

# Performance and Environment Monitoring for Whole-System Characterization and Optimization

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## Abstract

As performance advances achievable through chip fabrication technology are reaching their limits, other areas of system design need to be explored. Several different possibilities exist. Our research in the context of the DARPA HPCS project PERCS [11] aims at an infrastructure to characterize and understand the interactions between hardware and software and to affect optimizations based on those characterizations. To achieve this, we have designed and implemented a performance and environment monitoring (PEM) infrastructure that vertically integrates performance events from various layers in the execution stack. The performance understanding achieved with PEM can be used to help tune application behavior on existing systems or potentially to improve future architecture designs by analyzing the PEM data collected on a whole system simulator while varying architecture characteristics.

We have developed an architecture for continuous program optimization (CPO) to assist in, and automate the challenging task of performance tuning a system. CPO utilizes the data provided by PEM to detect, diagnose, and eliminate performance problems. We designed and implemented a PEM prototype that feeds the vertical event stream to a performance visualizer, our first PEM client. We describe the CPO architecture and how PEM interacts with CPO. We then present an experiment using the PEM visualization client to understand data gathered across multiple layers of the system, and show how that data was used to positively affect system performance.

## 1 Introduction

The need for increased performance and functionality has created a complex system stack consisting of multiple execution layers. Each layer in itself is complicated and challenging to understand. Understanding performance that involves multiple layers requires considerable expertise and sophisticated tools. Hardware resources may be added to or removed from the system dynamically, current machines may run a disparate and varying set of applications, and even single applications may go through phases with different performance behavior and resource requirements. To obtain good system performance in these complex environments an infrastructure that provides vertical integration of events from the hardware layer through the application is needed.

We have developed a performance and environment monitoring (PEM) infrastructure that supports understanding the interactions between hardware and software and allows us to make optimizations based on those characterizations. These optimizations could take the form of architectural design improvements achieved by varying hardware characteristics on a simulator with PEM providing data on the total system performance and details of the effects on components of the entire execution stack. For example, we have begun work on evaluating a new memory model in PERCS, IBM's prototype for the DARPA HPCS effort [11]. Although this paper does not focus on using PEM for evaluating potential architecture design, we believe PEM provides architects a crisper view of how a particular feature affects program behavior.

Another optimization approach supported by PEM is vertical performance tuning across execution layers. The PEM infrastructure provides data about the interaction of hardware and software, and of all the layers within the software. In order to be effective in a complex environment, a performance tuning infrastructure must be able to not only gather data from all the layers of the execution stack, but must also be able to continuously react to per-

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formance problems as they arise throughout the lifetime of an application and system.

We have developed a software architecture for continuous program optimization (CPO) as an approach to help automate the challenging task of performance tuning. In CPO, performance tuning is a continual process of feedback-directed adaptation along two dimensions: (1) adapting applications to their current execution environment and (2) adapting the execution environment to enhance application performance.

CPO may be conceptualized as two phases: monitoring and optimizations. Monitoring involves obtaining and analyzing performance information at varying granularities and across layers of the system. Optimization involves using the information to affect changes in the application or system. Examples include: JIT (Just In Time) compiler optimizations [5], hot swapping operating system components [3], or redistributing application workloads. While CPO is conceptually divided into two phases, both are continually occurring to evaluate the effectiveness of tuning and to instantiate adjustments as needed.

The PEM infrastructure, which is the focus of this paper, is a crucial part of CPO as illustrated in Figure 1(a). Each participating execution layer emits its performance events into PEM, which provides an integrated view of performance to PEM clients. PEM clients are the modules that consume events, compute correlations between events from different layers and implement specific CPO tuning scenarios.

PEM consists of several components. There is a specification component that defines the events to be monitored. As described in Section 3.1, we chose XML as the specification language to provide a language-independent way to attach semantic meaning to the event definition.

Another reason to use XML is to facilitate the construction of PEM tools, which present the second component of PEM. Described in Section 3.2, PEM tools produce interfaces and stubs that tailor the generic specification to specific needs of the implementation of PEM clients. Also part of the tools are filters that convert the PEM event stream (optimized for fast event generation) into other formats, for example, a visualizer stream format.

