# Performance patterns and hardware metrics on modern multicore processors: Best practices for performance engineering

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## Hardware performance metrics

- … are ubiquitous as a starting point for performance analysis (including automatic analysis)
- … are supported by many tools
- … are often reduced to cache misses (what could be worse than cache misses?)

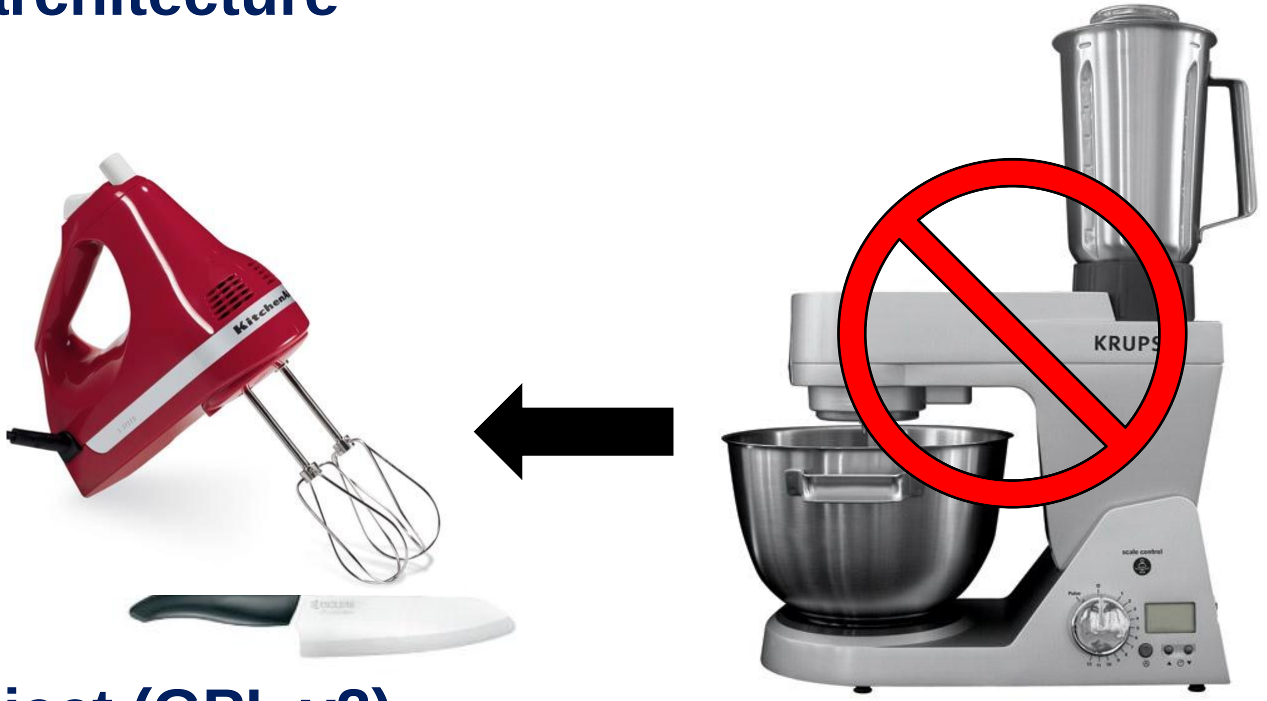
**Reality:**

- **Modern parallel computing is plagued by bottlenecks**
- **There are typical performance patterns that cover a large part of possible performance behaviors**
  - HPM signatures
  - Scaling behavior
  - Other sources of information

$\left.\begin{matrix}\text{HPM signatures}\\ \text{Scaling behavior}\\ \text{Other sources of information}\end{matrix}\right\}$ "Performance pattern"

## But still we need a HPM tool!

- LIKWID: Lightweight command line tools for Linux
- Help to face the challenges without getting in the way
- Focus on x86 architecture
- Philosophy:
  - Simple
  - Efficient
  - Portable
  - Extensible



Open source project (GPL v2):

http://code.google.com/p/likwid/

## Overview of LIKWID tools

- **Topology and Affinity:**
  - likwid-topology
  - likwid-pin
  - likwid-mpirun

- **Performance Profiling/Benchmarking:**
  - **likwid-perfctr**
  - likwid-bench
  - likwid-powermeter

