papi_cost.c
-+/** file cost.c
+/** file cost.c

-  * @brief papi_cost utility.
-  * @page papi_cost
-  * @section NAME
-  *        papi_cost - computes execution time costs for basic PAPI operations.
-  *
-  *    @section Synopsis
-  *        papi_cost [-dhs] [-b bins] [-t threshold]
-  *
-  *
-  *    @section Description
-  *        papi_cost is a PAPI utility program that computes the min / max / mean / std. deviation
-  *        of execution times for PAPI start/stop pairs and for PAPI reads.
-  *        This information provides the basic operating cost to a user's program
-  *        for collecting hardware counter data.
-  *
-  *
-  *        papi_cost is a PAPI utility program that computes the min / max / mean / std. deviation
-  *        of execution times for PAPI start/stop pairs and for PAPI reads.
-  *        This information provides the basic operating cost to a user's program
-  *        for collecting hardware counter data.
-  *
+  *        papi_cost is a PAPI utility program that computes the min / max / mean / std. deviation
+  *        of execution times for PAPI start/stop pairs and for PAPI reads.
+  *        This information provides the basic operating cost to a user's program
+  *        for collecting hardware counter data.
+  *
- Command line options control display capabilities.
+ 
@section Options

- <li>-b <bins> Define the number of bins into which the results are partitioned for display. The default is 100.
- <li>-d Display a graphical distribution of costs in a vertical histogram.
- <li>-h Display help information about this utility.
- <li>-s Show the number of iterations in each of the first 10 standard deviations above the mean.
- <li>-t <threshold> Set the threshold for the number of iterations to measure costs. The default is 100,000.

@section Bugs

There are no known bugs in this utility. If you find a bug, it should be reported to the PAPI Mailing List at perfapi@icl.utk.edu.

#include <stdio.h>
#include <stdlib.h>
#include <string.h>
#include "papi_test.h"
#include "cost_utils.h"
find_derived( int i , char *type)
{

    PAPI_event_info_t info;
}

printf( "\nTotal cost for %s over %d iterations\n", test[i], num_iters );
printf(-  "min cycles   : %lld
max cycles   : %lld
mean cycles  : %lf
std deviation: %lf
",
min, max, average, std );
}

printf( "\n"
);
int show_dist 
+ { 
+ int s[11]; 
+ long long min, max; 
+ double average, std; 
+ long long percent25,percent50,percent75,percent99; 
+ std = do_stats( array, &min, &max, &average); 
+ print_stats( test_type, min, max, average, std ); 
+ 
+ do_percentile(array,&percent25,&percent50,&percent75,&percent99); 
+ 
+ print_percentile(percent25,percent50,percent75,percent99); 
+ if ( show_std_dev ) {
+ do_std_dev( array, s, std, average );
+ print_std_dev( s );
+ } 
+ 
+ if ( show_dist ) { 
+ int *d; 
+ d = calloc( bins , sizeof ( int ));
+ do_dist( array, min, max, bins, d );
+ print_dist( min, max, bins, d );
+ free( d );
+ } 
+
+static void // add by YAN Liu for rdpmc outliers 
do_output_eventvalue( int test_type, long long *array, int bins, int show_std_dev,
+ int show_dist,long long*eventarray )
{
    int s[11];
    long long min, max;
    double average, std;
+   long long percent25,percent50,percent75,percent99;
+   long long min_i,max_i;
+   std = do_stats_eventvalue( array, &min, &max, &average,&min_i,&max_i);
+   print_stats( test_type, min, max, average, std );

-   std = do_stats( array, &min, &max, &average );
  do_percentile(array,&percent25,&percent50,&percent75,&percent99);

-   print_stats( test_type, min, max, average, std );
+   print_percentile(percent25,percent50,percent75,percent99);

+   printf("\n  eventvalue  for  min(%lld)  which  located  at  array[%d]:
  %lld",min,min_i,eventarray[min_i]);
+   printf("\n  eventvalue  for  max(%lld)  which  located  at  array[%d]:   %lld
\n",max,max_i,eventarray[max_i]);  // add by YAN LIU for rdpmc outliers
    if ( show_std_dev ) {
        do_std_dev( array, s, std, average );
        print_std_dev( s );
    }

int i, retval, EventSet = PAPI_NULL;
int retval_start,retval_stop;
int bins = 100;
-   int show_dist = 0, show_std_dev = 0;
-   long long totcyc, values[2];
+   int show_dist = 0, show_std_dev = 0;
+   long long totcyc, values[4];
long long *array;
int event;
PAPI_event_info_t info;
+ long long *eventarray;
+ /*add by yanliu for event recording*/
+ eventarray =( long long * ) malloc( ( size_t ) num_iters * sizeof ( long long ) );
+ if ( eventarray == NULL ){printf("eventarray malloc failed\n"); return -1;};
+
+ tests_quiet( argc, argv ); /* Set TESTS QUIET variable */

for ( i = 1; i < argc; i++ ) {
    if ( !strcmp( argv[i], "-b" ) ) {
        printf( "Cost of execution for PAPI start/stop, read and accum.\n" );
        printf( "This test takes a while. Please be patient...\n" );

        - retval = PAPI_library_init( PAPI_VER_CURRENT );
        - if (retval != PAPI_VER_CURRENT ) {
            - fprintf(stderr,"PAPI_library_init\n");
            - exit(retval);
        - }
        - retval = PAPI_set_debug( PAPI_VERB_ECONT );
        - if (retval != PAPI_OK ) {
            - fprintf(stderr,"PAPI_set_debug\n");
            - exit(retval);
        - }
        - retval = PAPI_query_event( PAPI_TOT_CYC );
        - if (retval != PAPI_OK ) {
            - fprintf(stderr,"PAPI_query_event\n");
            - exit(retval);
        - }
        - retval = PAPI_query_event( PAPI_TOT_CYC );
        - if (retval != PAPI_OK ) {
            - fprintf(stderr,"PAPI_query_event\n");
            - exit(retval);
        - }
        - retval = PAPI_query_event( PAPI_TOT_CYC );
        - if (retval != PAPI_OK ) {
            - fprintf(stderr,"PAPI_query_event\n");
            - exit(retval);
        - }
    }
retval = PAPI_query_event( PAPI_TOT_INS );
if (retval != PAPI_OK ) {
    fprintf(stderr,"PAPI_query_event\n");
    exit(retval);
}
retval = PAPI_create_eventset( &EventSet );
if (retval != PAPI_OK ) {
    fprintf(stderr,"PAPI_create_eventset\n");
    exit(retval);
}
retval = PAPI_add_event( EventSet, PAPI_TOT_CYC );
if (retval != PAPI_OK ) {
    fprintf(stderr,"PAPI_add_event\n");
    exit(retval);
}
retval = PAPI_add_event( EventSet, PAPI_TOT_INS );
if (retval != PAPI_OK ) {
    retval = PAPI_add_event( EventSet, PAPI_TOT_IIS );
    if (retval != PAPI_OK ) {
        fprintf(stderr,"PAPI_add_event\n");
        exit(retval);
    }
}
if ( ( retval = PAPI_library_init( PAPI_VER_CURRENT ) ) != PAPI_VER_CURRENT )
    testfail( __FILE__, __LINE__, "PAPI_library_init", retval );
if ( ( retval = PAPI_set_debug( PAPI_VERB_ECONT ) ) != PAPI_OK )
    testfail( __FILE__, __LINE__, "PAPI_set_debug", retval );
if ( ( retval = PAPI_query_event( PAPI_TOT_CYC ) ) != PAPI_OK )

