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FORSCHUNGSZENTRUM

# Performance Counters and Tools

## OpenPOWER Tutorial, SC17, Denver

**Andreas Herten**, Forschungszentrum Jülich, 13 November 2017

# Outline

Goals of this session

- Get to know Performance Counters
- Measure counters on POWER8

→ Hands-on

- *Additional material in appendix*

*[…] premature optimization is the root of all evil.*

*– Donald Knuth*

*[. . .] premature optimization is the root of all evil.* ***Yet we should not pass up our [optimization] opportunities [. . .]***

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*Full quote in appendix*

# Optimization ⟳ Measurement

*Making educated decisions*

- Only optimize code **after** measuring its performance
  *Measure! Don't trust your gut!*

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  - Operations per cycle (FLOP/s)
  - Usage of architecture features ($, (S)MT, SIMD, ...)

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- Correlate measurements with code

  $\rightarrow$ hot spots/performance limiters

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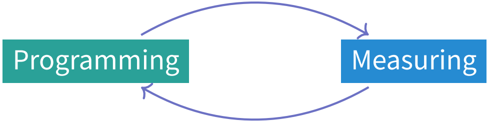
  - Usage of architecture features (\$, (S)MT, SIMD, …)
- Correlate measurements with code
  $\rightarrow$ hot spots/performance limiters
- Iterative process



# Measurement

Two options for insight

Coarse Timestamps to time program / parts of program

- Only good for first glimpse
- No insight to inner workings

Detailed **Performance counters** to study usage of hardware architecture

- Instructions
- Cycles

→ CPI, IPC

- Floating point operations
- Stalled cycles
- Cache misses, cache hits
- Prefetches
- Flushs
- Branches
- CPU migrations
- ...

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- Cycles → CPI, IPC
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- …

- *Native*
- *Derived*
- *Software*

# Performance Counters

# Performance Monitoring Unit

*Right next to the core*

- Part of processor periphery, but dedicated registers
- History
  - First occurrence: Intel Pentium, reverse-engineered 1994 (`RDPMC`) [1]
  - Originally for chip developers
  - Later embraced for software developers and tuners
- Operation: Certain events counted at logic level, then aggregated to registers

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## Pros

- Low overhead
- Very specific requests possible; detailed information
- Information about CPU core, *nest*, cache, memory

## Cons

- Processor-specific
- Hard to measure
- Limited amount of counter registers
- Compressed information content

# Working with Performance Counters

*Some caveats*

- Mind the clock rates!
  - Modern processors have dynamic clock rates (CPUs, GPUs)
    $\rightarrow$ Might skew results
  - Some counters might not run at nominal clock rate
- Limited counter registers
  POWER8: 6 slots for hardware counters
- Cores, Threads (OpenMP)
  - Absolutely possible
  - Complicates things slightly
  - Pinning necessary
    $\rightarrow$ `OMP_PROC_BIND`, `OMP_PLACES`; `PAPI_thread_init()`
- Nodes (MPI): Counters independent of MPI, but aggregation tool useful (Score-P, …)

# Performance Counters on POWER8

# POWER8 Compartments

*Sources of PMU events*

POWER8

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POWER8

Core-Level

Nest-Level

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*Sources of PMU events*

POWER8

Core-Level

Nest-Level

- Core / thread level
- Core pipeline analysis
  - Frontend
  - Branch prediction
  - Execution units
  - …
- Behavior investigation
  - Stalls
  - Utilization
  - …

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*Sources of PMU events*

POWER8

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Nest-Level

- L3 cache, interconnect fabric, memory channels
- Analysis of
  - Main memory access
  - Bandwidth

# POWER8 Performance Counters

*Instructions, Stalls*

`PM_LD_MISS_L1` Load missed L1 cache

*Store: `PM_ST_MISS_L1`; Local L4 Hit: `PM_DATA_FROM_LL4`*

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*Also: `PM_RUN_INST_CMPL`*

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*Processor cycles gated by the run latch*

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*Global Completion Table has no slots from thread*

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*Floating point divide or square root instructions*

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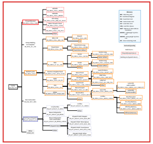

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## Number of counters for POWER8:

$\approx 1063$

*See appendix for more on counters*

*(CPI stack; resources)*

# Measuring Counters

# Overview

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| | |
|---|---|
| `perf` | Linux' tool (also called *perf_events*) |
| PAPI | C/C++ API |
| Score-P | Measurement environment *(appendix)* |
| Likwid | Set of command line utilities for detailed analysis |
| `perf_event_open()` | Linux system call from `linux/perf_event.h` |
| ... | Many more solutions, usually relying on `perf` |

# perf

*Linux' own performance tool*

- Part of Linux kernel since 2009 (v. 2.6.31)
- Example usage: `perf stat ./app`

```
$ perf stat ./poisson2d
Performance counter stats for './poisson2d':

     65703.208586      task-clock (msec)         #    1.000 CPUs utilized
              355      context-switches          #    0.005 K/sec
                0      cpu-migrations            #    0.000 K/sec
           10,847      page-faults               #    0.165 K/sec
  228,425,964,399      cycles                    #    3.477 GHz                     (66.67%)
      299,409,593      stalled-cycles-frontend   #    0.13% frontend cycles idle    (50.01%)
  147,289,312,280      stalled-cycles-backend    #  64.48% backend cycles idle      (50.01%)
  323,403,983,324      instructions              #    1.42  insn per cycle
                                                 #    0.46  stalled cycles per insn  (66.68%)
   12,665,027,391      branches                  #  192.761 M/sec                   (50.00%)
        4,256,513      branch-misses             #    0.03% of all branches         (50.00%)

     65.715156815 seconds time elapsed
```

