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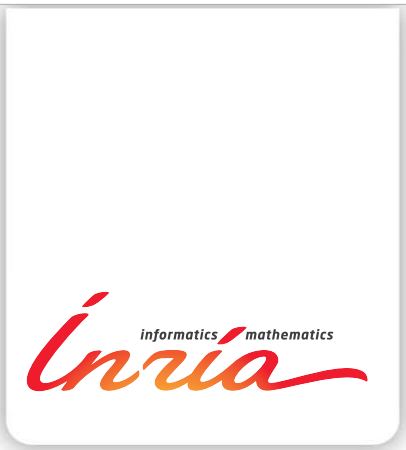

numap: A Portable Library For Low Level Memory Profiling

Manuel Selva *†, Lionel Morel‡§, Kevin Marquet‡ §

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Abstract: The memory subsystem of modern multi-core architectures is becoming more and more complex with the increasing number of cores integrated in a single computer. This complexity leads to profiling needs to let software developers understand how programs use the memory subsystem. Modern processors come with hardware profiling features to help building tools for these profiling needs. Regarding memory profiling, many processors provide means to monitor memory traffic and to sample read and write memory accesses. Unfortunately, these hardware profiling mechanisms are often very complex to use and are specific to each micro-architecture. In this report, we present numap, a library dedicated to the profiling of the memory subsytem of modern multi-core architectures. numap is portable across many micro-architectures and comes with a clean application programming interface allowing to easily build profiling tools on top of it.

Key-words: NUMA, Non-Uniform Access, Memory Profiling, Memory Accesses Sampling, Portable library

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`numap`: Une librairie portable pour le profilage mémoire bas niveau

Résumé : Pour suivre l'augmentation du nombre de coeurs intégrés au sein d'une même machine, le sous-système mémoire des architectures multi-coeurs devient de plus en plus complexe. Cette complexité induit des besoins en terme de profilage, afin de permettre aux développeurs une meilleure compréhesion de l'usage que font leur programme du sous-système mémoire. Les processeurs modernes intègrent des mécanismes qui permettent de construire des outils logiciels répondant à ces besoins. Concernant le profilage mémoire, de nombreux processeurs fournissent des moyens de suivre le traffic mémoire et d'échantillonner les accès en lecture et en écriture vers la mémoire. Néanmoins, ces mécanismes sont très complexes à utiliser et sont spécifiques à chaque micro-architecture. Dans ce rapport, nous présentons numap, une librairie dédiée au profilage du sous-sytème mémoire des architectures multi-coeurs modernes. numap est portable sur de nombreuses micro-architectures et fournit une interface simple et claire permetant de construire des outils de profilage.

Mots-clés : Accés mémoire non uniforme, Profilage mémoire, Echantillonage accés mémoire, Bibliothèque logicielle portable

1 Introduction

The increasing number of cores sharing memory in a single computer system leads to the so-called *memory wall*. The memory subsystem can not satisfy the simultaneous requests of all the cores and thus becomes a serious performance bottleneck. To alleviate this issue, computer architects have proposed many changes to memory architectures [MHSN15]. In particular, new cache levels have been added to centralized shared memory architectures and new distributed shared memory architectures, also known as Non Uniform Memory Access (NUMA) architectures, have been designed. However these hardware innovations have increased the burden on the software for getting the best possible performance out of the hardware [BZDF11, LQF15]. In other words, the software must be aware of the underlying memory organization to efficiently exploit these complex memory architectures. Nevertheless, statically knowing the memory architecture details is not enough to exploit it efficiently. In particular, the dynamism of modern operating systems and applications leads to a form of non-determinism regarding the memory hierarchy usage. As a consequence, software developers need runtime profiling mechanisms to deeply understand how the software interacts with the memory and to identify memory bottlenecks. To allow the low-level performance measurement needed by the software, modern processors now provide hardware profiling mechanisms often referred to as Performance Monitoring Unit (PMU). Intel, AMD and ARM all include a PMU in their processors.

As far as memory is concerned, PMUs usually allow for two modes of operation. A first mode permits to count the number of memory requests that reach the memory controllers. From this count, one can monitor the memory bandwidth. A second mode, named sampling, periodically records samples that can contain more information about the initiator of the memory request (typically address of the instruction that initiates the request), the level into the memory hierarchy where the data was found and information about the latency of the access.

Unfortunately, using these profiling mechanisms is a daunting task because of low-level concerns. In particular, it requires writing micro-architecture dependent code to assign the correct model specific registers (MSR) with the correct configuration values. This code can be different even for different micro-architectures from the same processor vendor.