+    test_fail(__FILE__, __LINE__, "PAPI_query_event", retval);
+    if ( ( retval = PAPI_query_event( PAPI_TOT_INS ) ) != PAPI_OK )
+        test_fail(__FILE__, __LINE__, "PAPI_query_event", retval);
+    if ( ( retval = PAPI_create_eventset( &EventSet ) ) != PAPI_OK )
+        test_fail(__FILE__, __LINE__, "PAPI_create_eventset", retval);
+
+    if ( ( retval = PAPI_add_event( EventSet, PAPI_L3_TCM ) ) != PAPI_OK ) //add by YAN Liu for rdpmc outliers
+        test_fail(__FILE__, __LINE__, "PAPI_add_event", retval);
+
+    if ( ( retval = PAPI_add_event( EventSet, PAPI_TOT_CYC ) ) != PAPI_OK )
+        test_fail(__FILE__, __LINE__, "PAPI_add_event", retval);
+
+    if ( ( retval = PAPI_add_event( EventSet, PAPI_TOT_INS ) ) != PAPI_OK )
+        if ( ( retval = PAPI_add_event( EventSet, PAPI_TOT_IIS ) ) != PAPI_OK )
+            test_fail(__FILE__, __LINE__, "PAPI_add_event", retval);
+
+    /* Make sure no errors and warm up */
+
+    totcyc = PAPI_get_real_cyc( );
+    if ( ( retval = PAPI_start( EventSet ) ) != PAPI_OK ) {
+        fprintf(stderr,"PAPI_start");
+        exit(retval);
+    }
+    if ( ( retval = PAPI_stop( EventSet, NULL ) ) != PAPI_OK ) {
+        fprintf(stderr,"PAPI_stop");
+        exit(retval);
+    }
+    if ( ( retval = PAPI_start( EventSet ) ) != PAPI_OK )
array =
    ( long long * ) malloc( ( size_t ) num_iters * sizeof ( long long ) );
-   if ( array == NULL ) {
-       fprintf(stderr,"PAPI_stop");
-       exit(retval);
-    }
+   if ( array == NULL )
+       test_fail( __FILE__, __LINE__, "PAPI_stop", retval );

/* Determine clock latency */

@@ -299,8 +318,7 @@
totcyc = PAPI_get_real_cyc( ) - totcyc;
    array[i] = totcyc;
    if (retval_start || retval_stop) {
-        fprintf(stderr,"PAPI start/stop\n");
-        exit(retval_start );
+        test_fail( __FILE__, __LINE__, "PAPI start/stop", retval_start );
     }
 }

@@ -309,10 +327,8 @@
/* Start the read eval */
    printf( "\nPerforming read test...\n" );

-   if ( (retval = PAPI_start( EventSet )) != PAPI_OK ){
fprintf(stderr,"PAPI_start");
exit(retval);
}
+
if ( ( retval = PAPI_start( EventSet ) ) != PAPI_OK )
+
test_fail( __FILE__, __LINE__, "PAPI_start", retval );
PAPI_read( EventSet, values );

for ( i = 0; i < num_iters; i++ ) {
@@ -320,30 +336,27 @@
PAPI_read( EventSet, values );
totcyc = PAPI_get_real_cyc( ) - totcyc;
array[i] = totcyc;
+eventarray[i]=values[0];// add by YAN LIU for rdpmc outliers
+
}
- if ( ( retval = PAPI_stop( EventSet, values ) ) != PAPI_OK ) {
- fprintf(stderr,"PAPI_stop");
- exit(retval);
- }
+ if ( ( retval = PAPI_stop( EventSet, values ) ) != PAPI_OK )
+ test_fail( __FILE__, __LINE__, "PAPI_stop", retval );

- do_output( 2, array, bins, show_std_dev, show_dist );
+ do_output_eventvalue( 2, array, bins, show_std_dev, show_dist,eventarray );// add by YAN LIU for rdpmc outliers
+// do_output( 2, array, bins, show_std_dev, show_dist );

/* Start the read with timestamp eval */
printf( "nPerforming read with timestamp test...n" );
if ( ( retval = PAPI_start( EventSet ) ) != PAPI_OK ) {
    fprintf(stderr,"PAPI_start");
    exit(retval);
}

PAPI_read_ts( EventSet, values, &totcyc );

for ( i = 0; i < num_iters; i++ ) {
    PAPI_read_ts( EventSet, values, &array[i] );
}

if ( ( retval = PAPI_stop( EventSet, values ) ) != PAPI_OK ) {
    fprintf(stderr,"PAPI_stop");
    exit(retval);
}

/* post-process the timing array */
for ( i = num_iters - 1; i > 0; i-- ) {
    /* Start the accum eval */
    printf( "\nPerforming accum test...\n" );

    if ( ( retval = PAPI_start( EventSet ) ) != PAPI_OK ) {
        fprintf(stderr,"PAPI_start");
        exit(retval);
    }
    test_fail( __FILE__, __LINE__, "PAPI_start", retval );
+    PAPI_read_ts( EventSet, values, &totcyc );

    if ( ( retval = PAPI_stop( EventSet, values ) ) != PAPI_OK ) {
+        test_fail( __FILE__, __LINE__, "PAPI_stop", retval );
    }

    /* post-process the timing array */

    /* Start the accum eval */
    printf( "Performing accum test...\n" );

    if ( ( retval = PAPI_start( EventSet ) ) != PAPI_OK ) {
        fprintf(stderr,"PAPI_start");
        exit(retval);
    }
    test_fail( __FILE__, __LINE__, "PAPI_start", retval );

PAPI_accum(EventSet, values);

for ( i = 0; i < num_iters; i++ ) {
    @@ -368,20 +379,16 @@
    totcyc = PAPI_get_real_cyc() - totcyc;
    array[i] = totcyc;
}
-   if ( ( retval = PAPI_stop( EventSet, values ) ) != PAPI_OK ) {
-       fprintf(stderr,"PAPI_stop");
-       exit(retval);
-   }
+   if ( ( retval = PAPI_stop( EventSet, values ) ) != PAPI_OK )
+       test_fail( __FILE__, __LINE__, "PAPI_stop", retval );

do_output( 4, array, bins, show_std_dev, show_dist );

    /* Start the reset eval */
    printf( "\nPerforming reset test...\n" );

-   if ( ( retval = PAPI_start( EventSet ) ) != PAPI_OK ) {
-       fprintf(stderr,"PAPI_start");
-       exit(retval);
-   }
+   if ( ( retval = PAPI_start( EventSet ) ) != PAPI_OK )
+       test_fail( __FILE__, __LINE__, "PAPI_start", retval );

    for ( i = 0; i < num_iters; i++ ) {
        totcyc = PAPI_get_real_cyc();
@@ -389,10 +396,8 @@
        totcyc = PAPI_get_real_cyc() - totcyc;
array[i] = totcyc;
}
- if ( ( retval = PAPI_stop( EventSet, values ) ) != PAPI_OK ) {
-   fprintf(stderr,"PAPI_stop");
-   exit(retval);
- }
+ if ( ( retval = PAPI_stop( EventSet, values ) ) != PAPI_OK )
+   test_fail( __FILE__, __LINE__, "PAPI_stop", retval );

do_output( 5, array, bins, show_std_dev, show_dist );

@@ -411,14 +416,12 @@

retval = PAPI_add_event( EventSet, event);
if ( retval != PAPI_OK ) {
-   fprintf(stderr,"PAPI_add_event");
-   exit(retval);
+   test_fail(__FILE__, __LINE__, "PAPI_add_event", retval);
  }

retval = PAPI_start( EventSet );
if ( retval != PAPI_OK ) {
-   fprintf(stderr,"PAPI_start");
-   exit(retval);
+   test_fail(__FILE__, __LINE__, "PAPI_start", retval );
  }

PAPI_read( EventSet, values );
@@ -432,8 +435,7 @@
retval = PAPI_stop( EventSet, values );
if ( retval != PAPI_OK ) {
    - fprintf(stderr,"PAPI_stop");
    - exit(retval);
    + test_fail(__FILE__, __LINE__, "PAPI_stop", retval);
}

do_output( 6, array, bins, show_std_dev, show_dist );
@@ -458,14 +460,12 @@

retval = PAPI_add_event( EventSet, event);
if ( retval != PAPI_OK ) {
    - fprintf(stderr,"PAPI_add_event\n");
    - exit(retval);
    + test_fail(__FILE__, __LINE__, "PAPI_add_event", retval);
}

retval = PAPI_start( EventSet );
if ( retval != PAPI_OK ) {
    - fprintf(stderr,"PAPI_start");
    - exit(retval);
    + test_fail(__FILE__, __LINE__, "PAPI_start", retval);
}

PAPI_read( EventSet, values );
@@ -479,8 +479,7 @@

retval = PAPI_stop( EventSet, values );
if ( retval != PAPI_OK ) {
    - fprintf(stderr,"PAPI_stop");

-    exit(retval);
+    test_fail(__FILE__, __LINE__, "PAPI_stop", retval );
    }

    do_output(7, array, bins, show_std_dev, show_dist );
@@ -490,6 +489,6 @@
    }

    free( array );
    -
-    return 0;
+    test_pass(__FILE__, NULL, 0 );
+    exit( 1 );
    }