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*Linux' own performance tool*

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- Usage: `perf stat ./app`
- Raw counter example: `perf stat -e r600f4 ./app`

```
$ perf stat -e r600f4 ./poisson2d

 Performance counter stats for './poisson2d':

   228,457,525,677      r600f4

      65.761947405 seconds time elapsed
```

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- More in appendix

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*Measure where it hurts…*

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- Goal: Create common (and easy) interface to performance counters
- Two API layers *(Examples in appendix!)*
  - High-Level API: Most-commonly needed information capsuled by convenient functions
  - Low-Level API: Access all the counters!

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| `papi_avail` | List aliased, common counters<br>Use `papi_avail -e EVENT` to get description and options for `EVENT` |
| `papi_native_avail` | List all possible counters, with details |

- Extendable by Component PAPI (GPU!)

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- Extendable by Component PAPI (GPU!)
- Comparison to `perf`: Instrument specific parts of code, with different counters

# PAPI

## papi_avail

```
$ papi_avail
Available PAPI preset and user defined events plus hardware information.
--------------------------------------------------------------------------------
PAPI Version             : 5.5.0.0
Vendor string and code   : IBM (3)
Model string and code    : 8335-GCA (0)
CPU Revision             : 2.000000
CPU Max Megahertz        : 3491
CPU Min Megahertz        : 2061
Hdw Threads per core     : 8
Cores per Socket         : 10
Sockets                  : 2
NUMA Nodes               : 1
CPUs per Node            : 160
Total CPUs               : 160
Running in a VM          : no
Number Hardware Counters : 6
```

# PAPI

## papi_avail

```
Max Multiplex Counters   : 192
--------------------------------------------------------------------------------


================================================================================
  PAPI Preset Events
================================================================================
    Name        Code     Avail Deriv Description (Note)
PAPI_L1_DCM  0x80000000  Yes   Yes   Level 1 data cache misses
PAPI_L1_ICM  0x80000001  Yes   No    Level 1 instruction cache misses
PAPI_L2_DCM  0x80000002  Yes   No    Level 2 data cache misses
PAPI_L2_ICM  0x80000003  No    No    Level 2 instruction cache misses
PAPI_L3_DCM  0x80000004  No    No    Level 3 data cache misses
PAPI_L3_ICM  0x80000005  Yes   No    Level 3 instruction cache misses
PAPI_L1_TCM  0x80000006  No    No    Level 1 cache misses
PAPI_L2_TCM  0x80000007  No    No    Level 2 cache misses
PAPI_L3_TCM  0x80000008  No    No    Level 3 cache misses
PAPI_CA_SNP  0x80000009  No    No    Requests for a snoop
```

# PAPI

## papi_avail

```
$ papi_avail -e PM_DATA_FROM_L3MISS
Available PAPI preset and user defined events plus hardware information.
--------------------------------------------------------------------------------

Event name:                     PM_DATA_FROM_L3MISS
Event Code:                     0x40000011
Number of Register Values:      0
Description:                   |Demand LD - L3 Miss (not L2 hit and not L3 hit).|

Unit Masks:
 Mask Info:                    |:u=0|monitor at user level|
 Mask Info:                    |:k=0|monitor at kernel level|
 Mask Info:                    |:h=0|monitor at hypervisor level|
 Mask Info:                    |:period=0|sampling period|
 Mask Info:                    |:freq=0|sampling frequency (Hz)|
 Mask Info:                    |:excl=0|exclusive access|
 Mask Info:                    |:mg=0|monitor guest execution|
```

# PAPI

*Notes on usage; Tipps*

- Important functions in **High Level API**

  `PAPI_num_counters()` # available counter registers

  `PAPI_flops()` Get real time, processor time, # floating point operations, and MFLOPs/s

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  `PAPI_add_event()` Add aliased event to event set

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  `PAPI_thread_init()` Initialize thread support in PAPI

- Documentation online and in `man` pages (`man papi_add_event`)

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→ `http://icl.cs.utk.edu/papi/`

# GPU Counters

*A glimpse ahead*

- Counters built right in
- Grouped into *domains* by topic
- NVIDIA differentiates between *(more examples in appendix)*

  **Event** Countable activity or occurrence on GPU device
  Examples: `shared_store`, `generic_load`, `shared_atom`

  **Metric** Characteristic calculated from one or more events
  Examples: `executed_ipc`, `flop_count_dp_fma`, `achieved_occupancy`

- Usually: access via `nvprof` / Visual Profiler; but exposed via CUPTI for 3rd party

→ **Afternoon session** / appendix

# Conclusions

*What we've learned*

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- Large set of performance counters on POWER8 processors
- Right next to (*inside*) core(s)
- Provide detailed insight for performance analysis on many levels
- Different measurement strategies and tools
  - `perf`
  - PAPI
  - Score-P
- Also on GPU

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**Thank you for your attention!**