From the programming point of view, the increasing complexity of hardware platforms has led to the emergence of numerous parallel programming models. Custom profiling tools are then needed, that ought to be aware of the way the application is written. In order to provide useful performance information to the application developer, low-level profiling events should be linked to the programming model. An abstraction of the memory profiling capabilities of the hardware is thus required as a basic building block of these high-level profiling tools. This will allow to isolate and alleviate the difficult task of using the PMU from the other difficult task of correlating performance samples with programming models. Several existing works provide programming abstractions on top of the PMUs, but none of them handle the sampling of memory requests. Moreover, none of these approaches propose a portable way of monitoring memory bandwidth using the PMU in counting mode.

The main contribution of this work is the `numap` low-level memory profiling library. `numap` stands for Non Uniform Memory Access architectures Profiling. `numap` abstracts the common memory profiling mechanisms exposed to software by processors from different vendors by providing a powerful yet simple interface. It is an open source library [1] that already supports many micro-architectures from Intel. `numap` has been initially thought and designed for profiling memory usage on NUMA architectures but it can definitely be used for memory profiling in centralized shared memory systems.

The remainder of the paper is organized as follows. We describe in Section 2 PMUs and how

[1] `https://github.com/numap-library/numap`

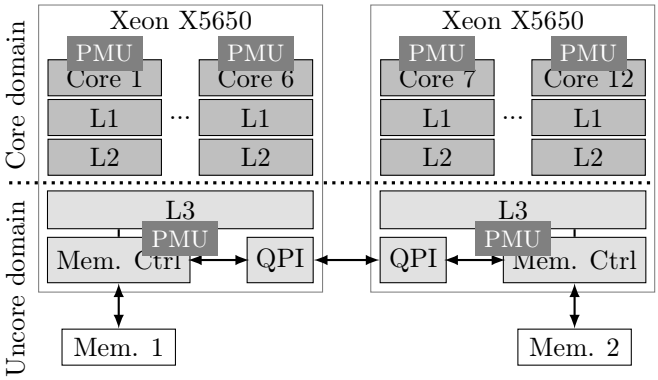

Figure 1: PMU on an Intel dual processors NUMA architecture. Some performance counters are located at Core level, and others at Uncore level. Uncore counters are not able to distinguish events according to the originated core.

to use them. In Section 3 we present related works. We then motivate the proposal of the `numap` library in Section 4. Section 5 gives the details of the library interface and implementation while Section 6 presents an example of using the library for profiling programs written in a high-level dataflow parallel programming model. Finally, we conclude and describe future works in Section 7.

2 Background

In this section we first describe the different features provided by PMUs. Then we present existing solutions to access these features.

2.1 Performance Monitoring Unit

A PMU provides means to characterize hardware usage through hardware performance counters. These counters can be configured by software to count some specific hardware events among a huge number of possibilities. As shown in fig. 1, counters are either located at the level of cores or at the level of memory controllers. At core level, examples of hardware events that can be profiled are clock cycles, number of floating point instructions, number of level 1 cache misses or number of branch mispredictions. At memory level, counters can be configured to count the exact number of memory read or memory write requests.

In addition to this *counting* mode, most PMUs provide a *sampling* mode for events at core level. Intel's technique for sampling is called Precise Event-Based Sampling (PEBS) [Int15] and AMD's is called Instruction-based Sampling (IBS) [Dro07]. On Intel platforms, when sampling, instead of counting the occurrences of a specific event, the PMU is configured to generate a sample with detailed information every time the event occurred a specified number of times. On AMD platforms, IBS allows sampling all instructions independently for a particular event. On both Intel and AMD platforms, information that can be recorded in samples includes the address of the instruction that has generated the event and, in the case of memory-related events, the targeted memory address, the memory level that served the memory access and latency of the memory access. From this information, one can associate low-level information about memory accesses to source code.

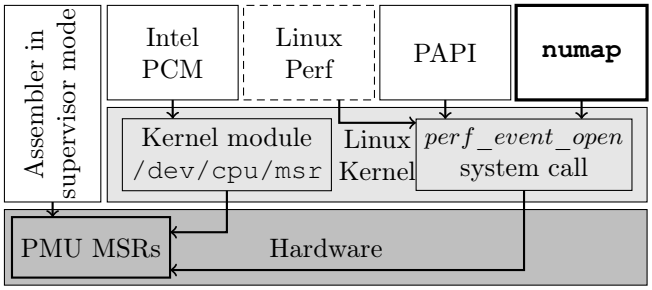

Figure 2: Different ways of accessing the PMU from code. On top of Linux, the PMU MSRs can be accessed either through the `perf_event_open` system call or through a kernel module. For commodity reasons, the `numap` profiling library we propose is built on top of `perf_event_open`. Compare to Intel PCM, PAPI and `numap`, Linux perf is not a library but a command line tool.