--- cost_utils.c  2017-10-26 15:39:11.775482486 -0400
+++ cost_utils1.c  2017-10-26 15:38:34.083178869 -0400
@@ -1,10 +1,6 @@
-#include <stdio.h>
-#include <math.h>
-
-#define NUM_ITERS 1000000
+#include "papi_test.h"

 int num_iters = NUM_ITERS;
-
 /* computes min, max, and mean for an array; returns std deviation */
 double
do_stats( long long *array, long long *min, long long *max, double *average )
@@ -17,7 +13,7 @@
 for ( i = 0; i < num_iters; i++ ) {
     *average += ( double ) array[i];
     if ( *min > array[i] )
-           *min = array[i];
+             *min = array[i];
     if ( *max < array[i] )
         *max = array[i];
 }
@@ -76,3 +72,84 @@
 }
}

+int partition( long long a[], int l, int r) {
+    long  pivot, i, j, t;
+    pivot = a[l];
+    i = l; j = r+1;
+
+    + while( 1 )
+    + {  
+        do ++i; while( a[i] < pivot && i < r );
+        do --j; while( a[j] > pivot );
+        if( i >= j ) break;
+        t = a[i]; a[i] = a[j]; a[j] = t;
+    } +  
+    + t = a[l]; a[l] = a[j]; a[j] = t;
+    + return j;
+} +
+void quickSort( long long a[], int l, int r)
```c
int j;

if( l < r )
{
    // divide and conquer
    j = partition( a, l, r);
    quickSort( a, l, j-1);
    quickSort( a, j+1, r);
}

void do_percentile(long long *a, long long *percent25, long long *percent50, long long *percent75,long long *percent99)
{
    long long *a_sort;
    a_sort = calloc(num_iters,sizeof(long long));
    memcpy(a_sort,a,num_iters*sizeof(long long));
    int i_25=(int)num_iters/4;
    int i_50=(int)num_iters/2;
    int i_75=(int)num_iters/4*3; // index for 75%, not quite accurate cause didn't take even or odd in consideration
    int i_99=(int)num_iters/10*9.9;
    quickSort(a_sort,0,num_iters-1);
    
    *percent25=a_sort[i_25];
    *percent50=a_sort[i_50];
    *percent75=a_sort[i_75];
    *percent99=a_sort[i_99];
```

+ *percent99=a_sort[i_99];
+ free(a_sort);
+ a_sort=NULL;
+
+
+}
+double // add by YAN Liu for rdpmc outliers
+do_stats_eventvalue( long long *array, long long *min, long long *max, double *average,long long *min_i,long long *max_i )
+{
+    int i;
+    double std, tmp;
+
+    *min = *max = array[0];
+    *average = 0;
+    for ( i = 0; i < num_iters; i++ ) {
+        *average += (double) array[i];
+        if ( *min > array[i] )
+        {
+            *min = array[i];
+            *min_i=i;
+        }
+        if ( *max < array[i] )
+        {
+            *max = array[i];
+            *max_i=i;
+        }
+        *average = *average / (double) num_iters;
+        std = 0;
+        for ( i = 0; i < num_iters; i++ ) {
+         tmp = ( double ) array[i] - ( *average );
+         std += tmp * tmp;
+     }
+     std = sqrt( std / ( num_iters - 1 ) );
+     return ( std );
+
+--- cost_utils.h    2017-10-26 15:39:19.167542110 -0400
+++ cost_utils1.h   2017-10-26 15:38:23.867096692 -0400
@@ -5,5 +5,6 @@
 extern double  do_stats(long long*, long long*, long long *, double *);
 extern void        do_std_dev( long long*, int*, double, double );
 extern void        do_dist( long long*, long long, long long, int, int*);
+extern double   do_stats_eventvalue(long  long*,  long  long*,  long  long  *,  double  *,long long*,long long*);

 #endif /* __PAPI_COST_UTILS_H__ */
Appendix B: Sobel code

/* sobel benchmark for Papi overhead measurement */
/* modified based on ece574 example code */
/* Yan Liu */
#include <stdlib.h>
#include <stdio.h>
#include <string.h>
#include <stdint.h>
#include <errno.h>
#include <math.h>

#include <jpeglib.h>
#include "../papi/papi/src/papi.h"
#define MAX 1000000

/* Filters */
static int sobel_x_filter[3][3] = {{-1,0,+1}, {-2,0,+2}, {-1,0,+1}};
static int sobel_y_filter[3][3] = {{-1,-2,-1}, {0,0,0}, {1,2,+1}};

/* Structure describing the image */
struct image_t {
    int x;
    int y;
    int depth; /* bytes */
    unsigned char *pixels;
};
struct convolve_data_t {
    struct image_t *old;
    struct image_t *new;
    int(*filter)[3][3];
    int papiEventset;
};

int partition(longlong a[], int l, int r) {
    long pivot, i, j, t;
    pivot = a[l];
    i = l; j = r + 1;

    while (1)
    {
        while (a[i] < pivot && i < r);
        while (a[j] > pivot);
        if (i >= j) break;
            t = a[i]; a[i] = a[j]; a[j] = t;
        }
    t = a[l]; a[l] = a[j]; a[j] = t;
    return j;
}

void quickSort(longlong a[], int l, int r) {
    int j;

    if (l < r )
    {
        // divide and conquer
            j = partition( a, l, r);
        quickSort( a, l, j-1);
    }
quickSort( a, j+1, r);

}

}

void do_percentile(int num_iters, jlonglong *a, jlonglong *percent25, jlonglong *percent50, jlonglong *percent75, jlonglong *percent99)
{
    jlonglong *a_sort;
    a_sort = calloc(num_iters, sizeof(jlonglong));
    memcpy(a_sort, a, num_iters * sizeof(jlonglong));
    int i_25=(int)num_iters/4;
    int i_50=(int)num_iters/2;
    int i_75=(int)num_iters/4*3;// index for 75%, not quite accurate cause didn’t take even or odd in consideratio
    int i_99=(int)num_iters/10*9.9;
    quickSort(a_sort,0,num_iters-1);

    *percent25=a_sort[i_25];
    *percent50=a_sort[i_50];
    *percent75=a_sort[i_75];
    *percent99=a_sort[i_99];
    free(a_sort);
    a_sort=NULL;

}

static void print_percentile(jlonglong percent25, jlonglong percent50, jlonglong percent75, jlonglong percent99)
{  
    printf("25%% cycles : %lld
50%% cycles : %lld
75%% cycles : %lld
99%% cycles : %lld",  
    percent25,percent50,percent75,percent99);  
}

static void cal_stats(int num_iters, longlong *array, longlong *min,  
longlong *max, double *avag, double *std){  
    int i;  
    double tmp;  
    longlong percent25, percent50, percent75, percent99;  
    *max=*min=array[0];  
    for(i=0;i<num_iters;i++)  
        if(*max<array[i]) *max=array[i];  
    if(*min>array[i]) *min=array[i];  
    *avag+=(*double)array[i];  
    //      printf("%d-%lld 
",i,array[i]);
}

*avag=*avag/(double)num_iters;  
for(i = 0; i < num_iters; i++)  
    tmp =(*double)array[i]-(*avag );  
*std += tmp * tmp;  
}

*std=sqrt(*std/num_iters);  
do_percentile(num_iters,array,&percent25,&percent50,&percent75,&percent99);  

    print_percentile(percent25,percent50,percent75,percent99);  
}
/ * very inefficient convolve code */
static void *generic_convolve(void *argument){

int x, y, k, l, d;
int32_t color;
int sum, depth, width, height;
longlong totcyc, *array, values[3];
struct image_t *old;
struct image_t *new;
int(*filter)[3][3];
struct convolve_data_t *data;
int eventset;
int result;
longlong min, max;
double avag, std;
int num_iters;

/* Convert from void pointer to the actual data type */
data=(struct convolve_data_t *)argument;
old=data->old;
new=data->new;
filter=data->filter;
    eventset=data->papiEventset;
depth=old->depth;
width=old->x*old->depth;
height=old->y;
min=max=0;
avag=std=0;
array=(longlong*)malloc(width*height*sizeof(longlong));
num_iters=0;