*a.herten@fz-juelich.de*

bit.ly/sc17-eval

# Appendix

- Knuth on Optimization
- POWER8 Performance Counters
- `perf`
- PAPI Supplementary
- Score-P
- GPU Counters
- Glossary
- References

# Appendix

## Knuth on Optimization

# Knuth on Optimization

*The full quote, finally*

*There is no doubt that the grail of efficiency leads to abuse. Programmers waste enormous amounts of time thinking about, or worrying about, the speed of noncritical parts of their programs, and these attempts at efficiency actually have a strong negative impact when debugging and maintenance are considered. We should forget about small efficiencies, say about 97 % of the time: pre mature optimization is the root of all evil.*

*Yet we should not pass up our opportunities in that critical 3 %. A good programmer will not be lulled into complacency by such reasoning, he will be wise to look carefully at the critical code; but only after that code has been identified*

*– Donald Knuth in "Structured Programming with Go to Statements" [2]*

# Appendix

## POWER8 Performance Counters

# POWER8 Performance Counters

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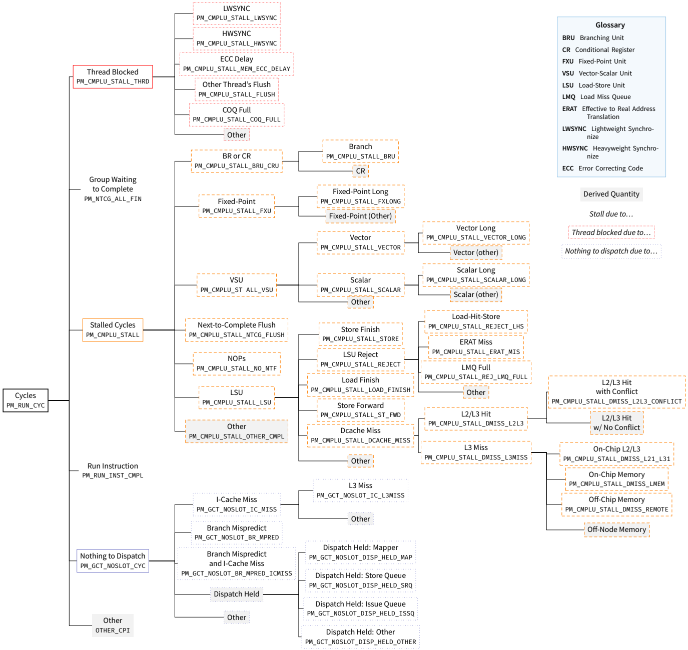
- Further information on counters at IBM website
  - JSON overview of OpenPOWER PMU events on Github
  - CPI events and metrics for POWER8
  - Events and groups supported on POWER8 architecture
  - Derived metrics defined for POWER8 architecture
  - Table 11-18 and Table D-1 of POWER8 Processor User's Manual for the Single-Chip Module
  - OProfile: ppc64 POWER8 events
- List available counters on system
  - With PAPI: `papi_native_avail`
  - With `showevtinfo` from `libpfm`'s `/examples/` directory

```
./showevtinfo | \
  grep -e "Name" -e "Desc" | sed "s/^.\+: //g" | paste -d'\t' - -
```

- See next slide for CPI stack visualization
- Most important counters for **OpenMP**: `DMISS_PM_CMPLU_STALL_DMISS_L3MISS`, `PM_CMPLU_STALL_DMISS_REMOTE`, *`PM_CMPLU_STALL_DMISS_DISTANT`*