2.2 Performance Monitoring Unit Usage

Using hardware monitoring counters requires a deep understanding of the processor's architecture and requires to write very low-level code. On Intel and AMD architectures, the PMU is accessed through Model Specific Registers (MSR) that can be written in processor's supervisor mode only. Figure 2 illustrates various ways to access these registers.

First, performance counters can be manually programmed by writing assembly code executed in supervisor mode on bare metal (left part of fig. 2). Second, using Linux, a kernel module can be used, such as the `/dev/cpu/msr` standard module. This module only allows to access the PMU configuration registers in supervisor mode, it does not provide any abstraction.

Lastly, the `perf_event_open` system call can be used. It was introduced to support the Linux perf command line profiler [pera], and provides a first level of abstraction to access hardware performance counters. This system call abstracts the need to manually write bits to MSRs to start and stop hardware profiling. Nevertheless, much work is still required from the developer willing to profile his/her applications.

The main difficulties consist in finding which events to count or to sample, setting-up all the parameters to be passed to the system call, and performing several system calls depending on the number of threads of the profiled application and the number of cores of the hardware. The PMU events to be used are obviously different across processor vendors, but they are also different between micro-architectures from the same vendor. Finding them requires to step into the specific documentation for the targeted micro-architecture and to understand the low-level details of the underlying hardware. This task is daunting and time consuming.

Another difficulty lies in understanding how to use the system `perf_event_open` system call. To support this claim it is worth mentioning that the corresponding man page[2] is 1583 lines long. Figure 3 shows the signature of the main system call. Quoting the man page, "*the `pid` and `cpu` arguments allow specifying which process and CPU to monitor. The `group_fd` argument allows event groups to be created*". Note that the `pid` argument is not a process id but a thread id. The `flags` argument is mainly used to associate a new event to an existing group. Finally, and quoting the man page again, the `attr` structure argument provides "*detailed configuration information for the event being created*". This structure contains all the hardware-dependent information, in the form of raw numbers, the meaning of which depends on the micro-architecture. The system call returns a file descriptor to be used for reading count values or access

[2] `http://man7.org/linux/man-pages/man2/perf_event_open.2.html`

```
int perf_event_open(struct perf_event_attr *attr,
                    pid_t pid, int cpu,
                    int group_fd,
                    unsigned long flags);
```

Figure 3: `perf_event_open` system call signature. Parameters specify what and when to count or to sample. The system call returns a file descriptor to be used for reading count value or access recorded samples.

recorded samples. When sampling is required, the user code that calls `perf_event_open` must use the returned file descriptor to allocate memory where the kernel will record samples. When this allocated memory is full, the kernel can't record samples anymore until user code indicates which samples it has already read. Section 4 shows in detail the complexity of using `perf_event_open` to sample memory reads on a particular Intel micro-architecture.

To hide etheir the complexity of `perf_event_open` or the one of using directly the `msr` kernel module, libraries such as PAPI [DLM+01] and Intel Performance Counter Monitor (PCM) [PCM] have been proposed. Their main goal, as demonstrated in the next section, is to provide abstractions for common profiling mechanisms based on the PMU but, as far as the authors know, they do not provide abstractions for memory sampling nor a portable way of monitoring memory bandwidth.

3 Related Work

This section first focuses on work regarding how to use the PMU. We then review existing profiling tools that use memory sampling capabilities.

3.1 Libraries For Accessing PMUs

As stated in the previous section, the Linux kernel provides the `perf_event_open` [perb] system call for accessing the PMU of the underlying hardware. Because Linux supports many different processors with a PMU, kernel developers had to leave the burden of a lot of low level micro-architecture dependent details on the user code. As a consequence, this system call is very complex to use, and can't be used in a portable way. Intel PCM [PCM] library is another way to access the PMU. It is available for both Linux and Windows. Nevertheless, it doesn't provide access to memory sampling features and works only for Intel processors as the name suggests. PAPI [DLM+01] is an API aiming at simplifying the use of PMUs of different architectures. PAPI provides an abstraction for the common counters found on all the targeted architectures in such a way that the programmer only needs to say, *e.g.* "*I want to count the number of instructions retired*". Unfortunately, as Intel PCM, the current PAPI version[3](5.4.3) doesn't provide any way to use the memory sampling capabilities of modern PMUs. Moreover, counting memory requests using PAPI requires to know which hardware event to use for every targeted micro-architecture. A work proposing the addition of sampling capabilities in PAPI has been published very recently [LMW15]. The main difference between this work and our proposed `numap` library concerns the interface exposed to user code. We advocate for a higher level of abstraction to let developers using `numap` focus only on analyzing the data and not on how to

[3] `http://icl.cs.utk.edu/papi`

get the memory samples. Moreover, to the best of our knowledge, this PAPI extension is not open source and its official integration into PAPI is not planned yet.