The final component of PEM, described in Section 3.3, is the PEM library which is an implementation of the specification on a given system. We implemented the PEM library on the K42 open-source research operating system [14]. K42 already has a significant performance monitoring infrastructure [25] and provides an easy prototyping environment. Further, K42 was designed to be scalable and contains support for hot swapping [22], a useful feature for CPO. As we develop experience with the PEM

infrastructure, the successful portions can be implemented on other operating systems, and work has begun to investigate ports to AIX and Linux.

Figure 1(b) shows our prototype implementation of the PEM infrastructure on PowerPC970 along with a PEM visualization client to display the collected PEM event stream. We have written an XML specification and used it to monitor events from the hardware, operating system, libraries, and applications. The visualization client consists of the Performance Explorer (PE) visualizer, and two PEM clients generated by our PEM tools: one online tracing client to log the monitored events and produce a PEM trace, and a filter client that converts the PEM event trace into the format expected by PE.

We have used the PEM infrastructure and visualization client to study and improve the behavior of one of the ASCII Purple benchmarks, UMT2K [2]. In a short period of time, using the PEM infrastructure, we analyzed the performance of UMT2K, determined a performance deficit, implemented an environment optimization, re-evaluated the performance, and fine tuned the optimization. We present this experiment in Section 4.

## 2 The CPO Approach

Continuous Program Optimization is an architecture to assist in and automate the challenging task of performance tuning. In CPO, performance tuning is viewed as a continual process of feedback-directed adaptation along two dimensions: (1) adapting the application to its current execution environment and (2) adapting the execution environment to optimally enhance application performance.

While the idea of feedback-directed optimization is not new, CPO extends it to a more dynamic, negotiation-based optimization process. Optimizations are implemented through agents that are instances of PEM clients. These CPO agents model the application behavior based on performance data, which may come from all layers of the hardware and software. Based on these performance models, CPO agents negotiate resources that may either directly enhance performance or do so indirectly, by enabling further code adaptations. The CPO agents implement performance tuning by continuously executing the following steps:

1. *Base monitoring*: Use models of expected performance to detect performance deviations and bottlenecks.
2. *Tuning*: Apply the optimization with the highest expected benefits based on the performance modeling

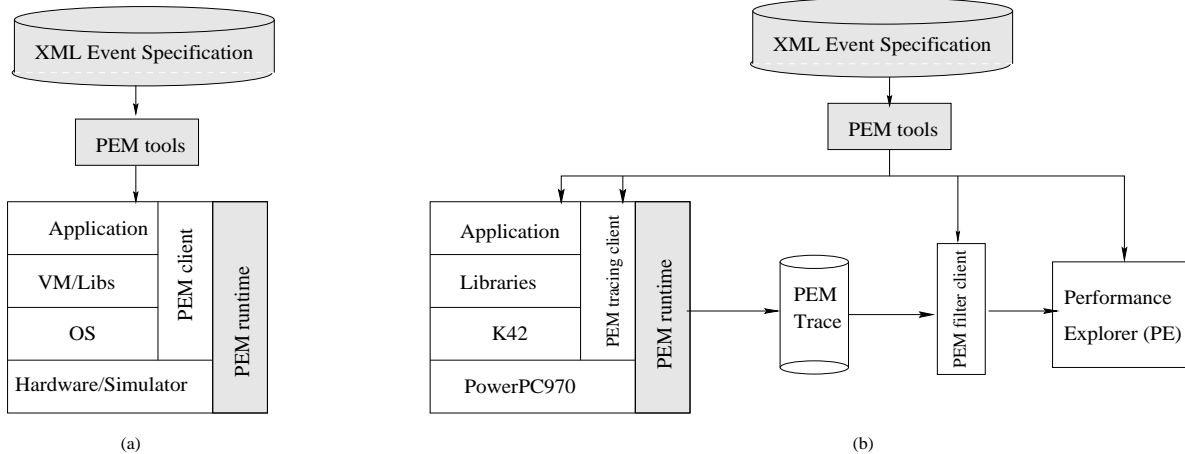


Figure 1: Overview of CPO: (a) the PEM infrastructure and (b) the PEM visualization client.

given the currently available resources; negotiate additional resources with other software layers, and if resources are granted, apply further optimizations.