//PAPI start
// if((result=PAPI_start(eventset))!=PAPI_OK)
//  printf("Error PAPI start:%s\n",PAPI_strerror(result));
// PAPI_read(eventset,values);
for(d=0;d<3;d++){
  for(x=0;x<old->x;x++){
    for(y=0;y<old->y;y++){

      sum=0;
      for(k=-1;k<2;k++){
        for(l=-1;l<2;l++){
          color=old->pixels[((y+l)*width)+(x*depth+d+k*depth)];
          sum+=color [*(*filter)[k+1][l+1];
        }
      }

      if(sum<0) sum=0;
      if(sum>255) sum=255;

      new->pixels[(y*width)+x*depth+d]=sum;
  }
}

if(num_iters<=MAX)
{
  totcyc=PAPI_get_real_cyc();
  PAPI_read(eventset,values);
  totcyc=PAPI_get_real_cyc()-totcyc;
  array[num_iters]=totcyc;
  num_iters++;
}
}
if((result=PAPI_stop(eventset,values))!=PAPI_OK)
    printf("Error PAPI stop:%s\n",PAPI_strerror(result));
printf("Total cost for PAPI_read over %d iterations \n",-num_iters);
cal_stats(num_iters,array,&min,&max,&avag,&std);
printf("min cycles : %lld\nmax cycles : %lld\naverage cycles : %lf\nstandard deviation: %lf\n", 
    min,max,avag,std);

returnNULL;
}

staticint load_jpeg(char*filename,struct image_t *image){

    FILE*fff;
    struct jpeg_decompress_struct cinfo;
    struct jpeg_error_mgr jerr;
    JSAMPROW output_data;
    unsignedint scanline_len;
    int scanline_count=0;

    fff=fopen(filename,"rb");
    if(fff==NULL){
        fprintf(stderr,"Could not load %s: %s\n",filename,strerror(errno));
        return-1;
    }

    /* set up jpeg error routines */
    cinfo.err = jpeg_std_error(&jerr);
/* Initialize cinfo */
jpeg_create_decompress(&cinfo);

/* Set input file */
jpeg_stdio_src(&cinfo, fff);

/* read header */
jpeg_read_header(&cinfo, TRUE);

/* Start decompressor */
jpeg_start_decompress(&cinfo);

printf("output_width=%d, output_height=%d, output_components=%d\n",
cinfo.output_width,
cinfo.output_height,
cinfo.output_components);

image->x=cinfo.output_width;
image->y=cinfo.output_height;
image->depth=cinfo.output_components;

scanline_len = cinfo.output_width * cinfo.output_components;
image->pixels=malloc(cinfo.output_width * cinfo.output_height * cinfo.output_components);

while(scanline_count < cinfo.output_height){
    output_data = (image->pixels + (scanline_count * scanline_len));
    jpeg_read_scanlines(&cinfo,&output_data,1);
    scanline_count++;
}
/* Finish decompressing */
jpeg_finish_decompress(&cinfo);

jpeg_destroy_decompress(&cinfo);

fclose(fff);

return 0;
}

static int store_jpeg(char* filename, struct image_t *image){

struct jpeg_compress_struct cinfo;
struct jpeg_error_mgr jerr;
int quality=90;/* % */
int i;

FILE* fff;

JSAMPROW row_pointer[1];
int row_stride;

/* setup error handler */
cinfo.err = jpeg_std_error(&jerr);

/* initialize jpeg compression object */
jpeg_create_compress(&cinfo);
/* Open file */
    fff = fopen(filename, "wb");
    if(fff == NULL){
        fprintf(stderr, "can't open %s: %s\n",
                filename, strerror(errno));
        return -1;
    }

    jpeg_stdio_dest(&cinfo, fff);

/* Set compression parameters */
    cinfo.image_width = image->x;
    cinfo.image_height = image->y;
    cinfo.input_components = image->depth;
    cinfo.in_color_space = JCS_RGB;
    jpeg_set_defaults(&cinfo);
    jpeg_set_quality(&cinfo, quality, TRUE);

/* start compressing */
    jpeg_start_compress(&cinfo, TRUE);

    row_stride=image->x*image->depth;

    for(i=0;i<image->y;i++){
        row_pointer[0]=& image->pixels[i * row_stride];
        jpeg_write_scanlines(&cinfo, row_pointer, 1);
    }

/* finish compressing */
    jpeg_finish_compress(&cinfo);
/* close file */
fclose(fff);

/* clean up */
jpeg_destroy_compress(&cinfo);

return 0;
}

static int combine(struct image_t *s_x, struct image_t *s_y, struct image_t *new){
   int i;
   int out;

   for(i=0;i<(s_x->depth * s_x->x * s_x->y );i++){

      out=sqrt(
      (s_x->pixels[i]*s_x->pixels[i])+
      (s_y->pixels[i]*s_y->pixels[i])
      );
      if(out>255) out=255;
      if(out<0) out=0;
      new->pixels[i]=out;
   }

   return 0;
}
int main(int argc,char** argv){

struct image_t image,sobel_x,sobel_y,new_image;
struct convolve_data_t sobel_data[2];

longlong time_start,time_end,time_total,values[3]; //for PAPI time measuring

/* Check command line usage */
if(argc<2){
    fprintf(stderr,"Usage: %s image_file\n",argv[0]);
    return-1;
}

int eventset=PAPI_NULL;
int result;

if((result=PAPI_library_init(PAPI_VER_CURRENT))!=PAPI_VER_CURRENT)
    printf("Error PAPI library init:%s\n",PAPI_strerror(result));

/*create papi eventset and add events*/
if((result=PAPI_create_eventset(&eventset))!=PAPI_OK)
    printf("Error PAPI create event:%s\n",PAPI_strerror(result));

/* if((result=PAPI_add_named_event(eventset,"PAPI_L1_TCM"))!=PAPI_OK)
    printf("Error PAPI add event:%s\n",PAPI_strerror(result));
if((result=PAPI_add_named_event(eventset,"PAPI_L2_TCM"))!=PAPI_OK)
    printf("Error PAPI add event:%s\n",PAPI_strerror(result));
*/
if((result=PAPI_add_named_event(eventset,"BR_MISP RETIRED:CONDITIONAL:k=1"))!=PAPI_OK)
    printf("Error PAPI add event1:%s\n",PAPI_strerror(result));
if((result=PAPI_add_named_event(eventset,"BR_MISP RETIRED:CONDITIONAL:u=1"))!=PAPI_OK)
    printf("Error PAPI add event2:%s\n",PAPI_strerror(result));
```c
// if((result=PAPI_add_named_event(eventset,"INSTRUCTIONS_RETIRED:k=1:u=1"))!=PAPI_OK)
//  printf("Error PAPI add event3:%s\n",PAPI_strerror(result));

if((result=PAPI_add_named_event(eventset,"PAPI_BR_MSP"))!=PAPI_OK)
    printf("Error PAPI add event4:%s\n",PAPI_strerror(result));

PAPI_start(eventset);
// time_start=PAPI_get_real_usec();

/* Load an image */
load_jpeg(argv[1],&image);

PAPI_stop(eventset,values);
//printf("L1 load jpeg %lld\n",values[0]);
//printf("L2 load jpeg%lld\n",values[1]);

PAPI_start(eventset);
/* Allocate space for output image */
new_image.x=image.x;
new_image.y=image.y;
new_image.depth=image.depth;
new_image.pixels=malloc(image.x*image.y*image.depth*sizeof(char));

/* Allocate space for output image */
sobel_x.x=image.x;
sobel_x.y=image.y;
sobel_x.depth=image.depth;
sobel_x.pixels=malloc(image.x*image.y*image.depth*sizeof(char));
```
/* Allocate space for output image */
sobel_y.x=image.x;
sobel_y.y=image.y;
sobel_y.depth=image.depth;
sobel_y.pixels=malloc(image.x*image.y*image.depth*sizeof(char));

/* convolution */
sobel_data[0].old=&image;
sobel_data[0].new=&sobel_x;
sobel_data[0].filter=&sobel_x_filter;
sobel_data[0].papiEventset=eventset;
generic_convolve((void *)&sobel_data[0]);

sobel_data[1].old=&image;
sobel_data[1].new=&sobel_y;
sobel_data[1].filter=&sobel_y_filter;
sobel_data[1].papiEventset=eventset;
// generic_convolve((void *)&sobel_data[1]);