3.2 Profilers And Runtimes Using Memory Sampling

We now review existing profiling and runtime software approaches that are based on memory sampling capabilities. These tools are either non portable or require very expensive work to support different micro architectures. All of them, except the Linux perf profiler, could benefit from `numap` to ease their development and to increase their portability.

The Linux perf [pera] command line profiler provides a memory sampling feature. It is portable on all the processors supported by Linux. perf is based on the `perf_event_open` system call and hardware dependent code is developed by Linux kernel developers for supporting various models. It is a very complex tool designed to be used by end users. The only provided interface is the command line, no API is provided. As a consequence, compared to `numap`, it is impossible to build programming model aware profilers on top of perf.

Memphis [MV10] and MemProf [LLQ12] are memory profilers dedicated to identify remote memory accesses in concurrent applications running on NUMA architectures. These tools work only for AMD processors and required the development of a specific Linux Kernel module dedicated to memory sampling on AMD processors based on IBS [Dro07]. Carrefour [DFF+13] is a runtime extension of MemProf integrated into the Linux kernel memory management subsystem. Its main goal is to limit remote memory accesses on NUMA architectures and to alleviate memory load imbalance. As MemProf, Carrefour required expensive developments only for running on AMD processors. HPCToolkit is a profiler that has been recently extended to support memory profiling [LMC14]. These extensions were required to identify memory bottlenecks in parallel applications. This profiler is portable on different micro architectures. It relies on PAPI for the profiling aspects not related to memory and relies on micro architecture dependent code for memory sampling. ScaAnalyzer [LW15] is another extension to HPCToolkit allowing to detect memory scalability bottlenecks. It also relies heavily on memory sampling, and required a lot of development to support different micro-architectures. The development of all these tools could be easier using the `numap` library.

4 Motivation

None of the existing PMU libraries provide high-level abstractions for memory sampling. More specifically, they don't provide any abstraction for techniques like Intel Precise Event-Based Sampling (PEBS) [Int15] and AMD Instruction-Based Sampling (IBS) [Dro07]. Developers willing to analyze memory usage and performance thus have to use the `perf_event_open` system call or MSRs to setup memory profiling. Again, using any of these two solutions requires to find which event to profile in the documentation of the targeted processor and to write a lot of setup code. We now describe step by step the burden of doing memory sampling using `perf_event_open`.

Once a developer knows which event he/she needs to use for memory sampling using `perf_event_open`, the first thing to do is to setup the parameters and then to effectively make the call using these parameters. Figure 4 illustrates the burden for this task.

Line 3 specifies the event that must be recorded for the Intel Westmere micro-architecture in this case. These events are part of the several hundreds of events documented in processors' datasheets (Intel's Software Developer Manual [Int15] chapter 18 for Intel processors). Line 4 specifies that a sample must be recorded only if the latency of the read access is above 3 cycles (which is the minimal latency for a memory load on the considered Westmere platform). Then, line 5 indicates the rate at which sampling must occur. This rate is in number of events. In

```
1  // Set system call parameters
2  struct perf_event_attr pe_attr;
3  attr.config = 0x100b;
4  attr.config1 = 3;
5  attr.sample_period = 20000;
6  attr.sample_type = PERF_SAMPLE_IP
7      | PERF_SAMPLE_ADDR | PERF_SAMPLE_WEIGHT
8      | PERF_SAMPLE_DATA_SRC;
9  attr.precise_ip = 2;
10 attr.mmap = 1;
11 attr.task = 1;
12 attr.exclude_kernel = 1;
13 attr.exclude_hv = 1;
14 attr.disabled = 1;
15
16 // Make the call
17 int fd = perf_event_open(&attr, TID, -1, -1, 0);
```

Figure 4: `perf_event_open` system call complexity. This example shows how to sample memory loads for a single thread with id TID.

this example, we record a sample every 20000 memory loads. In practice, the sampling rate will depend on the hardware cost of sampling memory accesses and on the acceptable overhead. The acceptable overhead for profiling tools dedicated to offline analyzes should be greater than the one for runtime decisions based on memory sampling. Lines 6 to 8 indicate which information must be recorded in each sample. Lines from 9 to 14 configure other details about the memory sampling. In these lines we indicate that we want precise recording of the instruction address, that we want to record `mmap` information for offline symbol decoding and that we exclude kernel and hypervisor code from sampling. Line 17 finally performs the system call and we get a file descriptor as a result. In this example, the kernel is told to record samples only for the Linux thread with the given `TID` identifier.