3. *Validation monitoring*: Continuously monitor and validate that the optimizations performed meet the projected benefits.

To ensure progress, CPO agents maintain the history of past optimizations and their projected and actual performance metrics.

Examples of CPO adaptation include: (a) tuning of compiler optimization heuristics in a Java JIT compiler, such as inlining policies, loop unrolling and tiling parameters, etc.; (b) tuning of linear algebra [21, 24, 10] and communication libraries to adapt to the actual application usage; (c) selecting different algorithms to solve a specific problem based on the characteristics of the input data set [16]; (d) environment adaptation such as the tuning of Java Virtual Machine (JVM) components (e.g., heap size and garbage collection policies), tuning operating system resources such as memory available for the JVM, or changing the page size for different regions of memory allocated to an application [19]; and (e) modifying the operating system page replacement policy based on the application’s memory usage patterns [22].

There may be several CPO agents active concurrently, and their resource requirements may be conflicting. The common PEM infrastructure is a means for resolving potential conflict by providing each agent with a view of performance events across the entire system. Through PEM, CPO agents can coordinate their activities by monitoring the system for performance events issued by other agents.

### 3 PEM Infrastructure

PEM is the backbone of our vertical monitoring infrastructure. This section discusses its three components in more detail.

#### 3.1 XML Event Specification

The first component of PEM consists of a repository of XML event specifications that defines the monitoring scope. The XML specification of an event defines the event semantics and may contain several fields to describe event attributes. The XML event specification provides a unified location for encoding event semantics. For example, the fact that a send and a receive event in a library (such as MPI) establish a communication pair based on a common communication port identifier constitutes semantic information. Any two such events will be linked, even though the ports may differ between pairs of events. Figure 2 shows an example, in XML, of encoding the event of reading the contents of hardware performance counters. The specification defines the context of the event and lists several fields defining attributes that will be stored with the event.

We have written an XML specification containing several hundred hardware, operating system, and application layer events. Besides the benefits of readability and availability of XML parsers that can be used to build tools, we chose to use XML to satisfy several crucial design requirements:

- *Language-independent support* for building tools to aid in the development of PEM clients, as explained in the next section;

```

<event name='HW::HWPerf::HPMsAndPC'
  description='Hardware counter events
  and program counter for threadId'>
  <layerId value='HW' />
  <classId value='HWPerf' />
  <specifier value='HPMsAndPC' />
  <fields>
    <field name='pc' type='uint64'
      description='program counter' />
    <field name='threadId' type='uint64'
      description='kernel thread id' />
    <field name='counterValues' type='list'
      eltType='uint64'
      description='counter values.' />
  </fields>
</event>

```

Figure 2: Example of an XML event specification

- *Flexibility* to add and modify events. Additional execution layers that produce new events (e.g., new libraries) can easily be integrated into PEM by adding new event specifications into the repository;
- *Documentation*. Having a single place with explicit field names and descriptions for entities stored in an event record encourages developers to better document event semantics.

### 3.2 PEM XML Tools

We have implemented a set of tools that take the XML specification as input and generate language-specific interfaces and stubs. We currently support the C, C++, Fortran, and Java languages. The tool set contains three classes of tools:

1. Instrumentation tools
2. PEM library tools
3. Client-specific tools

The first class of tools facilitates instrumentation of the execution layers to emit event notifications to PEM. The tools automatically generate language-specific header files for the instrumentation interface.

The second class facilitates the development of the PEM library, for example, the K42-based implementation. These tools generate the header files and stubs for event record definition and the interfaces that are implemented by the PEM library.