/* Combine to form output */
combine(&sobel_x,&sobel_y,&new_image);

/* Write data back out to disk */
store_jpeg("out.jpg",&new_image);
PAPI_stop(eventset,values);
//printf("L1 rest %lld\n",values[0]);
//printf("L2 rest %lld\n",values[1]);
 printf("kernel %lld\n",values[0]);
 printf("user %lld\n",values[1]);
 printf("k+u %lld\n",values[2]);
printf("papi event %lld\n", values[2]);

// time_end=PAPI_get_real_usec();
// time_total=time_end-time_start;
// printf("PAPI_time_measure for main func: %lld us\n", time_total);

PAPI_shutdown();

return 0;
}

Appendix C: Code patch for HPL benchmark

--- 1HPL_pdgev0.c  2017-08-30 15:42:32.546218175 -0400
+++ HPL_pdgesv0.c  2017-10-25 15:59:21.716712958 -0400
@@ -48,6 +48,100 @@
 * Include files
 */
#include "hpl.h"
+/* Add for papi test stats */
+#include "/home/yanliu/research/papioverhead/papi/papi/src/papi.h"
+#include "stdio.h"
+#include "math.h"
+// rdpmc code
+static inline unsigned long long rdpmc(unsigned int counter) {
+  
+  unsigned int low, high;
+  
+  __asm__ volatile("rdpmc" : "=a" (low), "=d" (high) : "c" (counter));
+  
+  return (unsigned long long)low | ((unsigned long long)high) <<32;
+}
+
+int partition( long long a[], int l, int r) {
+  long pivot, i, j, t;
+  pivot = a[l];
+  i = l; j = r+1;
+  
+  while( 1)
+    {


+ do ++i; while( a[i] < pivot && i < r );
+ do --j; while( a[j] > pivot );
+ if( i >= j ) break;
+ t = a[i]; a[i] = a[j]; a[j] = t;
+ }
+ t = a[l]; a[l] = a[j]; a[j] = t;
+ return j;
+
+void quickSort( long long a[], int l, int r)
+
+{
+  int j;
+
+  if( l < r )
+  {
+    // divide and conquer
+    j = partition( a, l, r);
+    quickSort( a, l, j-1);
+    quickSort( a, j+1, r);
+  }
+
+}
+
+void do_percentile(int num_iters,long long *a, long long *percent25, long long *percent50,
long long *percent75,long long *percent99)
+
+{
+  long long *a_sort;
+  a_sort = calloc(num_iters,sizeof(long long));
+  memcpy(a_sort,a,num_iters*sizeof(long long));
+  int i_25=(int)num_iters/4;
+  int i_50=(int)num_iters/2;
+  int i_75=(int)num_iters/4*3; // index for 75%, not quite accurate cause didn't take even or
Odd in consideration

+    int i_99=(int)num_iters/10*9.9;
+    quickSort(a_sort,0,num_iters-1);
+
+
+    *percent25=a_sort[i_25];
+    *percent50=a_sort[i_50];
+    *percent75=a_sort[i_75];
+    *percent99=a_sort[i_99];
+    free(a_sort);
+    a_sort=NULL;
+
+
+}  
+static void
+print_percentile(long long percent25, long long percent50, long long percent75,long long percent99)
+
+{
+    printf
+        ("25%% cycles   : %lld
50%% cycles   : %lld
75%% cycles   : %lld
99%% cycles   : %lld
",
+    percent25,percent50,percent75,percent99);
+}

+static void cal_stats(int num_iters,long long *array, long long *min,
+    long long *max, double *avag,double *std)
++    int i; double tmp;
++    long long percent25, percent50, percent75, percent99;
++    *max=*min=array[0];
++    *avag=0; *std=0;
++    for(i=0;i<num_iters;i++)
++        if(*max<array[i]) *max=array[i];
++        if(*min>array[i]) *min=array[i];
+    *avag+=(double)array[i];
+    //        printf("%d-%lld \n",i,array[i]);
+
+    }
+    *avag=(double)*avag/num_iters;
+    for ( i = 0; i < num_iters; i++ ) {
+        tmp = (double)array[i] - ( *avag );
+        *std += tmp * tmp;
+    }
+    *std=sqrt(*std/num_iters);
+    do_percentile(num_iters,array,&percent25,&percent50,&percent75,&percent99);
+
+    print_percentile(percent25,percent50,percent75,percent99);
+}
+
+
+#ifdef STDC_HEADERS

void HPL_pdgesv0
{

@@ -95,8 +189,48 @@

*/
     HPL_T_panel                * * panel = NULL;
     HPL_T_UPD_FUN              HPL_pdupdate;
-    int                      N, j, jb, n, nb, tag=MSGID_BEGIN_FACT,
-    test=HPL_KEEP_TESTING;
+    int                      N, j, jb, n, nb, tag=MSGID_BEGIN_FACT, test=HPL_KEEP_TESTING;
+
+/*start PAPI setup*/
+    int max_iters=1000;
+    int readNum=7;
+ long long totcyc, array[readNum][max_iters], values[3], lastVal1, lastVal2,
+ eventVal1[readNum][max_iters], eventVal2[readNum][max_iters],
+ rawVal1[readNum][max_iters], rawVal2[readNum][max_iters],
+ rawBefore1, rawBefore2, rawAfter1, rawAfter2;
+ long long min[readNum], max[readNum];
+ double avg[readNum], std[readNum];
+ int num_iters=0;
+ int eventset=PAPI_NULL;
+ int result;
+ #define USER_EVENT 0 //1073741825
+ #define KERNEL_EVENT 1
+ /*
+ haswell machine event name table
+ "PRESET,PAPI_TOT_CYC,NOT_DERIVED,CPU_CLK_THREAD_UNHALTED:THREAD_P\n"
+ "PRESET,PAPI_TOT_INS,NOT_DERIVED,INST_RETIRED:ANY_P\n" (user 1073741825 kernel 1)
+ "PRESET,PAPI_L1_DCM,NOT_DERIVED,L1D:REPLACEMENT\n"
+ "PRESET,PAPI_L1_TCM,DERIVED_ADD,L1D:REPLACEMENT,L2_RQSTS:ALL_CODE_RD\n"
+ "PRESET,PAPI_BR_MSP,NOT_DERIVED,BR_MISP_RETIRED:CONDITIONAL\n"
+ "PRESET,PAPI_TLB_DM,DERIVED_ADD,DTLB_LOAD_MISSES:MISS_CAUSES_A_WALK,DTLB_STORE_MISSES:MISS_CAUSES_A_WALK\n"
+ "PRESET,PAPI_TLB_IM,NOT_DERIVED,ITLB_MISSES:MISS_CAUSES_A_WALK\n"
+ /*
+ // array=(long long*)malloc(max_iters*sizeof(long long));
+ if((result=PAPI_library_init(PAPI_VER_CURRENT))!=PAPI_VER_CURRENT)
+ printf("Error PAPI library init:%s\n",PAPI_strerror(result));
+ /*create papi eventset and add events*/
+ if((result=PAPI_create_eventset(&eventset))!=PAPI_OK)
+ printf("Error PAPI create event:%s\n",PAPI_strerror(result));
+ +
if((result=PAPI_add_named_event(eventset,"L1D:REPLACEMENT,L2_RQSTS:ALL_CODE_RD:u=1"))!=PAPI_OK)
            printf("Error PAPI add event1:%s\n",PAPI_strerror(result));
+
if((result=PAPI_add_named_event(eventset,"L1D:REPLACEMENT,L2_RQSTS:ALL_CODE_RD:u=0:k
    =1"))!=PAPI_OK)
            printf("Error PAPI add event2:%s\n",PAPI_strerror(result));
+
    if((result=PAPI_start(eventset))!=PAPI_OK)
            printf("Error PAPI start:%s\n",PAPI_strerror(result));
+
    PAPI_read(eventset,values);
+
+/*end PAPI setup*/
+
/* ..
   * .. Executable Statements ..
   */
@@ -115,29 +249,205 @@
/*
   * Loop over the columns of A
   */
-    for( j = 0; j < N; j += nb )
-    {
-        n = N - j; jb = Mmin( n, nb );
+    for( j = 0; j < N; j += nb )
+    {
+        n = N - j; jb = Mmin( n, nb );
+        /*
+         * Release panel resources - re-initialize panel data structure
+         */
+        (void) HPL_pdpanel_free( panel[0] );
- HPL_pdpanel_init( GRID, ALGO, n, n+1, jb, A, j, j, tag, panel[0] );
- */
- * Factor and broadcast current panel - update
+ (void) HPL_pdpanel_free( panel[0] );
+ /*start papi read*/
+ 
+ + PAPI_start(eventset);
+ 
+ + HPL_pdpanel_init( GRID, ALGO, n, n+1, jb, A, j, j, tag, panel[0] );
+ 
+ rawBefore1=rdpmc(USER_EVENT); //raw rdpmc measure USER_EVENT for PAPI_read
+ rawBefore2=rdpmc(KERNEL_EVENT); // raw rdpmc measure KERNEL_EVENT for PAPI_read
+ 
+ // totcyc=PAPI_get_real_cyc();
+ PAPI_read(eventset,values);
+ //totcyc=PAPI_get_real_cyc()-totcyc; // measure total cycle cost by PAPI_read
+ 
+ rawAfter1=rdpmc(USER_EVENT);
+ rawAfter2=rdpmc(KERNEL_EVENT);
+ 
+ PAPI_stop(eventset,values);
+ 
+ array[0][num_iters]=totcyc;
+ eventVal1[0][num_iters]=values[0]; // event value measured by papi_start/stop
+ eventVal2[0][num_iters]=values[1];
+ rawVal1[0][num_iters]=rawAfter1-rawBefore1; // event value measured by rdpmc
+ rawVal2[0][num_iters]=rawAfter2-rawBefore2;
+ 