Once the `perf_event_open` call has been issued, user code must map the memory containing the records in its address space. User code must also effectively start the sampling using another system call, namely `ioctl`. Figure 5 shows how to do these two tasks. The `mmap` system call must be used with the file descriptor previously returned by `perf_event_open` with a particular size and with the appropriate protection arguments. As shown on line 6, the size of the mapped memory area must be in the form $1 + 2^n$ *pages* where *pages* is the system default page size. Finally, the `ioctl` call should be made twice with two specific perf flags to first reset and then start the sampling (lines 10 and 11).

When user code wants to stop sampling, an `ioctl` call must be performed (symmetric to the one to start sampling) as shown on line 4 of fig. 6.

To analyze the samples, extra precautions should also be taken as shown by lines 7 to 19 in fig. 6. First (line 7) we must get the position of the last sample written by the kernel to know when we have to stop reading the samples. Then, a memory barrier instruction should be issued (line 8) as specified in the `perf_event_open` man page ("*On SMP-capable platforms, after reading the data_head value, user space should issue an rmb()*"). Lines 9 and 10 get the address of the header of the first sample. From then on, we can iterate over samples whose body is located at address `header + 8` as shown by lines 12 to 19.

```
1  // Map result, size should be 1+2^n pages
2  size_t mmap_pages_count = 2048;
3  size_t p_size = sysconf(_SC_PAGESIZE);
4  size_t len = p_size*(1 + mmap_pages_count);
5  struct perf_event_mmap_page *metadata
6      = mmap(NULL, mmap_len, PROT_WRITE,
7             MAP_SHARED, fd, 0);
8
9  // Start sampling
10 ioctl(fd, PERF_EVENT_IOC_RESET, 0);
11 ioctl(fd, PERF_EVENT_IOC_ENABLE, 0);
```

Figure 5: Map in user space the result of `perf_event_open` system call and start sampling. There are constraints on the size of the mapped memory.

```
1 #define rmb() asm volatile("lfence":::"memory")
2
3  // Stop sampling
4  ioctl(fd, PERF_EVENT_IOC_DISABLE, 0);
5
6  // Analyze the samples
7  uint64_t head_samp = metadata -> data_head;
8  rmb();
9  struct perf_event_header *header =
10        metadata + p_size;
11 uint64_t consumed = 0;
12 while (consumed < head_samp) {
13   if (header->type == PERF_RECORD_SAMPLE){
14     // Do something with the sample which
15     // fields start at address header + 8
16   }
17   consumed += header->size;
18   header = (struct perf_event_header *)
19            ((char *)header + header -> size);
20 }
```

Figure 6: Stop sampling and analyze the results. The iteration over the samples recorded using `perf_event_open` requires dealing with low level concerns.

5 The Library

We propose the `numap` library to alleviate developers from knowing which exact hardware events need to be used for monitoring memory bandwidth and sampling memory requests. `numap` also remove most of the burden described in the previous section when using `perf_event_open`. By automatically choosing the correct event for the underlying hardware, `numap` provides a portable support for low level memory profiling.

5.1 Application Programming Interface

The main functions of the `numap` Application Programming Interface (API) are shown on fig. 7. These functions count memory requests, generate memory samples and provide access to them for analyzing memory behavior of applications.

Because `numap` relies on specific hardware components and operating system configurations, it can sometimes be complex just to know whether or not memory sampling is available on particular machine. To alleviate this problem, all the `numap` functions return an integer for error management. From this error code, user code can get a human readable message using the `error_message` function. The message may indicate that the micro-architecture doesn't provide memory sampling, that `numap` doesn't support yet the micro-architecture or that the system policy doesn't allow memory sampling (along with information about how to enable it).

All functions except the error management, take a custom structure as a parameter that is used both to provide results to the caller and to internally keep track of the events that have been activated. There is one structure for functions related to sampling and another one for functions related to counting. The definitions of these structures are shown on fig. 8.

Regarding sampling, this structure is called `samp_session`. It contains a list of thread ids. User code must fill this list to specify the threads to be profiled before passing the structure to functions starting profiling. The `samp_session` structure is also used to specify the sampling rate and the number of pages to allocate for saving the samples (this number is used to compute the size in the correct form which is then passed to the `mmap` call described in the previous section). The current version of `numap` only allows to save samples until the specified size is filled. As stated in Section 7, we plan to allow the profiling of very long lived applications. The `init_samp_session` function is provided to setup all the input parameters at once.