The third class facilitates the development of PEM clients by tailoring the generic event specification to the specific

needs of a client. Both, the PEM library and the PEM clients are concerned with event streams. However, the requirements of how the event stream should be structured may differ between the PEM library (i.e., the event generating agent) and PEM clients (i.e., the event consuming agents).

Event generation is best implemented as a *raw event stream* that minimizes the information contained in each event record so as to log events as quickly and as space-efficiently as possible. Contextual information, such as the currently executing process and thread ID, is omitted since it can be recovered from previously logged raw context switch events.

In contrast, event consumption in PEM clients is typically based on an interpreted event stream. Interpretation of the event stream is needed to implement client-specific filtering. During interpretation, relevant contextual information that was omitted from individual raw event records is recovered based on client-specific semantic criteria.

For example, consider our visualization filter client from Figure 1(b); the client acts as a bridge between the raw event stream coming from PEM and the event requirements of the visualizer, Performance Explorer (PE). PE provides a rich GUI for selecting and configuring various views of the event stream. To efficiently support this GUI, PE expects complete context information to be available in every record in the visualization event stream.

To accommodate PE requirements, the visualization client translates the raw PEM event stream into a context-enriched visualization stream for PE. The semantic information about what constitutes the event context is fully contained in the XML event specification. Thus, we were able to write a client-specific tool to automatically generate the filter code, in this case Java class files.

### 3.3 PEM Library on K42

We implemented the PEM infrastructure for gathering event information from all layers of the system, leveraging the efficient tracing facility in K42 [14, 25]. Because vertical event integration is one of the goals, we implemented a single shared buffer across all layers of the system. On a per-processor basis, the buffer provided a single, shared, monotonically time increasing log of events. This was accomplished by mapping the event buffer and control structures into the address space of each process.

The event buffer is implemented as a circular set of smaller buffers. The event control structure maintains an index that points to the current offset in the currently active buffer. The event buffer supports variable length events [25]. Advantages of using variable length events

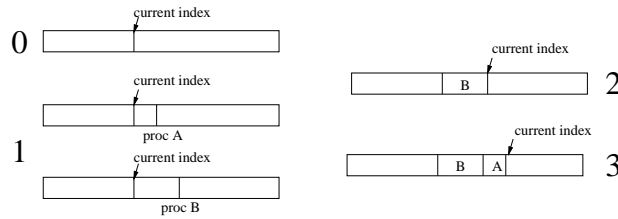


Figure 3: Illustration of lock-free event logging

include the efficient logging of short events without requiring special continuation events for logging longer events. Our PEM library implementation uses atomic primitives to achieve an efficient lock-free multiprocessor implementation of variable length events.

Conceptually, each process attempts to *reserve* sufficient space in the buffer for the event it intends to log. Once the process makes a successful reservation, it may proceed to log its data. To reserve space, a process attempts to atomically increment the current index using a `compare` and `store` operation. The process that successfully increments the index (as determined by the return value of the `compare` and `store` operation) has the right to proceed to log data into the buffer. Failing processes retry. Figure 3 shows the lockless event logging for two processes, A and B. In step 0, the current index shows the initial configuration. In step 1, both A and B read the current index and attempt to atomically increment the current index by the size of the event being logged. The winner, in this case process B, will log the event immediately following the old current index (step 2). This will be followed by process's A data, assuming no other competing processes attempt to log more data (step 3). Because it is important to guarantee monotonically increasing timestamps, processes must re-determine the timestamp during each attempt to atomically increment the index. If the timestamp was not determined as part of the atomic reserve operation then that process may be interrupted by another process that succeeds in reserving the next slot in the buffer, but obtains an earlier timestamp.

The memory for logging events is logically divided into buffers. The size of each buffer in K42 determines the alignment boundary for allowing random access into the buffer space even with variable length events. Once a buffer is full, the logging facility proceeds to the subsequent buffer, and the previous buffer is available to be written out (to disk or network).

## 4 Preliminary Experiments

This section presents our first experience using PEM and a visualization client to understand performance events across execution layers and to improve the performance of an application using the event information. Although below we describe a manual process, it is only the first step towards understanding what data needs to be collected and what event patterns need to be detected to automate this process in the CPO framework.