+/* end papi read*/
+
+*/ Factor and broadcast current panel - update */
+
-              HPL_pdfact( panel[0] );
-              (void) HPL_binit( panel[0] );
+  /*start papi read*/
+
+  PAPI_start(eventset);
+
+  HPL_pdfact( panel[0] );
+
+  rawBefore1=rdpmc(USER_EVENT);  //raw rdpmc measure USER_EVENT for PAPI_read
+  rawBefore2=rdpmc(KERNEL_EVENT); // raw rdpmc measure KERNEL_EVENT for PAPI_read
+
+  // totcyc=PAPI_get_real_cyc();
+  PAPI_read(eventset,values);
+  // totcyc=PAPI_get_real_cyc()-totcyc; // measure total cycle cost by PAPI_read
+
+  rawAfter1=rdpmc(USER_EVENT);
+  rawAfter2=rdpmc(KERNEL_EVENT);
+
+  PAPI_stop(eventset,values);
+
+  array[1][num_iters]=totcyc;
+
+  eventVal1[1][num_iters]=values[0]; // event value measured by papi_start/stop
+  eventVal2[1][num_iters]=values[1];
+  rawVal1[1][num_iters]=rawAfter1-rawBefore1; // event value measured by rdpmc
+  rawVal2[1][num_iters]=rawAfter2-rawBefore2;
+  /*end papi read*/
/** initialize panel */

/** start papi read */

PAPI_start(eventset);

(void) HPL_binit(panel[0]);

rawBefore1=rdpmc(USER_EVENT); //raw rdpmc measure USER_EVENT for PAPI_read
rawBefore2=rdpmc(KERNEL_EVENT); // raw rdpmc measure KERNEL_EVENT for PAPI_read

// totcyc=PAPI_get_real_cyc();
PAPI_read(eventset,values);

//totcyc=PAPI_get_real_cyc()-totcyc; // measure total cycle cost by PAPI_read

rawAfter1=rdpmc(USER_EVENT);
rawAfter2=rdpmc(KERNEL_EVENT);

PAPI_stop(eventset,values);

array[2][num_iters]=totcyc;
eventVal1[2][num_iters]=values[0]; // event value measured by papi_start/stop
eventVal2[2][num_iters]=values[1];
rawVal1[2][num_iters]=rawAfter1-rawBefore1; // event value measured by rdpmc
rawVal2[2][num_iters]=rawAfter2-rawBefore2;

/** end papi read */

/** broadcast */
/*start papi read*/

PAPI_start(eventset);

do
{
    // (void) HPL_bcast( panel[0], &test );
    while( test != HPL_SUCCESS );
}

rawBefore1=rdpmc(USER_EVENT);  // raw rdpmc measure USER_EVENT for PAPI_read
rawBefore2=rdpmc(KERNEL_EVENT); // raw rdpmc measure KERNEL_EVENT for PAPI_read

// totcyc=PAPI_get_real_cyc();
PAPI_read(eventset,values);
// totcyc=PAPI_get_real_cyc()-totcyc; // measure total cycle cost by PAPI_read

rawAfter1=rdpmc(USER_EVENT);
rawAfter2=rdpmc(KERNL_EVENT);
PAPI_stop(eventset,values);

array[3][num_iters]=totcyc;

eventVal1[3][num_iters]=values[0]; // event value measured by papi_start/stop

eventVal2[3][num_iters]=values[1];

rawVal1[3][num_iters]=rawAfter1-rawBefore1; // event value measured by rdpmc

rawVal2[3][num_iters]=rawAfter2-rawBefore2;

/*end papi read*/

/*HPL_bwait*/

/*start papi read*/

/*end papi read*/
+ PAPI_start(eventset);
    (void) HPL_bwait( panel[0] );
- HPL_pdupdate( NULL, NULL, panel[0], -1 );
+ rawBefore1=rdpmc(USER_EVENT); //raw rdpmc measure USER_EVENT for PAPI_read
+ rawBefore2=rdpmc(KERNEL_EVENT); // raw rdpmc measure KERNEL_EVENT for PAPI_read
+ // totcyc=PAPI_get_real_cyc();
+ PAPI_read(eventset,values);
+ // totcyc=PAPI_get_real_cyc()-totcyc; // measure total cycle cost by PAPI_read
+
+ rawAfter1=rdpmc(USER_EVENT);
+ rawAfter2=rdpmc(KERNEL_EVENT);
+
+ PAPI_stop(eventset,values);
+
+ array[4][num_iters]=totcyc;
+ eventVal1[4][num_iters]=values[0]; // event value measured by papi_start/stop
+ eventVal2[4][num_iters]=values[1];
+ rawVal1[4][num_iters]=rawAfter1-rawBefore1; // event value measured by rdpmc
+ rawVal2[4][num_iters]=rawAfter2-rawBefore2;
+
+ /*end papi read*/
+
+ /*pannel update*/
+
+ /*start papi read*/
+
+ PAPI_start(eventset);
+ HPL_pdupdate( NULL, NULL, panel[0], -1 );
+ rawBefore1=rdpmc(USER_EVENT); //raw rdpmc measure USER_EVENT for PAPI_read
+ rawBefore2=rdpmc(KERNEL_EVENT); // raw rdpmc measure KERNEL_EVENT for PAPI_read
+
+   // totcyc=PAPI_get_real_cyc();
+   PAPI_read(eventset,values);
+   // totcyc=PAPI_get_real_cyc()-totcyc; // measure total cycle cost by PAPI_read
+
+   rawAfter1=rdpmc(USER_EVENT);
+   rawAfter2=rdpmc(KERNEL_EVENT);
+
+   PAPI_stop(eventset,values);
+
+   array[5][num_iters]=totcyc;
+   eventVal1[5][num_iters]=values[0]; // event value measured by papi_start/stop
+   eventVal2[5][num_iters]=values[1];
+   rawVal1[5][num_iters]=rawAfter1-rawBefore1; // event value measured by rdpmc
+   rawVal2[5][num_iters]=rawAfter2-rawBefore2;
+
+   /*end papi read*/
+
+ /*
* Update message id for next factorization
*/
+   /*start papi read*/
+
+   PAPI_start(eventset);

    tag = MNxtMgid( tag, MSGID_BEGIN_FACT, MSGID_END_FACT );
- }
+ rawBefore1=rdpmc(USER_EVENT); //raw rdpmc measure USER_EVENT for PAPI_read
+ rawBefore2=rdpmc(KERNEL_EVENT); // raw rdpmc measure KERNEL_EVENT for PAPI_read
        //totcyc=PAPI_get_real_cyc();
        PAPI_read(eventset,values);
        //totcyc=PAPI_get_real_cyc()-totcyc; // measure total cycle cost by PAPI_read
        
        rawAfter1=rdpmc(USER_EVENT);
        rawAfter2=rdpmc(KERNEL_EVENT);
        