The `samp_read_start` and `samp_write_start` functions internally performs the `mmap` system call described in the previous section. There may be several calls in case the user code specifies several threads to be profiled. The result of each of them is stored in the `metadatas` list of the `samp_session` object passed as parameter.

Finally, the `samp_session` structure contains internal fields that should only be read and written by `numap` itself. These fields are needed to handle all the details described in Section 4.

For counting, the structure is called `count_session`. It contains the list of NUMA nodes to be profiled. As for sampling, user code must fill this list to specify the nodes to be profiled. The structure also contains a file descriptor for each profiled NUMA node. When counting has been stopped, user code gets the actual count value by calling the `get_count` function using this file descriptor.

As shown in fig. 7, `numap` provides functions to start and stop profiling both for sampling and counting. In both modes, `numap` differentiates memory read and memory write profiling. The reason for that is the hardware, PMUs provide different events for read and write profiling. The counting functions are used to start counting

The second type of functions provided by `numap` are used to let user code easily access the samples generated by the library. All these functions take as input the `samp_session`

```
// Init sampling parameters
int init_samp_session(
    struct samp_session *ses, int nb_threads,
    int sampling_rate, int mmap_pages_count);

// Start and stop memory sampling
int samp_read_start (struct samp_session *s);
int samp_read_stop  (struct samp_session *s);
int samp_write_start(struct samp_session *s);
int samp_write_stop (struct samp_session *s);

// Analyze the samples
int print_rd(File *f, struct samp_session *s);
int print_wr(File *f, struct samp_session *s);
int cpy_samples(struct samp_session *s,
            struct samp **dest, int *nb_sp);

// Init counting parameters
int init_count_session(
    struct count_session *ses, int nb_nodes,
    int *nodes);

// Start and stop counting memory traffic
int count_read_start (struct count_session *s);
int count_read_stop  (struct count_session *s);
int count_write_start(struct count_session *s);
int count_write_stop (struct count_session *s);

// Get count value
long get_count(struct count_session *s);

// Get human readable error message
const char *error_message(int error);
```

Figure 7: The main functions of numap API

```
// Structure for a sampling session
struct samp_session {

  // Fields to be written by user code
  // before using numap functions
  unsigned int nb_threads;
  pid_t *tids;
  unsigned int sampling_rate;
  unsigned int mmap_pages_count;

  // Field to be read by user code
  // where to find the samples
  struct perf_event_mmap_page **metadatas;

  // Fields to be written and/or
  // read internally by numap only
  size_t page_size;
  size_t mmap_len;
  long *fd_per_tid;
};

// Sample structure
struct samp {
  uint64_t ip;
  uint64_t addr;
  uint64_t weight;
  union perf_mem_data_src data_src;
}

// Structure for a counting session
struct count_session {

  // Fields to be written by user code
  // before using numap functions
  unsigned int nb_nodes;
  int *nodes;

  // Fields to be written and/or
  // read internally by numap only
  long *fds;
};
```

Figure 8: The `numap` API data structures. The structure `samp_session` is used by user code to specify to `numap` what should be profiled and to get the result. The structure `samp` represents a single sample.

structure to avoid the user code having to deal with low level details. The library provides functions allowing to print the samples generated by `numap` either in a file or on the console.

To perform custom work on the generated samples, `numap` provides the `samp_cpy` function. This function produces a ready-to-use list of simple sample objects. This list is then accessible through the `dest` pointer. This list is dynamically allocated on the heap by `numap`, and its size is returned to user code through the `nb_sp` parameter. Each element of this list is of type `struct samp`. As shown on fig. 8, this structure contains the address of the instruction that generated the sample, the targeted address, the latency of the access (weight) and the memory level that served it. These values are the fundamental information needed to build appropriate profiling or runtime mechanisms such as the one described in Sections 3.2 and 6. This `samp_cpy` function alleviates the user code from the details described in the previous section required to read the memory filled by the kernel.

Figure 9 summarizes the usage of `numap` for sampling read memory accesses. User code must first call the `init_samp_session` function (line 3) and specify the identifiers of the threads to be profiled (line 8). In this example we are profiling only the current thread whose identifier is retrieved through the `syscall(SYS_gettid)` call. Then, sampling is started just before the code to be profiled with `samp_read_start` (line 11) and stopped with `samp_read_stop` when needed (line 20). At this point the samples are available for use. Figure 9 only prints them on standard output using the `numap` built-in `print_rd` function (line 28). A real life usage of `numap` will deeply analyze the samples either using `samp_cpy`, or directly accessing the `s.metadatas`. This example also shows the usage of the `error_message` function (lines 5, 13 and 22).

5.2 Implementation

The implementation of `numap` relies on the classic `perf_event_open` usage such as described in Section 4. Indeed, the main goal of `numap` is to provide an abstraction on top of the Linux kernel to allow both portability and usability. Usability is handled through the simple interface described in the previous section.