We have collected a PEM event trace for UMT2K, one of the PERCS scientific applications, running on K42 on a Power Mac G5 with PowerPC970 processors [1]. The UMT2K application, written in a mix of C and Fortran, is a 3D, deterministic, multi-group, photon transport code for unstructured meshes [2]. We have collected events across the following execution layers:

- *Application Layer:* The core of UMT2K takes place in a loop nest and we instrumented the code to emit phase marker events that indicate the iterations in the loop nest. Although we currently instrumented the application manually, the insertion of phase markers at code boundaries such as loops can easily be automated in a compiler;
- *Operating System Layer:* K42 was instrumented to emit a variety of operating system events, such as context switches, system and kernel calls, locking and synchronization events, and page faults;
- *Hardware Layer:* Power Mac G5 provides a rich set of hardware performance counter events. Among others, we collected: Instructions completed Per Cycle (IPC), L1 data cache load misses (L1 misses), data TLB misses (TLB misses), and data ERAT (Effective-to-Real Address Translation) table misses (ERAT misses).

### 4.1 Initial Run

Figure 4 shows a view of the UMT2K event trace in PE. The X-axis represents time and the six event plots show data for a selected interval. The overview plot at the top of the figure shows the entire run and the arrows indicate the interval that was selected. As illustrated by this snapshot, the power of PEM is the vertical integration it provides. Within the same framework we can analyze application, library, virtual machine (if applicable), operating system, and hardware events. The strip entitled "innermost loop" shows the application markers for the innermost loop (phase 6). Each marker indicates the beginning

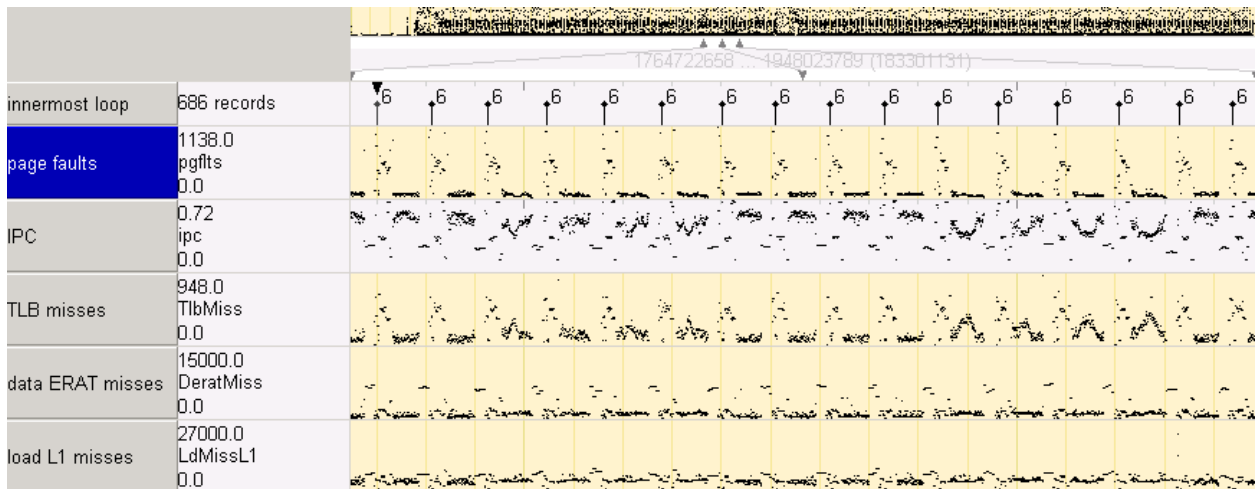


Figure 4: Initial Run: PE view of UMT2K across execution layers for small pages.