Cycles
PM_RUN_CYC
Thread Blocked
PM_CMPLU_STALL_THRD
LWSYNC
PM_CMPLU_STALL_LWSYNC
HWSYNC
PM_CMPLU_STALL_HWSYNC
ECC Delay
PM_CMPLU_STALL_MEM_ECC_DELAY
Other Thread's Flush
PM_CMPLU_STALL_FLUSH
COQ Full
PM_CMPLU_STALL_COQ_FULL
Other
Group Waiting to Complete
PM_NTCG_ALL_FIN
Stalled Cycles
PM_CMPLU_STALL
BR or CR
PM_CMPLU_STALL_BRU_CRU
Branch
PM_CMPLU_STALL_BRU
CR
Fixed-Point
PM_CMPLU_STALL_FXU
Fixed-Point Long
PM_CMPLU_STALL_FXLONG
Fixed-Point (Other)
VSU
PM_CMPLU_ST ALL_VSU
Vector
PM_CMPLU_STALL_VECTOR
Vector Long
PM_CMPLU_STALL_VECTOR_LONG
Vector (other)
Scalar
PM_CMPLU_STALL_SCALAR
Scalar Long
PM_CMPLU_STALL_SCALAR_LONG
Scalar (other)
Other
Next-to-Complete Flush
PM_CMPLU_STALL_NTCG_FLUSH
NOPs
PM_CMPLU_STALL_NO_NTF
LSU
PM_CMPLU_STALL_LSU
Store Finish
PM_CMPLU_STALL_STORE
LSU Reject
PM_CMPLU_STALL_REJECT
Load-Hit-Store
PM_CMPLU_STALL_REJECT_LHS
ERAT Miss
PM_CMPLU_STALL_ERAT_MIS
LMQ Full
PM_CMPLU_STALL_REJ_LMQ_FULL
Other
Load Finish
PM_CMPLU_STALL_LOAD_FINISH
Store Forward
PM_CMPLU_STALL_ST_FWD
Dcache Miss
PM_CMPLU_STALL_DCACHE_MISS
L2/L3 Hit
PM_CMPLU_STALL_DMISS_L2L3
L2/L3 Hit with Conflict
PM_CMPLU_STALL_DMISS_L2L3_CONFLICT
L2/L3 Hit w/ No Conflict
L3 Miss
PM_CMPLU_STALL_DMISS_L3MISS
On-Chip L2/L3
PM_CMPLU_STALL_DMISS_L21_L31
On-Chip Memory
PM_CMPLU_STALL_DMISS_LMEM
Off-Chip Memory
PM_CMPLU_STALL_DMISS_REMOTE
Off-Node Memory
Other
Other
PM_CMPLU_STALL_OTHER_CMPL
Run Instruction
PM_RUN_INST_CMPL
Nothing to Dispatch
PM_GCT_NOSLOT_CYC
I-Cache Miss
PM_GCT_NOSLOT_IC_MISS
L3 Miss
PM_GCT_NOSLOT_IC_L3MISS
Other
Branch Mispredict
PM_GCT_NOSLOT_BR_MPRED
Branch Mispredict and I-Cache Miss
PM_GCT_NOSLOT_BR_MPRED_ICMISS
Dispatch Held
Dispatch Held: Mapper
PM_GCT_NOSLOT_DISP_HELD_MAP
Dispatch Held: Store Queue
PM_GCT_NOSLOT_DISP_HELD_SRQ
Dispatch Held: Issue Queue
PM_GCT_NOSLOT_DISP_HELD_ISSQ
Dispatch Held: Other
PM_GCT_NOSLOT_DISP_HELD_OTHER
Other
Other
OTHER_CPI
Glossary
BRU Branching Unit
CR Conditional Register
FXU Fixed-Point Unit
VSU Vector-Scalar Unit
LSU Load-Store Unit
LMQ Load Miss Queue
ERAT Effective to Real Address Translation
LWSYNC Lightweight Synchronize
HWSYNC Heavyweight Synchronize
ECC Error Correcting Code
Derived Quantity
Stall due to…
Thread blocked due to…
Nothing to dispatch due to…

# Appendix

`perf`

# perf

*Sub-commands*

- Sub-commands for perf

| | |
|---|---|
| `perf list` | List available counters |
| `perf stat` | Run program; report performance data |
| `perf record` | Run program; **sample** and save performance data |
| `perf report` | Analyzed saved performance data (*appendix*) |
| `perf top` | Like `top`, live-view of counters |

# `perf`

*Tipps, Tricks*

- Option `--repeat` for statistical measurements

```
1.239 seconds time elapsed    ( +-  0.16% )
```

- Restrict counters to certain user-level modes by `-e counter:m`, with `m` = `u` (user), = `k` (kernel), = `h` (hypervisor)
- `perf` modes: Per-thread (default), per-process (`-p PID`), per-CPU (`-a`)
- Other options

| | | | |
|---|---|---|---|
| `-d` | More details | `-B` | Add thousands' delimiters |
| `-d -d` | More more details | `-x` | Print machine-readable output |

- More info
  - `web.eece.maine.edu/~vweaver/projects/perf_events/`
  - Brendan Gregg's examples on `perf` usage

→ `https://perf.wiki.kernel.org/`

# Deeper Analysis with `perf`

## *perf record*

Usage: `perf record ./`*app*

```
$ perf record ./poisson2d
[ perf record: Woken up 41 times to write data ]
[nf_conntrack_ipv4] with build id ada66fe00acc82eac85be0969a935e3167b09c88 not found, continuing without symbols
[nf_conntrack] with build id 2911e97a3bde3302788e8388d1e3c19408ad86cf not found, continuing without symbols
[ebtables] with build id b0aa834b86d596edeb5a72d1ebf3936a98b17bcf not found, continuing without symbols
[ip_tables] with build id 23fe04e7292b66a2cc104e8c5b026b4b3a911cac not found, continuing without symbols
[bridge] with build id b7a0fcdbca63084c22e04fcf32e0584d04193954 not found, continuing without symbols
[ perf record: Captured and wrote 10.076 MB perf.data (263882 samples) ]

$ ll perf.data
-rw------- 1 aherten zam 10570296 Aug 26 19:24 perf.data
```

