PAPI-NUMA: Middleware to Support Hardware Sampling

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SCALABLE TOOLS WORKSHOP

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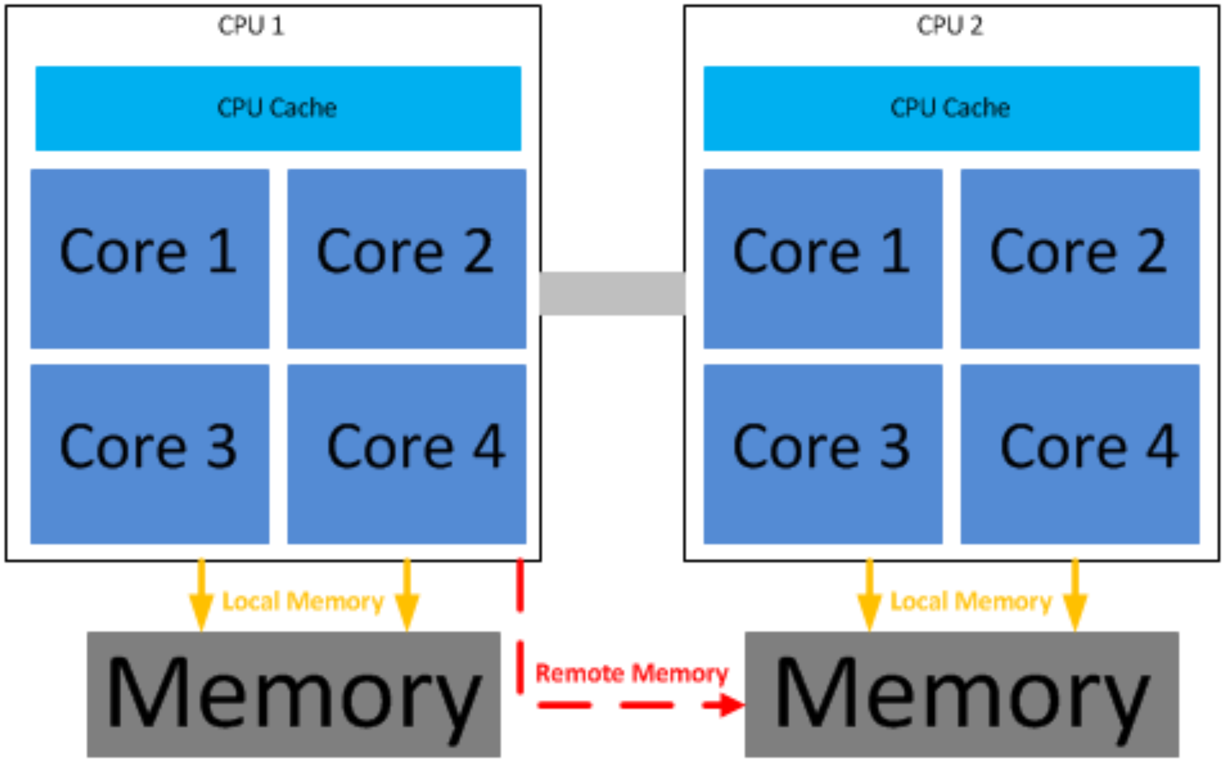
Motivation

- Modern architectures have complex shared cache and memory hierarchies with non-uniform memory access (NUMA).
- Sub-optimal data/thread placement resulting in non-local data accesses can seriously degrade performance.
- Application developers need tools to help diagnose NUMA performance issues.
- Tool developers have to implement low-level access to sampling data
  - Redundant effort
  - Measurement part of tool is not released or not usable on production machines.

NUMA



CPU 1
CPU Cache
Core 1
Core 2
Core 3
Core 4
CPU 2
CPU Cache
Core 1
Core 2
Core 3
Core 4
Local Memory
Local Memory
Remote Memory
Memory
Memory

NUMA Example: STREAM on Stampede with 16 threads

With first touch:

Function	Best Rate MB/s	Avg time	Min time	Max time
Copy:	44840.9	0.005951	0.003568	0.017847
Scale:	47127.0	0.004679	0.003395	0.012240
Add:	52849.9	0.005304	0.004541	0.011292
Triad:	53368.3	0.005225	0.004497	0.010981

Without first touch:

Function	Best Rate MB/s	Avg time	Min time	Max time
Copy:	7387.9	0.023044	0.021657	0.026183
Scale:	7259.9	0.023979	0.022039	0.028078
Add:	10768.7	0.025722	0.022287	0.030115
Triad:	10942.4	0.026642	0.021933	0.034551

Hardware Counters

- Model Specific Registers (MSRs) that count hardware *events* (e.g., cycles, instructions retired, cache misses, different types of operations)
- Data collection methodologies
  - Counting: count how many times a given event occurs
  - Sampling: sample event and correlate with other information (e.g., program counter, data address, access latency, data source)

PAPI

- The Performance Application Programming Interface (PAPI) aims to provide the tool designer and application engineer with a consistent interface and methodology for use of the **performance counter hardware** found in most major microprocessors.
- PAPI enables software engineers to see, in near real time, the relation between software performance and processor events.
- It is being widely used to collect low level performance metrics (e.g. instruction counts, clock cycles, cache misses) of computer systems running UNIX/Linux operating systems.