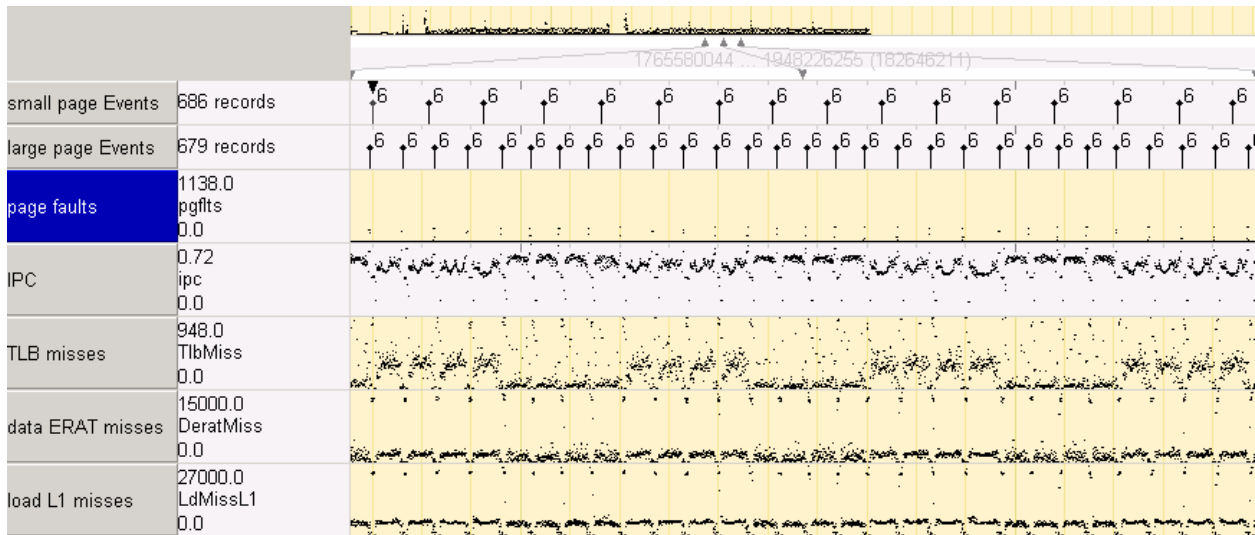


Figure 5: Second Run: PE view of UMT2K across execution layers for large pages.

of a loop iteration. The remaining strips show frequency plots, where each dot indicates the frequency of events for a 4 million cycle interval. The first frequency plot shows an OS event: the number of page faults. The frequency of page faults ranges from 0 to 1138 per 4 million cycle interval. The next strips show hardware events: the IPC, L1 misses, TLB misses, and ERAT misses. This is just one of the multiple views PE provides, and we show only a sample of the data events that PEM collects.

#### 4.1.1 Periodicity Across Layers

The first observation is the periodic pattern of the metrics during execution. The application phase markers show that this pattern is correlated with the innermost loop. The periodic pattern persists across execution layers. It has been observed that similar periodic patterns tend to persist across hardware counter events [9] and the looping structure of the program was assumed to be the cause of periodicity. PEM provides the necessary infrastructure to pinpoint the exact loop that is correlated with the observable periodic patterns. Moreover, PEM illustrates that the periodic pattern is not limited to hardware counter events and extends into operating system software events, such as page faults.

#### 4.1.2 Event Correlation

The second observation is the correlation of the behavior within each periodic phase (i.e., within each loop iteration). Figure 4 shows a strong inverse correlation between TLB misses and IPC. As TLB misses rise during each iteration IPC goes down, suggesting that TLB miss behavior is a strong factor in overall application performance. There is also a visible inverse correlation between page faults and IPC. At the beginning of each loop iteration, there is a sudden rise in page faults along with a drop in IPC.

#### 4.1.3 Persistent Page Faults

The final observation is the persistent occurrence of page faults. Over the entire UMT2K run 12,227,841 page faults occurred. As the view in Figure 4 shows each iteration triggers a new rise in page faults to load the next iteration's working set. Closer inspection of the page fault events and their attributes, which include the faulting address, showed that each iteration of the innermost loop traverses a large address range. At the beginning of each iteration, a number of large data structure in the range of 8-10MB is allocated, initialized, and then processed. This pattern pointed to a potential optimization: mapping the traversed

data structures to large pages to avoid the excessive page faults.