        PAPI_stop(eventset,values);
        
        array[6][num_iters]=totcyc;
        eventVal1[6][num_iters]=values[0]; // event value measured by papi_start/stop
        eventVal2[6][num_iters]=values[1];
        rawVal1[6][num_iters]=rawAfter1-rawBefore1; // event value measured by rdpmc
        rawVal2[6][num_iters]=rawAfter2-rawBefore2;
        //printf("%lld %lld\n",rawAfter2,rawBefore2);
        /*end papi read*/
        num_iters++;
        
        }
    
    /*
    * Release panel resources and panel list
    */
    
    /*
    * End of HPL_pdgesv0
    */
    +/-/*start papi message*/
    +
    +if((result=PAPI_stop(eventset,values))!=PAPI_OK)
printf("Error PAPI stop:%s\n",PAPI_strerror(result));
*/  for(int i=0;i<num_iters;i++)
{  
    printf("%d 1-panelinit %ld %lld   ",&i,array[0][i],eventVal1[0][i],eventVal2[0][i]);
    printf("2-pdfact %d %ld %lld   ",&array[1][i],eventVal1[1][i],eventVal2[1][i]);
    printf("3-binit %d %ld %lld   ",&array[2][i],eventVal1[2][i],eventVal2[2][i]);
    printf("4-bcast %d %ld %lld   ",&array[3][i],eventVal1[3][i],eventVal2[3][i]);
    printf("5-bwait %d %ld %lld   ",&array[4][i],eventVal1[4][i],eventVal2[4][i]);
    printf("6-update %d %ld %lld   ",&array[5][i],eventVal1[5][i],eventVal2[5][i]);
    printf("7-mnxtmgrid %d %ld %lld   
",array[6][i],eventVal1[6][i],eventVal2[6][i]);
  }
*/
for(int i=0;i<7;i++)
{
    printf("%dth read cycle********
",i+1);
    cal_stats(num_iters,array[i],&min[i],&max[i],&avag[i],&std[i]);
    printf("Total cost for PAPI_read over %d iterations \n", num_iters);
    printf("min cycles : %lld
max cycles : %lld
average cycles : %lf
standard deviation:
%lf\n",
    min[i],max[i],avag[i],std[i]);

    printf("-------the %dth l1-icm event-------\n",i+1);
    cal_stats(num_iters,eventVal1[i],&min[i],&max[i],&avag[i],&std[i]);
    printf("min val : %lld
max val : %lld
average val : %lf
standard deviation: %lf\n",
    min[i],max[i],avag[i],std[i]);
    printf("-------the %dth l1-dcm event-------\n",i+1);
    cal_stats(num_iters,eventVal2[i],&min[i],&max[i],&avag[i],&std[i]);
    printf("min val : %lld
max val : %lld
average val : %lf
standard deviation: %lf\n",
    min[i],max[i],avag[i],std[i]);
}
Appendix D: Code patch for STREAM benchmark

--- stream.c    2017-10-26 15:33:09.632593045 -0400
+++ stream1.c   2017-10-26 15:32:20.980177391 -0400
@@ -46,6 +46,10 @@
 # include <float.h>
 # include <limits.h>
 # include <sys/time.h>
+## include ".../papi/papi/src/papi.h"
+## include "stdio.h"
+## include "stdlib.h"
+## include "string.h"

 /*---------------------------------------------------------------------------------
   * INSTRUCTIONS:

@@ -109,7 +113,7 @@
 #endif
 #endif
 ifndef NTIMPES
-## define NTIMES 10
+## define NTIMES 1000
 #endif

 /* Users are allowed to modify the "OFFSET" variable, which *may* change the
@@ -204,6 +208,97 @@
 ifndef _OPENMP
 extern int omp_get_num_threads();
 #endif
+/*add for papi test stats */
+// rdpmc code
+static inline unsigned long long rdpmc(unsigned int counter) {
+    unsigned int low, high;
+
+    __asm__ volatile("rdpmc" : =a" (low), =d" (high) : =c" (counter));
+
+    return (unsigned long long)low | ((unsigned long long)high) <<32;
+}
+
+int partition( long long a[], int l, int r) {
+    long pivot, i, j, t;
+    pivot = a[l];
+    i = l; j = r+1;
+    
+    while( 1 )
+    {
+        do ++i; while( a[i] < pivot && i < r );
+        do --j; while( a[j] > pivot );
+        if( i >= j ) break;
+        t = a[i]; a[i] = a[j]; a[j] = t;
+    }
+    t = a[l]; a[l] = a[j]; a[j] = t;
+    return j;
+}
+
+void quickSort( long long a[], int l, int r)
+{
+    int j;
+    
+    if( l < r )

+ {  
+    // divide and conquer  
+    j = partition(a, l, r);  
+    quickSort(a, l, j-1);  
+    quickSort(a, j+1, r);  
+  }
+
+}
+
+}  
+void do_percentile(int num_iters,long long *a, long long *percent25, long long *percent50, long long *percent75,long long *percent99) 
+{  
+  long long *a_sort;  
+  a_sort = calloc(num_iters,sizeof(long long));  
+  memcpy(a_sort,a,num_iters*sizeof(long long));  
+  int i_25=(int)num_iters/4;  
+  int i_50=(int)num_iters/2;  
+  int i_75=(int)num_iters/4*3;  // index for 75%, not quite accurate cause didn't take even or odd in consideration  
+  int i_99=(int)num_iters/10*9.9;  
+  quickSort(a_sort,0,num_iters-1);  
+  
+
+  *percent25=a_sort[i_25];  
+  *percent50=a_sort[i_50];  
+  *percent75=a_sort[i_75];  
+  *percent99=a_sort[i_99];  
+  free(a_sort);  
+  a_sort=NULL;  
+}
+static void
+print_percentile(long long percent25, long long percent50, long long percent75, long long percent99)
+{
+    printf("25%% cycles : %lld\n50%% cycles : %lld\n75%% cycles : %lld\n99%% cycles : %lld\n",
+        percent25, percent50, percent75, percent99);
+
+    percent25, percent50, percent75, percent99);
+}
+
+static void cal_stats(int num_iters, long long *array, long long *min,
+                        long long *max, double *avag, double *std)[
+    int i; double tmp;
+    long long percent25, percent50, percent75, percent99;
+    *max=*min=array[0];
+    *avag=0; *std=0;
+    for(i=0;i<num_iters;i++){
+        if(*max<array[i]) *max=array[i];
+        if(*min>array[i]) *min=array[i];
+        *avag+=(double)array[i];
+        // printf("%d-%lld \n",i,array[i]);
+        
+    }
+    *avag=*avag/(double)num_iters;
+    for ( i = 0; i < num_iters; i++ ) {
+        tmp = (double)array[i] - ( *avag );
+        *std += tmp * tmp;
+    }
+    *std=sqrt(*std/num_iters);
+    do_percentile(num_iters, array, &percent25, &percent50, &percent75, &percent99);
+    
+    print_percentile(percent25, percent50, percent75, percent99);
int main()
{
    ssize_t j;
    STREAM_TYPE scalar;
    double t, times[4][NTIMES];

    /*-- setup -- papi read TLB miss*/
    int eventset=PAPI_NULL;
    int  result;
    int readNum=4;
    int num_iters=0;
    int max_iters=NTIMES;
    long long totcyc,array[readNum][max_iters],values[3],lastVal1,lastVal2,
    eventVal1[readNum][max_iters],eventVal2[readNum][max_iters],
    rawVal1[readNum][max_iters],rawVal2[readNum][max_iters],
    rawBefore1,rawBefore2,rawAfter1,rawAfter2;
    long long min[readNum],max[readNum];
    double avg[readNum].std[readNum];
    
    #define USER_EVENT 0//1073741825
    #define KERNEL_EVENT 1
    /*
    haswell machine event name table
    