# Deeper Analysis with `perf`

## *`perf report`: Overview*

```
Samples: 263K of event 'cycles:ppp', Event count (approx.): 228605603717, Thread: poisson2d
Overhead  Command    Shared Object        Symbol
  93.00%  poisson2d  poisson2d            [.] main
   4.70%  poisson2d  libm-2.17.so         [.] __fmaxf
   1.84%  poisson2d  poisson2d            [.] 00000017.plt_call.fmax@@GLIBC_2.17
   0.21%  poisson2d  libm-2.17.so         [.] __exp_finite
   0.01%  poisson2d  [kernel.kallsyms]    [k] hrtimer_interrupt
   0.01%  poisson2d  [kernel.kallsyms]    [k] update_wall_time
   0.01%  poisson2d  libm-2.17.so         [.] __GI___exp
   0.01%  poisson2d  [kernel.kallsyms]    [k] task_tick_fair
   0.01%  poisson2d  [kernel.kallsyms]    [k] rcu_check_callbacks
   0.01%  poisson2d  [kernel.kallsyms]    [k] __hrtimer_run_queues
   0.01%  poisson2d  [kernel.kallsyms]    [k] __do_softirq
   0.01%  poisson2d  [kernel.kallsyms]    [k] _raw_spin_lock
   0.01%  poisson2d  [kernel.kallsyms]    [k] timer_interrupt
   0.01%  poisson2d  [kernel.kallsyms]    [k] update_process_times
   0.01%  poisson2d  [kernel.kallsyms]    [k] tick_sched_timer
   0.01%  poisson2d  [kernel.kallsyms]    [k] rcu_process_callbacks
   0.01%  poisson2d  poisson2d            [.] 00000017.plt_call.exp@@GLIBC_2.17
   0.01%  poisson2d  [kernel.kallsyms]    [k] ktime_get_update_offsets_now
   0.01%  poisson2d  [kernel.kallsyms]    [k] account_process_tick
   0.01%  poisson2d  [kernel.kallsyms]    [k] run_posix_cpu_timers
   0.00%  poisson2d  [kernel.kallsyms]    [k] trigger_load_balance
   0.00%  poisson2d  [kernel.kallsyms]    [k] scheduler_tick
   0.00%  poisson2d  [kernel.kallsyms]    [k] clear_user_page
   0.00%  poisson2d  [kernel.kallsyms]    [k] update_cfs_shares
   0.00%  poisson2d  [kernel.kallsyms]    [k] tick_do_update_jiffies64
```

# Deeper Analysis with `perf`

*`perf report`: Zoom to `main()`*

```
main  /gpfs/homeb/zam/aherten/NVAL/OtherProgramming/OpenPOWER-SC17/PAPI-Test/poisson2d
  0.00 │       lwz    r9,100(r31)
       │       mullw  r9,r10,r9
  1.01 │       extsw  r9,r9
       │       lwz    r10,140(r31)
  0.00 │       add    r9,r10,r9
       │       extsw  r9,r9
  0.00 │       rldicr r9,r9,3,60
  0.00 │       ld     r10,184(r31)
 14.28 │       add    r9,r10,r9
  0.00 │       lfd    f12,0(r9)
  0.00 │       lwz    r10,136(r31)
  0.00 │       lwz    r9,100(r31)
  0.00 │       mullw  r9,r10,r9
       │       extsw  r9,r9
  1.32 │       lwz    r10,140(r31)
  0.00 │       add    r9,r10,r9
  0.00 │       extsw  r9,r9
       │       rldicr r9,r9,3,60
  0.00 │       ld     r10,168(r31)
       │       add    r9,r10,r9
 22.54 │       lfd    f0,0(r9)
  0.01 │       fsub   f0,f12,f0
  0.00 │       fabs   f0,f0
  0.00 │       fmr    f2,f0
       │       lfd    f1,128(r31)
       │       bl     10000780 <00000017.plt_call.fmax@@GLIBC_2.17>
  1.03 │       ld     r2,24(r1)
Press 'h' for help on key bindings
```

# Appendix

## PAPI Supplementary

# PAPI: High Level API

*Usage: Source Code*

```
// Setup
float realTime, procTime, mflops, ipc;
long long flpins, ins;

// Initial call
PAPI_flops(&realTime, &procTime, &flpins, &mflops);
PAPI_ipc(&realTime, &procTime, &ins, &ipc);

// Compute
mult(m, n, p, A, B, C);

// Finalize call
PAPI_flops(&realTime, &procTime, &flpins, &mflops);
PAPI_ipc(&realTime, &procTime, &ins, &ipc);
```

# PAPI: Low Level API

*Usage: Source Code*

```
int EventSet = PAPI_NULL;
long long values[2];

// PAPI: Setup
PAPI_library_init(PAPI_VER_CURRENT);
PAPI_create_eventset(&EventSet);
// PAPI: Test availability of counters
PAPI_query_named_event("PM_CMPLU_STALL_VSU");
PAPI_query_named_event("PM_CMPLU_STALL_SCALAR");
// PAPI: Add counters
PAPI_add_named_event(EventSet, "PM_CMPLU_STALL_VSU");
PAPI_add_named_event(EventSet, "PM_CMPLU_STALL_SCALAR");
// PAPI: Start collection
PAPI_start(EventSet);
// Compute
do_something();
// PAPI: End collection
PAPI_CALL( PAPI_stop(EventSet, values) , PAPI_OK );
```

# PAPI: Low Level API

*Usage: Source Code*

```
int EventSet = PAPI_NULL;
long long values[2];

// PAPI: Setup
PAPI_library_init(PAPI_VER_CURRENT);
PAPI_create_eventset(&EventSet);
// PAPI: Test availability of counters
PAPI_query_named_event("PM_CMPLU_STALL_VSU");
PAPI_query_named_event("PM_CMPLU_STALL_SCALAR");
// PAPI: Add counters
PAPI_add_named_event(EventSet, "PM_CMPLU_STALL_VSU");
PAPI_add_named_event(EventSet, "PM_CMPLU_STALL_SCALAR"
// PAPI: Start collection
PAPI_start(EventSet);
// Compute
do_something();
// PAPI: End collection
PAPI_CALL( PAPI_stop(EventSet, values) , PAPI_OK );
```