Software Stack for NUMA Sampling

Performance analysis tools (e.g., HPCToolkit-NUMA, MemAxes, TAU)
PAPI-NUMA
Linux perf_event
Platform-specific Interface (e.g., Intel PEBS-LL, AMD IBS)
Hardware Performance Counters

Linux perf_event

- Linux kernel infrastructure that exposes hardware and software events
  - Provides an abstraction of performance events to user space
  - Provides a flexible interface for architecture-specific usage
- Exposed through perf_event_open() system call
  - int perf_event_open(struct perf_event_attr *attr, pid_t pid, int cpu, int group_fd, unsigned long flags);
  - perf_event_attr struct is populated before the call
  - returns a file descriptor
- Different counting and sampling configurations
- Counted events accessed through read()
- Sampled events accessed through mmap()

PAPI-NUMA Interface

- Goal: Provide a stable sampling interface to which tool developers can program
- PAPI-NUMA routines
  - PAPI_sample_init(): sets up perf_event_attr structure and calls perf_event_open (leaves sampling disabled)
  - PAPI_sample_start(): enables sampling
  - PAPI_sample_stop(): disables sampling

PAPI_sample_init()

```
int PAPI_sample_init(
    int EventSet,
    int EventCode,
    int sample_type,
    int sample_period,
    int threshold,   /* user-defined threshold for latency events */
    PAPI_sample_handler_t handler);
typedef  void PAPI_sample_handler_t(int signum, siginfo_t *info,
    void *ucontext);
```

Getting Per-thread Samples

- Highly desirable to obtain per-thread samples, since multithreaded codes may need to be analyzed for NUMA effects.
- Remote memory access on a NUMA system can degrade performance.
- Samples are collected only for the calling process and thread.
- perf_event kernel code specifically blocks getting mmap samples if inherit is enabled.
- Solution: Set up a counter on each logical CPU, each with its own mmap buffer.
- Currently requires kernel patch to propagate per-thread samples

Modified PAPI_sample_init()

```
int PAPI_sample_init (
    int EventSet,
    int EventCode,
    int sample_type,
    int sample_period,
    int threshold,
    PAPI_sample_handler_t handler,
    int *fds);
```

- Returns file descriptor from perf_event_open() for each logical CPU

Client code

- Sets up and associates mmap buffer with each file descriptor
- Calls PAPI_sample_start(fd) for each file-descriptor to start per-thread sampling
- Interrupt handler checks which file descriptor is passed in and reads mmap buffer for that file descriptor

Utility Code

- perf_mmap_read()
  - Parses the mmap buffer
  - Determines type of record
  - For PERF_RECORD_SAMPLE
    - Prints values of fields that were requested by PAPI_sample_init()
- Example interrupt handler
  - Determines appropriate mmap buffer
  - Calls perf_mmap_read() on that buffer
  - Counts samples

Sample Results

- From instrumented OpenMP version of STREAM run with 8 threads on Stampede node

PERF_SAMPLE_IP, IP: 4012c0

PERF_SAMPLE_TID, pid: 3144, tid: 3144

PERF_SAMPLE_WEIGHT, Weight: 7

PERF_SAMPLE_DATA_SRC, Raw: 68100142

Load Hit L1 cache No snoop Hit Level 1 TLB Level 2 TLB

PERF_SAMPLE_IP, IP: 401a78

PERF_SAMPLE_TID, pid: 3144, tid: 3167

PERF_SAMPLE_WEIGHT, Weight: 28

PERF_SAMPLE_DATA_SRC, Raw: 68100242

Load Hit Line fill buffer No snoop Hit Level 1 TLB Level 2 TLB

How to Best Help Tool Developers?

- How to provide results?
  - Provide common PAPI-specific generic sampling interface and have all components map their samples to it
    - PAPI would need to be constantly updated to extend and handle all of the various low-level changes.
  - Dump raw data for the user/tool to interpret
    - Requires additional user/tool code to interpret the data (could be provided as PAPI utility code)
  - Dump data in Linux perf tool format
  - All of the above?
- Survey tool developers to determine their requirements
- Investigate usefulness of sampling data besides NUMA data

Conclusions and Future Work

- Initial prototype is a low-level interface intended for performance tool developers.
- Plan to make our implementation available to tool developers to get feedback
- Plan to design a higher-level interface that will not require the user to provide the signal handler nor parse the mmap buffer.
- Having per-thread sampling of memory events available on stock Linux kernels through the PAPI interface will improve tool/user accessibility to NUMA data.
- Presented at XSEDE15, considerable interest from audience

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