## 4.2 Second Run with Large Page Mapping

The Power Mac G5 CPU offers two page sizes: small 4KB pages (default) and large 16MB pages. For our second run we tried to reduce page faults by mapping the important data structures in UMT2K to large pages. The application markers indicate that the majority of page faults were generated from the innermost loop. We used these markers to identify the relevant data structure in the code and mapped each of them to a large page. We then reran UMT2K to collect a second event trace.

Figure 6 shows the resulting performance improvement over the initial small page run (bar entitled "large page"). Page faults are virtually eliminated and execution time is reduced by 42%. Examining only the effects on page faults, our simple strategy for mapping large pages would appear to be successful. However, since PEM provides events from the entire stack, we were able to evaluate the impact of this optimization on other layers before declaring success. Moving to large pages should reduce the TLB pressure since fewer pages are touched over the entire run. Figure 6 shows a corresponding reduction in TLB misses. However, the figure also shows some inadvertent side effects of our optimization. Both ERAT and L1 misses were significantly increased. L1 misses were increased by 34% and ERAT misses by 93%.

To illuminate this performance phenomenon further, consider Figure 5 showing the PE view of the second run for the same time interval as in Figure 4. The topmost application marker bar is copied from Figure 4 to allow comparison between the two runs. As can be seen from the phase marker strips, the initial run completes 16 loop iterations while the second run completes 29 iterations in the same interval. The faster iteration completion time corresponds to the 42% overall execution time speedup.

Figure 5 shows that the drop in IPC at iteration boundaries is less pronounced in the second run, most likely as a result of the eliminated page faults at iteration boundaries. The inverse correlation between IPC and TLB misses is less visible because TLB misses have been reduced and are now more visually dispersed. The important observation in comparing the two runs are the new bands of high ERAT and L1 misses at the beginning of each iteration that were not present in the initial run. These additional bands of misses are the cause for the significant overall increase in L1 and ERAT misses seen in Figure 6.

Our optimization strategy for mapping large pages did not change the application's memory access patterns. Thus,

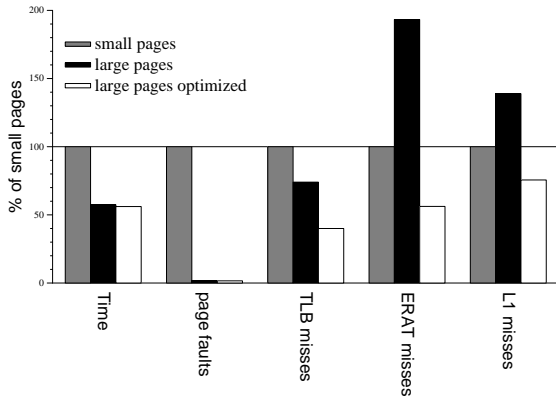


Figure 6: Performance of UMT2K with large pages relative to small page performance.

the only plausible explanation for the additional ERAT and L1 misses were conflicts. We therefore refined our initial naive implementation of large page allocation.

### 4.3 Third Run with Optimized Large Page Mapping

Our initial strategy for mapping large pages allocated each data structure accessed in the inner loop on a separate large page. The loop iterations proceed by accessing the same elements of several large arrays in each iteration. Large pages are aligned on 128-byte boundaries which is the size of a cache line. Thus, accessing the same elements of multiple 128-byte aligned arrays increases the potential for conflicts in the L1 cache. A similar explanation holds for the additional ERAT misses. Large pages are also aligned at 4KB boundary, which is the indexing granularity for the ERAT table.

We devised an optimized mapping strategy to stagger the starting addresses of the data structures mapped to the 16MB pages to avoid these conflicts. With this optimization, the same elements from different pages are no longer address-aligned, thereby avoiding conflicts in the L1 cache and the ERAT table.