Pre-processor macro for checking results!
*See next slides!*

# PAPI Error Macro: C++

*For easier status code checking*

```
#include "papi.h"
#define PAPI_CALL( call, success )                      \
{                                                       \
    int err = call;                                     \
    if ( success != err)                                \
    std::cerr << "PAPI error for " << #call << " in L" << __LINE__ << " of " <<
↪  __FILE__ << ": " << PAPI_strerror(err) << std::endl; \
}
// Second argument is code for GOOD,
// e.g. PAPI_OK or PAPI_VER_CURRENT or …
// …
// Call like:
PAPI_CALL( PAPI_start(EventSet), PAPI_OK );
```

# PAPI Error Macro: C

*For easier status code checking*

```
#include "papi.h"
#define PAPI_CALL( call, success )                  \
{                                                    \
    int err = call;                                  \
    if ( success != err)                             \
    fprintf(stderr, "PAPI error for %s in L%d of %s: %s\n", #call, __LINE__,
↪  __FILE__, PAPI_strerror(err)); \
}
// Second argument is code for GOOD,
// e.g. PAPI_OK or PAPI_VER_CURRENT or …
// …
// Call like:
PAPI_CALL( PAPI_start(EventSet), PAPI_OK );
```

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# libpfm4

*A helper Library*

- Helper library for setting up counters interfacing with `perf` kernel environment
- Used by PAPI to resolve counters
- Handy as translation: Named counters → raw counters
- Use command line utility `perf_examples/evt2raw` to get raw counter for `perf`

```
$ ./evt2raw PM_CMPLU_STALL_VSU
r2d012
```

→ http://perfmon2.sourceforge.net/docs_v4.html

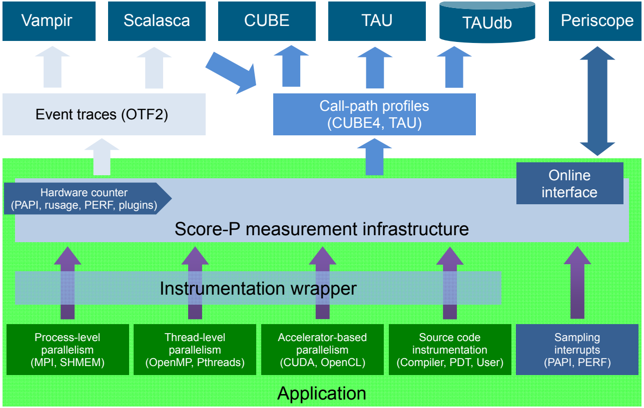
# Appendix

## Score-P

# Score-P

*Introduction*

- Measurement infrastructure for profiling, event tracing, online analysis
- Output format input for many analysis tools (Cube, Vampir, Periscope, Scalasca, Tau)



# Score-P

*Howto*

- Prefix compiler executable by `scorep`

```
$ scorep clang++ -o app code.cpp
```

→ Adds instrumentation calls to binary

- Profiling output is stored to file after run of binary
- Steer with environment variables at **run time**

```
$ export SCOREP_METRIC_PAPI=PAPI_FP_OPS,PM_CMPLU_STALL_VSU
$ ./app
```

⇒ Use different PAPI counters per run!

- Quick visualization with Cube; scoring with `scorep-score`

# Score-P

*Principle analysis with `scorep-score`*

Usage: `scorep-score -r` *`FILE`*

herten — aherten@jupp00: ~/NVAL/Other/OpenPOWER-SC16/test — ssh ◂ ssh juppext

```
aherten@jupp00:~/NVAL/Other/OpenPOWER-SC16/test$ scorep-score -r -c 2 scorep-20160826_2106_1032520
6034857807/profile.cubex

Estimated aggregate size of event trace:                   149 bytes
Estimated requirements for largest trace buffer (max_buf): 149 bytes
Estimated memory requirements (SCOREP_TOTAL_MEMORY):       4097kB
(hint: When tracing set SCOREP_TOTAL_MEMORY=4097kB to avoid intermediate flushes
 or reduce requirements using USR regions filters.)

flt     type max_buf[B] visits time[s] time[%] time/visit[us]  region
         ALL        148      2    1.92   100.0      961066.48  ALL
         USR        148      2    1.92   100.0      961066.48  USR

         USR         74      1    1.89    98.4     1891933.34  _Z4multiiiPKfS0_Pf
         USR         74      1    0.03     1.6       30199.62  main
aherten@jupp00:~/NVAL/Other/OpenPOWER-SC16/test$
```