Regarding portability, `numap` implementation automatically selects the correct hardware event to be used for memory read or write sampling and for memory requests counting. The set of supported micro-architectures is coded as a list of structures tagged by processor and family identifiers. For each micro-architecture, the structure contains the identifier of the events to be used with `perf_event_open`. This identifiers are not directly the integer representation of the events to be passed to `perf_event_open` but a string representation. This string is feed to the `pfm` library [PFM] which purpose is only to convert a string event to a number usable by `perf_event_open`. To find the string identifiers of the events to be used for each supported Intel micro-architecture, we used the software developer manual chapter 18 [Int15]. Navigating through this document is really difficult for newcomers. It requires both having a clear overview of the history of Intel micro-architectures and a lot of time to find the particular event among all the events provided (often several hundreds). The micro-architectures currently supported are shown on Table 1. As shown in this table, write accesses sampling has been introduced by Intel with the Sandy Bridge family. All these micro-architectures support counting of memory requests.

The implementation of `numap` hides as much as possible the details described in Section 4. Calls to `perf_event_open`, `mmap`, `ioctl` and memory barriers are used internally by the implementation of the `numap` functions. `perf_event_open` calls are done by the `samp_xxx_start` and `count_xxx_start` (xxx is either read or write) functions. For sampling, the starting functions also perform the `mmap` call. The `ioctl` calls needed to start profiling are also done by the

```
1  // Init read sampling
2  struct samp_session s;
3  res = init_samp_session(&s, 1, 1000, 64);
4  if(res < 0) {
5    printf(``err:%s\n``, error_message(res));
6    return -1;
7  }
8  sm.tids[0] = syscall(SYS_gettid);
9
10 // Start memory read access sampling
11 res = samp_read_start(&s);
12 if(res < 0) {
13   printf(``err:%s\n``, error_message(res));
14   return -1;
15 }
16
17 // Code to be profiled here
18
19 // Stop memory read access sampling
20 res = samp_read_stop(&s);
21 if(res < 0) {
22   printf(``err:%s\n``, error_message(res));
23   return -1;
24 }
25
26 // Print memory read sampling results
27 printf(``Memory read sampling results\n``);
28 print_rd(stdout, &s);
```

Figure 9: Basic usage of `numap`. User code must use the sequence `init_samp_session`, `samp_read_start` and `samp_read_stop`. Then user code exploits the resulting samples. In this example, they are only printed on standard output using the `numap` built-in `print_rd` function.

Name	Read Sampling	Write Sampling
Nehalem - Lynfield decline	Yes	No
Westmere - EP decline	Yes	No
Sandy Bridge	Yes	Yes
Sandy Bridge - EP decline	Yes	Yes
Ivy Bridge	Yes	Yes
Ivy Bridge - E decline	Yes	Yes
Haswell - E decline	Yes	Yes
Haswell - DT decline	Yes	Yes

Table 1: Micro-architectures supported by numap

starting functions and the ones to stop profiling by `samp_xxx_stop` and `count_xxx_stop` ones. The `samp_cpy` function manages the call to the memory barrier and the conversion from the raw results provided by the kernel to the list of `struct samp` elements.

6 Library Usage Example

`numap` was initiated as a mean for memory profiling of dataflow applications executed on NUMA architectures [Sel15]. It started as an ad-hoc tool to evolve to a clean API to be used outside its initial scope. This section shows how we use `numap` to build a memory profiler dedicated to dataflow applications.

6.1 Dataflow Programming

In the dataflow programming model, an application is described as a graph. Each node of the graph, called an actor, represents an independent computing unit operating on input data to produce output data. Edges between actors specify the data dependencies between them and are the only mean for actors to communicate. More precisely, these edges behave as first-in-first-out (FIFO) channels. The independence between actors and the blocking-read semantics associated to channels allow the dataflow compiler and/or runtime to automatically distribute the computing work of actors among the available cores when targeting parallel hardware.

We use `numap` to profile dataflow applications written using the RVC-CAL language compiled with the Open RVC-CAL Compiler (Orcc) [YLJ+13]. This compiler is a source-to-source compiler producing C multi-threaded code to be compiled by GCC or LLVM Clang to produce the binary.

6.2 Profiling RVC-CAL Applications With `numap`

Understanding the memory performances of dataflow applications written in RVC-CAL is crucial to map the dataflow application on the hardware in an efficient way. `numap` allows to easily get memory samples for the dataflow application in a portable way.