The data in Figure 6 for the optimized large page run confirms that the staggering strategy significantly reduced the L1 and ERAT misses. In fact, by proactively avoiding alignment conflicts, we improved the ERAT and L1 cache miss behavior over the initial run. Execution time was further reduced by 3%.

### 4.4 CPO Approach to Large Page Mapping

In summary, our experiment emphasizes the importance of evaluating performance across execution layers. Without understanding the performance effects of our adjustments across both the operating system and the hardware layer we would not have been able to detect the adverse performance side effects of our initial large page mapping strategy.

So far, we have used PEM and the visualization client to manually tune application performance. Our goal in CPO is to develop PEM clients that automate the adjustments, such as the migration to large pages.

We are currently designing the details of the three CPO steps described in Section 2 for the large page scenario. Initially, we are planning to implement the migration to large pages across runs. In this model, base monitoring is implemented during an initial training run. The migration to large pages is implemented offline, between runs, and validation monitoring is implemented in a light-weight fashion as a permanent component of application execution.

The base monitoring uses PEM to keep track of memory access and paging behavior as the primary performance events affected by a change in page size. If a performance deficiency, such as an unusually high page fault or page table miss rate is detected, the PEM client switches to more detailed monitoring to identify the data structure that are candidates for large page mapping. One possibility we are currently pursuing is to use application markers for this process. In our experiment we manually inserted application markers into the code. However, markers may also be inserted by the compiler to mark important loops and regions where data structures are dynamically allocated (such as the innermost loop in UMT2K). By inspecting the memory access and paging behavior for specific application marker intervals, the PEM client identifies a pool of data structures that are likely to be the cause of the observed performance deficiency, analogously to what we did manually in our experiment for the innermost loop. By the end of the base monitoring run, the PEM client has produced a CPO log containing the pool of candidate data structures along with the monitor patterns that triggered their selection.

The base monitoring log is inspected by the compiler offline to implement the large page mapping by inserting the appropriate directive in the code. We are planning to implement validation monitoring with minimal overhead so that it can be a permanent component of the execution of the application. If the validation monitoring indicates a performance deviation from the intended effect, new CPO

log information is generated to trigger further offline tuning.

We are currently working on the many details that have to be developed in order to implement this CPO large page scenario.

## 5 Related Work

There has been considerable work in tracing for understanding kernel (LTT [26], KernInst [23], K42 [25]) and application behavior (Paradyn [17], SvPablo [8]). In addition, DTrace [6] and CrossWalk [18] allow event collection across system call boundaries. OProfile is a profiler for Linux for system-wide sampling of hardware performance counters [7]. Most of the previous work focuses on off-line data collection and post-mortem visualization. The main contribution of this paper is an infrastructure for vertical monitoring and on-line optimization. In addition to previous work, we enable data collection seamlessly across multiple layers of hardware and software. Our system is also designed to allow data to be processed on-line. If off-line traces are desired, we showed how a simple client can be written to extract the data from the collection stream.

Other performance visualization tools include: Intel's VTune [13], SGI's SpeedShop [27], Apple's Shark [4], and Paraver [20]. Kimelman et al. [15] present PV, a performance visualization infrastructure focused on presenting temporal information from multiple levels of the system. Hauswirth et al. [12] show that for understanding modern, object-oriented systems, a vertical approach to performance understanding across system layers is important. Much of the visualization functionality provided by their visualizer PE is present in any of the above tools and we could have chosen a different visualization tool to support our work on PEM.

## 6 Conclusions

We presented a Continuous Program Optimization (CPO) architecture to allow automatic tuning of application performance in today's complex hardware and software environment. The focus of this paper was on the Performance and Environment Monitoring (PEM) aspect of CPO that vertically integrates and analyzes performance events from the various layers of the execution stack. We presented our XML specification for describing PEM events and our implementation of the PEM infrastructure on K42, a prototype open-source research operating system.

We then showed how we used this infrastructure to detect and improve the performance of UMT2K, a scientific application. Through this experiment, we showed the benefits of the vertical integration PEM provides. Work is on-going to take the manual process and integrate it into the automatic CPO infrastructure.

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