# Score-P

*Performance counter analysis with cube_dump*

Usage: `cube-dump -m METRIC FILE`



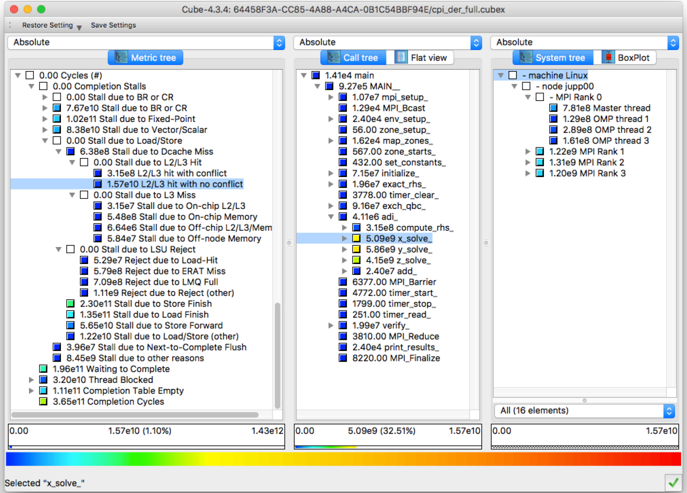
```
aherten@jupp00:~/NVAL/Other/OpenPOWER-SC16/test$ cube_dump -m PAPI_FP_OPS scorep-20160830_1138_106367049
09174321/profile.cubex


 ===================== DATA ===================
Print out the data of the metric PAPI_FP_OPS

                         Master thread
-------------------------------------------------------------------------------
main(id=0)                721459
_Z4multiiiPKfS0_Pf(id=1)  432004097
aherten@jupp00:~/NVAL/Other/OpenPOWER-SC16/test$
```

# Score-P

*Analysis with Cube*



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# Appendix

## GPU Counters

# GPU Example Events & Metrics

| NAME | NVIDIA Description (quoted) |
| --- | --- |
| `gld_inst_8bit` | Total number of 8-bit global load instructions that are executed by all the threads across all thread blocks. |
| `threads_launched` | Number of threads launched on a multiprocessor. |
| `inst_executed` | Number of instructions executed, do not include replays. |
| `shared_store` | Number of executed store instructions where state space is specified as shared, increments per warp on a multiprocessor. |
| `executed_ipc` | Instructions executed per cycle |
| `achieved_occupancy` | Ratio of the average active warps per active cycle to the maximum number of warps supported on a multiprocessor |
| `l1_cache_local_hit_rate` | Hit rate in L1 cache for local loads and stores |
| `gld_efficiency` | Ratio of requested global memory load throughput to required global memory load throughput. |
| `flop_count_dp` | Number of double-precision floating-point operations executed non-predicated threads (add, multiply, multiply-accumulate and special) |
| `stall_pipe_busy` | Percentage of stalls occurring because a compute operation cannot be performed because the compute pipeline is busy |

# Measuring GPU counters

*Tools*

CUPTI C/C++-API through `cupti.h`

- Activity API: Trace CPU/GPU activity
- Callback API: Hooks for own functions
- Event / Metric API: Read counters and metrics

→ Targets developers of profiling tools

PAPI All PAPI instrumentation through PAPI-C, e.g. `cuda:::device:0:threads_launched`

Score-P Mature CUDA support

- Prefix `nvcc` compilation with `scorep`
- Set environment variable `SCOREP_CUDA_ENABLE=yes`
- Run, analyze

`nvprof`, Visual Profiler NVIDIA's solutions

# nvprof

*GPU command-line measurements*

Usage: `nvprof --events AB --metrics C,D ./app`

herten — aherten@JUHYDRA: ~/cudaSamples/NVIDIA_CUDA-7.5_Samples/bin/x86_64/linux/release — ..linux/release — ssh juhydra

```
ixMulCUDA<int=32>(float*, float*, float*, int, int)" (0 of 3)==18158== Replaying kernel "void matrixMulCUDA<int=32>(float*, float*, flo
at*, int, int)" (0 of 3)==18158== Replaying kernel "void matrixMulCUDA<int=32>(float*, float*, float*, int, int)" (done)
==18158== Replaying kernel "void matrixMulCUDA<int=32>(float*, float*, float*, int, int)" (0 of 3)==18158== Replaying kernel "void matr
ixMulCUDA<int=32>(float*, float*, float*, int, int)" (0 of 3)==18158== Replaying kernel "void matrixMulCUDA<int=32>(float*, float*, flo
at*, int, int)" (0 of 3)==18158== Replaying kernel "void matrixMulCUDA<int=32>(float*, float*, float*, int, int)" (done)
Performance= 1.69 GFlop/s, Time= 77.513 msec, Size= 131072000 Ops, WorkgroupSize= 1024 threads/block
Checking computed result for correctness: Result = PASS

NOTE: The CUDA Samples are not meant for performance measurements. Results may vary when GPU Boost is enabled.
==18158== Profiling application: ./matrixMul
==18158== Profiling result:
==18158== Event result:
Invocations                                Event Name         Min         Max         Avg
Device "Tesla K40m (0)"
        Kernel: void matrixMulCUDA<int=32>(float*, float*, float*, int, int)
        301                          threads_launched      204800      204800      204800

==18158== Metric result:
Invocations                               Metric Name                        Metric Description         Min         Max         Avg
Device "Tesla K40m (0)"
        Kernel: void matrixMulCUDA<int=32>(float*, float*, float*, int, int)
        301                             flop_count_sp  Floating Point Operations(Single Precisi   131072000   131072000   131072000
        301                                       ipc                              Executed IPC    1.472345    1.486837    1.480249
        301                        achieved_occupancy                        Achieved Occupancy    0.960357    0.989658    0.975385

# aherten @ JUHYDRA in ~/cudaSamples/NVIDIA_CUDA-7.5_Samples/bin/x86_64/linux/release [21:47:45]
$ nvprof --events threads_launched --metrics flop_count_sp,ipc,achieved_occupancy ./matrixMul
```