Figure 10 shows the profiling toolchain we implemented inside Orcc. As presented on this figure, the Orcc compiler has been modified to include memory sampling mechanisms within the generated C code. Mainly, calls to `numap` start and stop sampling functions are inserted each time a thread is created. The generated C source code is then linked against `numap`. In this instrumented C source code, when a thread is stopped, the samples are recorded to a file for offline analysis.

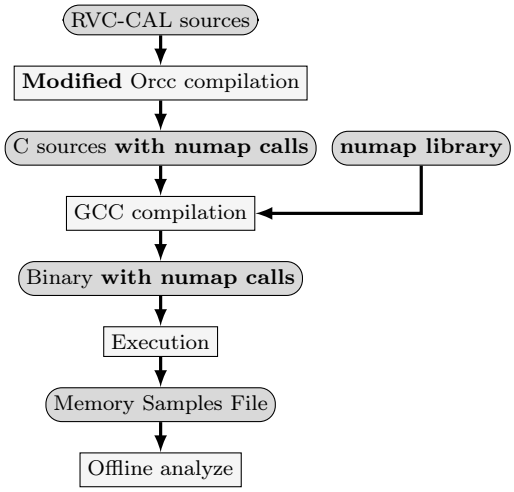

Figure 10: RVC-CAL memory profiler based on numap. The Orcc compiler is modified to generate code including `numap` function calls. During the execution of the application, memory samples provided by `numap` are recorded for offline analysis.

This offline analysis uses the information reported in each sample provided by `numap` in order to associate samples to channels and actors. This allows, typically, to determine the cost (in terms of latency) of an actor producing data tokens to a particular FIFO channel. This association is required to provide hints to the application programmer and the designer of the dataflow compiler. They can then modify and hopefully optimize either the application, the compiler or the dataflow runtime accordingly.

Using `numap`, the instrumentation of the Orcc compiler to perform low level memory profiling was straightforward. Only few calls to the library are required without the need to understand at all how the Linux `perf_event_open` system call is implemented and how the PMU gets the information. The `numap` user code (generated by the Orcc compiler in this case) just tells `numap` to perform memory read and/or memory write sampling for its own threads. Having a library such as `numap` also allows to perform very fine grain sampling, by allowing to start and stop profiling at any time.

7 Conclusion And Future Works

This work proposes the `numap` library to ease the usage of memory features proposed by the PMU of many modern processors. `numap` is both portable and easy to use. Portability is ensured by hiding micro-architectural dependent to user-code, while usability is provided by hiding all the burden to use the complex `perf_event_open` system call. We are successfully using `numap` as a basis of a memory profiler dedicated to dataflow applications [Sel15]. We believe that such libraries are required to help the software community build portable profiling tools and runtime mechanisms in an efficient way.

Nevertheless, to increase the adoption of `numap` we are working on several directions. First, we are currently porting `numap` on AMD processors. This requires to understand the details of IBS [Dro07], the PMU memory sampling capabilities for AMD. This task will be nevertheless straightforward because `perf_event_open` already supports IBS[lwn], and because we gained deep experience of this system call while developing `numap` for Intel platforms. Independently

of the complexity of porting `numap` on AMD micro-architectures, it is worth mentioning that our API will stay the same, because the IBS mechanism provides all the sampling attributes of the `numap samp` structure and because it also requires a frequency input parameter.

Second, we are planning to add better support for the management of long lived applications. Indeed, `numap` currently only allows to save a maximum number of events specified at initialization time. To support applications willing to process samples while running, we will extend the API with functions to indicate to the library the part of the samples already read that can be erased. This information will then be propagated to the Linux kernel to let him recycle corresponding memory pages. To support applications only requiring offline analysis of the samples, the library will provide a mechanism to automatically dump the samples into a file. This mechanism will be toggled with a simple additional parameter to the initialization function of `numap`.

Last, we think that the features provided by `numap` can and should be integrated into other profiling tools. Among those, a preferred target would be the widely used PAPI [DLM+01] library. In a near future, the best of both `numap` and the memory sampling abstraction API proposed in [LMW15] should be integrated into the main version of PAPI.

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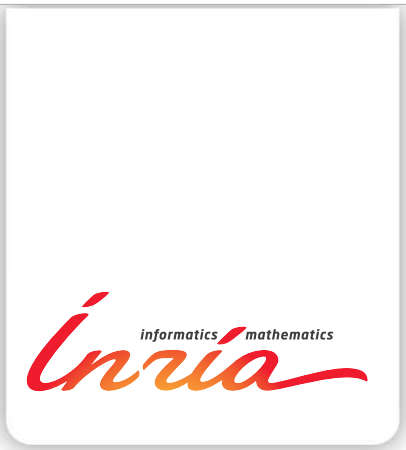

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