    "PRESET,PAPI_TOT_CYC,NOT_DERIVED,CPU_CLK_THREAD_UNHALTED:THREAD_P
    */

    // More code here...
if((result=PAPI_library_init(PAPI_VER_CURRENT))!=PAPI_VER_CURRENT)
             printf("Error PAPI library init:%s\n",PAPI_strerror(result));
+        /*create papi eventset and add events*/
+        if((result=PAPI_create_eventset(&eventset))!=PAPI_OK)
+             printf("Error PAPI create event:%s\n",PAPI_strerror(result));
+        
+        if((result=PAPI_add_named_event(eventset,"DTLB_LOAD_MISSES:MISS_CAUSES_A_WALK,DTLB_STORE_MISSES:MISS_CAUSES_A_WALK:u=1");)
+        printf("Error PAPI add event:%s\n",PAPI_strerror(result));
+        
+        if((result=PAPI_add_named_event(eventset,"DTLB_LOAD_MISSES:MISS_CAUSES_A_WALK,DTLB_STORE_MISSES:MISS_CAUSES_A_WALK:k=1:u=0");)
+        printf("Error PAPI add event:%s\n",PAPI_strerror(result));
+        PAPI_start(eventset);
+        PAPI_read(eventset,values);
+        
+        /* --- SETUP --- determine precision and check timing --- */
+
+        printf(HLINE);
scalar = 3.0;
for (k=0; k<NTIMES; k++)
{
+
	times[0][k] = mysecond();
+/*STREAM_COPY*/
+/*papi start*/
+   PAPI_start(eventset);
+
#ifdef TUNED
    tuned_STREAM_Copy();
#else
    #pragma omp parallel for
    for (j=0; j<STREAM_ARRAY_SIZE; j++)
-		c[j] = a[j];
+		{
+			c[j] = a[j];
+		}
#endif
+
    times[0][k] = mysecond() - times[0][k];
-
+
    times[1][k] = mysecond();
+
+
+  rawBefore1=rdpmc(USER_EVENT); //raw rdpmc measure USER_EVENT for PAPI_read
+  rawBefore2=rdpmc(KERNAL_EVENT); // raw rdpmc measure KERNEL_EVENT for PAPI_read
+
totcyc = PAPI_get_real_cyc();
PAPI_read(eventset, values);
totcyc = PAPI_get_real_cyc() - totcyc; // measure total cycle cost by PAPI_read

rawAfter1 = rdpmc(USER_EVENT);
rawAfter2 = rdpmc(KERN_EVENT);

PAPI_stop(eventset, values);

array[0][num_iters] = totcyc;
eventVal1[0][num_iters] = values[0]; // event value measured by papi_start/stop
eventVal2[0][num_iters] = values[1];
rawVal1[0][num_iters] = rawAfter1 - rawBefore1; // event value measured by rdpmc
rawVal2[0][num_iters] = rawAfter2 - rawBefore2;
/*papi stop*/

/*STREAM_scale*/
/*papi start*/
PAPI_start(eventset);

#ifdef TUNED
    tuned_STREAM_Scale(scalar);
#else
    @ @ -327.6 +491.29 @ @
    times[1][k] = mysecond() - times[1][k];

    times[2][k] = mysecond();
#endif

rawBefore1 = rdpmc(USER_EVENT); // raw rdpmc measure USER_EVENT for PAPI_read
rawBefore2 = rdpmc(KERN_EVENT); // raw rdpmc measure KERNEL_EVENT for PAPI_read

totcyc = PAPI_get_real_cyc();
PAPI_read(eventset, values);
totcyc = PAPI_get_real_cyc() - totcyc; // measure total cycle cost by PAPI_read

rawAfter1 = rdpmc(USER_EVENT);
rawAfter2 = rdpmc(KERNEL_EVENT);

PAPI_stop(eventset, values);

array[1][num_iters] = totcyc;
eventVal1[1][num_iters] = values[0]; // event value measured by papi_start/stop
eventVal2[1][num_iters] = values[1];
rawVal1[1][num_iters] = rawAfter1 - rawBefore1; // event value measured by rdpmc
rawVal2[1][num_iters] = rawAfter2 - rawBefore2;

PAPI_start(eventset);

 ifdef TUNED
    tuned_STREAM_Add();
#else
    times[2][k] = mysecond() - times[2][k];
    times[3][k] = mysecond();
#endif

rawBefore1 = rdpmc(USER_EVENT); // raw rdpmc measure USER_EVENT for PAPI_read
rawBefore2 = rdpmc(KERNEL_EVENT); // raw rdpmc measure KERNEL_EVENT for PAPI_read
totcyc = PAPI_get_real_cyc();
PAPI_read(eventset, values);
totcyc = PAPI_get_real_cyc() - totcyc; // measure total cycle cost by PAPI_read

rawAfter1 = rdpmc(USER_EVENT);
rawAfter2 = rdpmc(KERNEL_EVENT);

PAPI_stop(eventset, values);

array[2][num_iters] = totcyc;

eventVal1[2][num_iters] = values[0]; // event value measured by papi_start/stop
eventVal2[2][num_iters] = values[1];

rawVal1[2][num_iters] = rawAfter1 - rawBefore1; // event value measured by rdpmc
rawVal2[2][num_iters] = rawAfter2 - rawBefore2;

/*papi stop*/

/*STREAM_triad*/
/*papi start*/
PAPI_start(eventset);

#ifdef TUNED
    tuned_STREAM_Triad(scalar);
#else
    a[j] = b[j] + scalar * c[j];
#endif

times[3][k] = mysecond() - times[3][k];

rawBefore1 = rdpmc(USER_EVENT); // raw rdpmc measure USER_EVENT for PAPI_read
rawBefore2 = rdpmc(KERNEL_EVENT); // raw rdpmc measure KERNEL_EVENT for PAPI_read
totcyc = PAPI_get_real_cyc();
PAPI_read(eventset, values);
totcyc = PAPI_get_real_cyc() - totcyc; // measure total cycle cost by PAPI_read

rawAfter1 = rdpmc(USER_EVENT);
rawAfter2 = rdpmc(KERNEL_EVENT);

PAPI_stop(eventset, values);

array[3][num_iters] = totcyc;
eventVal1[3][num_iters] = values[0]; // event value measured by papi_start/stop
eventVal2[3][num_iters] = values[1];
rawVal1[3][num_iters] = rawAfter1 - rawBefore1; // event value measured by rdpmc
rawVal2[3][num_iters] = rawAfter2 - rawBefore2;

*/papi stop*/

++ num_iters;

/* --- SUMMARY --- */

/* --- Check Results --- */
checkSTREAMresults();
printf(HLINE);

/* print papi event*/
PAPI_stop(eventset, values);
/*papi message start*/
for(int i = 0; i < 4; i++){
    printf("\n*************** the %dth read", i);
}
+        cal_stats(num_iters,array[i],&min[i],&max[i],&avag[i],&std[i]);
+        printf("Total cost for PAPI_read over %d iterations \n", num_iters);
+        printf("average cycles : %lf\n",avag[i]);
+
+        printf("-------the %dth  papi_start/stop user event ---------\n",i+1);
+        cal_stats(num_iters,eventVal1[i],&min[i],&max[i],&avag[i],&std[i]);
+        printf("average val : %lf\n",avag[i]);
+        printf("-------the %dth  papi_start/stop kernel event ---------\n",i+1);
+        cal_stats(num_iters,eventVal2[i],&min[i],&max[i],&avag[i],&std[i]);
+        printf("average val : %lf\n",avag[i]);
+        printf("-------the %dth  raw user_event for papi_read ---------\n",i+1);
+        cal_stats(num_iters,rawVal1[i],&min[i],&max[i],&avag[i],&std[i]);
+        printf("average val : %lf\n",avag[i]);
+        printf("-------the %dth  raw kernel_event for papi_read ---------\n",i+1);
+        cal_stats(num_iters,rawVal2[i],&min[i],&max[i],&avag[i],&std[i]);
+        printf("average val : %lf\n",avag[i]);
+    }
+
    return 0;
+
# define   M   20
BIOGRAPHY OF THE AUTHOR

Yan Liu was born in September 24th of 1986 in China. She was raised in Shijiazhuang, Hebei, until 2006. She attended Central South University of Forestry & Technology in China and received a Bachelor of Science degree in Geographic Information System in 2010. After graduation, Yan continued her study at the same school as a master student. She achieved her Master of Science degree in Computer Science in June 2012. She worked as a software engineer for a year in NanJing Tornado Technology Company for a year after graduation. Yan started her new adventure in the department of Electrical & Computer Engineering at the University of Maine as a master graduate research assistant. She is a candidate for the master degree in computer engineering from the University of Maine in December 2017.