# `nvprof`

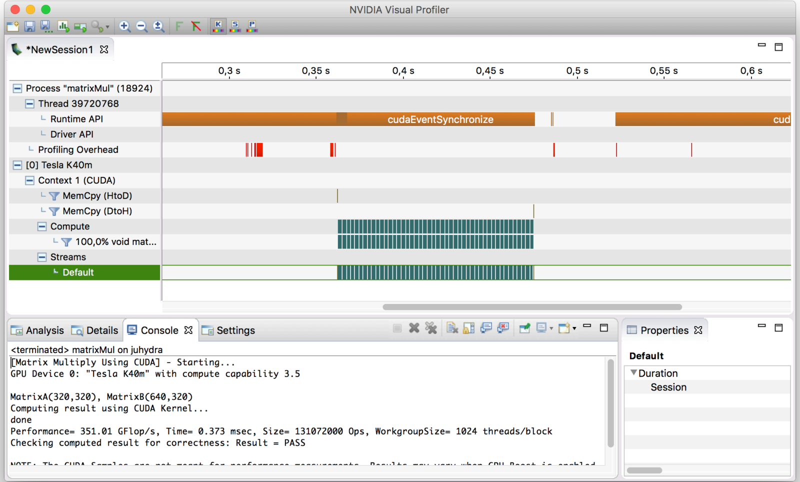
*Useful hints*

Useful parameters to `nvprof`

| | |
|---|---|
| `--query-metrics` | List all metrics |
| `--query-events` | List all events |
| `--kernels` *name* | Limit scope to kernel |
| `--print-gpu-trace` | Print timeline of invocations |
| `--aggregate-mode off` | No aggregation over all multiprocessors (average) |
| `--csv` | Output a CSV |
| `--export-profile` | Store profiling information, e.g. for Visual Profiler |

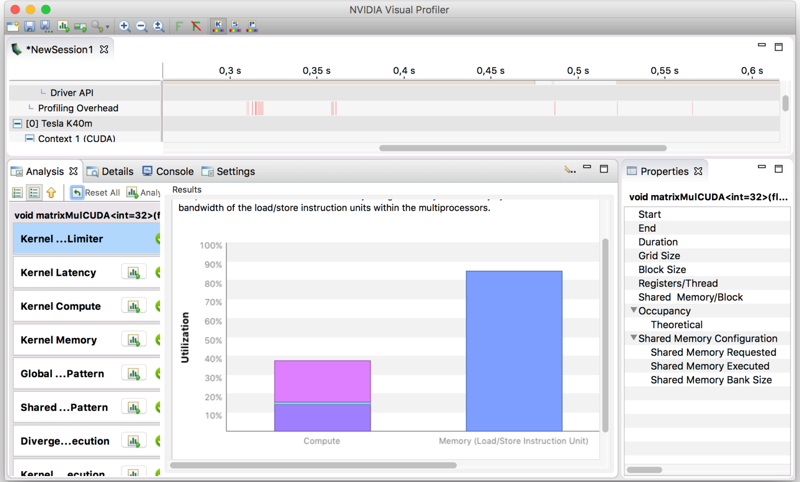
# Visual Profiler

*An annotated time line view*



# Visual Profiler

*Analysis experiments*



# Appendix

## Glossary & References

# Glossary I

CPI Cycles per Instructions; a metric to determine efficiency of an architecture or program. 9, 10

IPC Instructions per Cycle; a metric to determine efficiency of an architecture or program. 9, 10

MPI The Message Passing Interface, a API definition for multi-node computing. 14

NVIDIA US technology company creating GPUs. 46, 75, 76

OpenMP Directive-based programming, primarily for multi-threaded machines. 14

# Glossary II

JÜLICH FORSCHUNGSZENTRUM

**PAPI** The Performance API, a C/C++ API for querying performance counters. 2, 31, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 47, 48

**perf** Part of the Linux kernel which facilitates access to performance counters; comes with command line utilities. 2, 31, 32, 33, 34, 35, 36, 37, 38, 47, 48

**POWER8** CPU architecture from IBM, available also under the OpenPOWER Foundation. 2, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 47, 48, 49, 52, 53

**Score-P** Collection of tools for instrumenting and subsequently scoring applications to gain insight into the program's performance. 31, 47, 48

**CPU** Central Processing Unit. 9, 10, 12, 13, 14, 82

# Glossary III

GPU Graphics Processing Unit. 14, 35, 36, 37, 38, 46, 47, 48, 82

PMU Performance Measuring Unit. 16, 17, 18, 19

# References: Images, Graphics I

[3] Score-P Authors. *Score-P User Manual*. URL: http://www.vi-hps.org/projects/score-p/.

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# References: Literature I

JÜLICH FORSCHUNGSZENTRUM


[1] Terje Mathisen. *Pentium Secrets*. URL: http://www.gamedev.net/page/resources/_/technical/general-programming/pentium-secrets-r213 (pages 12, 13).

[2] Donald E. Knuth. "Structured Programming with Go to Statements". In: *ACM Comput. Surv.* 6.4 (Dec. 1974), pp. 261–301. ISSN: 0360-0300. DOI: 10.1145/356635.356640. URL: http://doi.acm.org/10.1145/356635.356640 (page 51).

# The End

*Thanks for reading until here!*