## Probing performance behavior with likwid-perfctr

- **How do we find out about the performance properties and requirements of a parallel code?**
  - Profiling via advanced tools is often overkill
- **A coarse overview is often sufficient**
  - likwid-perfctr (similar to “perfex” on IRIX, “hpmcount” on AIX, “lipfpm” on Linux/Altix)
  - Simple end-to-end measurement of hardware performance metrics
  - Operating modes:
    - Wrapper
    - Stethoscope
    - Timeline
    - Marker API
  - Preconfigured and extensible metric groups, list with `likwid-perfctr -a`

```
BRANCH: Branch prediction miss rate/ratio
CACHE: Data cache miss rate/ratio
CLOCK: Clock of cores
DATA: Load to store ratio
FLOPS_DP: Double Precision MFlops/s
FLOPS_SP: Single Precision MFlops/s
FLOPS_X87: X87 MFlops/s
L2: L2 cache bandwidth in MBytes/s
L2CACHE: L2 cache miss rate/ratio
L3: L3 cache bandwidth in MBytes/s
L3CACHE: L3 cache miss rate/ratio
MEM: Main memory bandwidth in MBytes/s
TLB: TLB miss rate/ratio
```

## likwid-perfctr

*Example usage with preconfigured metric group*

```
$ env OMP_NUM_THREADS=4 likwid-perfctr -C N:0-3 -t intel -g FLOPS_DP  ./stream.exe
-------------------------------------------------------------
CPU type:       Intel Core Lynnfield processor
CPU clock:      2.93 GHz
-------------------------------------------------------------
Measuring group FLOPS_DP
-------------------------------------------------------------
YOUR PROGRAM OUTPUT
+--------------------------------------+-------------+-------------+-------------+-------------+
|                Event                 |   core 0    |   core 1    |   core 2    |   core 3    |
+--------------------------------------+-------------+-------------+-------------+-------------+
|          INSTR_RETIRED_ANY           | 1.97463e+08 | 2.31001e+08 | 2.30963e+08 | 2.31885e+08 |
|        CPU_CLK_UNHALTED_CORE         | 9.56999e+08 | 9.58401e+08 | 9.58637e+08 | 9.57338e+08 |
|     FP_COMP_OPS_EXE_SSE_FP_PACKED    | 4.00294e+07 | 3.08927e+07 | 3.08866e+07 | 3.08904e+07 |
|     FP_COMP_OPS_EXE_SSE_FP_SCALAR    |     882     |      0      |      0      |      0      |
| FP_COMP_OPS_EXE_SSE_SINGLE_PRECISION |      0      |      0      |      0      |      0      |
| FP_COMP_OPS_EXE_SSE_DOUBLE_PRECISION | 4.00303e+07 | 3.08927e+07 | 3.08866e+07 | 3.08904e+07 |
+--------------------------------------+-------------+-------------+-------------+-------------+
+---------------------------+------------+----------+----------+----------+
|          Metric           |   core 0   |  core 1  |  core 2  |  core 3  |
+---------------------------+------------+----------+----------+----------+
|        Runtime [s]        |  0.326242  | 0.32672  | 0.326801 | 0.326358 |
|            CPI            |  4.84647   | 4.14891  | 4.15061  | 4.12849  |
| DP MFlops/s (DP assumed)  |  245.399   | 189.108  | 189.024  | 189.304  |
|      Packed MUOPS/s       |  122.698   |  94.554  | 94.5121  | 94.6519  |
|      Scalar MUOPS/s       | 0.00270351 |    0     |    0     |    0     |
|        SP MUOPS/s         |     0      |    0     |    0     |    0     |
|        DP MUOPS/s         |  122.701   |  94.554  | 94.5121  | 94.6519  |
+---------------------------+------------+----------+----------+----------+
```

Always measured

Configured metrics (this group)

Derived metrics

## likwid-perfctr
*Marker API*

- To measure only parts of an application a marker API is available.
- The API only turns counters on/off. The configuration of the counters is still done by likwid-perfctr application.
- Multiple named regions can be measured
- Results on multiple calls are accumulated
- Inclusive and overlapping Regions are allowed

```
likwid_markerInit();  // must be called from serial region

likwid_markerStartRegion("Compute");
. . .
likwid_markerStopRegion("Compute");


likwid_markerStartRegion("postprocess");
. . .
likwid_markerStopRegion("postprocess");

likwid_markerClose();  // must be called from serial region
```

# likwid-perfctr
*Group files*

```
SHORT PSTI
EVENTSET
FIXC0 INSTR_RETIRED_ANY
FIXC1 CPU_CLK_UNHALTED_CORE
FIXC2 CPU_CLK_UNHALTED_REF
PMC0  FP_COMP_OPS_EXE_SSE_FP_PACKED
PMC1  FP_COMP_OPS_EXE_SSE_FP_SCALAR
PMC2  FP_COMP_OPS_EXE_SSE_SINGLE_PRECISION
PMC3  FP_COMP_OPS_EXE_SSE_DOUBLE_PRECISION
UPMC0  UNC_QMC_NORMAL_READS_ANY
UPMC1  UNC_QMC_WRITES_FULL_ANY
UPMC2 UNC_QHL_REQUESTS_REMOTE_READS
UPMC3 UNC_QHL_REQUESTS_LOCAL_READS
METRICS
Runtime [s] FIXC1*inverseClock
CPI  FIXC1/FIXC0
Clock [MHz]  1.E-06*(FIXC1/FIXC2)/inverseClock
DP MFlops/s (DP assumed) 1.0E-06*(PMC0*2.0+PMC1)/time
Packed MUOPS/s   1.0E-06*PMC0/time
Scalar MUOPS/s 1.0E-06*PMC1/time
SP MUOPS/s 1.0E-06*PMC2/time
DP MUOPS/s 1.0E-06*PMC3/time
Memory bandwidth [MBytes/s] 1.0E-06*(UPMC0+UPMC1)*64/time;
Remote Read BW [MBytes/s] 1.0E-06*(UPMC2)*64/time;
LONG
Formula:
DP MFlops/s =  (FP_COMP_OPS_EXE_SSE_FP_PACKED*2 +  FP_COMP_OPS_EXE_SSE_FP_SCALAR)/ runtime.
```

- Groups are architecture-specific
- They are defined in simple text files
- **Code is generated on recompile**

## Performance patterns (1)

| Pattern | Peformance behavior | Metric signature |
|---|---|---|
| **Load imbalance** | Saturating/sub-linear speedup | Different amount of "work" on the cores (FLOPS_DP, FLOPS_SP, FLOPS_AVX); note that instruction count is not reliable! |
| **BW saturation in outer-level cache** | Saturating speedup across cores of OL cache group | OLC bandwidth meets BW of suitable streaming benchmark (L3) |
| **Memory BW saturation** | Saturating speedup across cores on a memory interface | Memory BW meets BW of suitable streaming benchmark (MEM) |
| **Strided or erratic data access** | Simple BW performance model much too optimistic | Low BW utilization / Low cache hit ratio, frequent CL evicts or replacements (CACHE, DATA, MEM) |

## Performance patterns (2)

| Pattern | Peformance behavior | Metric signature |
|---|---|---|
| **Bad instruction mix** | Peformance insensitive to problem size vs. cache levels | Large ratio of instructions retired to FP instructions if the useful work is FP / Many cycles per instruction (CPI) if the problem is large-latency arithmetic / Scalar instructions dominating in data-parallel loops (FLOPS_DP, FLOPS_SP, CPI) |
| **Limited instruction throughput** | Large discrepancy from simple performance model based on LD/ST and arithmetic throughput | Low CPI near theoretical limit if instruction throughput is the problem / Static code analysis predicting large pressure on single execution port / High CPI due to bad pipelining (FLOPS_DP, FLOPS_SP, DATA) |
| **Micro-architectural anomalies** | Large discrepancy from performance model | Relevant events are very hardware-specific, e.g., stalls due to 4k memory aliasing, conflict misses, unaligned vs. aligned LD/ST, requeue events. Code review required, with architectural features in mind. |

## Performance patterns (3)

| Pattern | Peformance behavior | Metric signature |
|---|---|---|
| **Synchronization overhead** | Speedup going down as more cores are added / No speedup with small problem sizes / Cores busy but low FP performance | Large non-FP instruction count (growing with number of cores used) / Low CPI (FLOPS_DP, FLOPS_DP, CPI) |
| **False sharing of cache lines** | Small speedup or slowdown when adding cores | Frequent (remote) CL evicts (CACHE) |
| **Bad ccNUMA page placement** | Bad or no scaling across NUMA domains | Unbalanced bandwidth on memory interfaces / High remote traffic (MEM) |

## The problem of instructions retired (1)

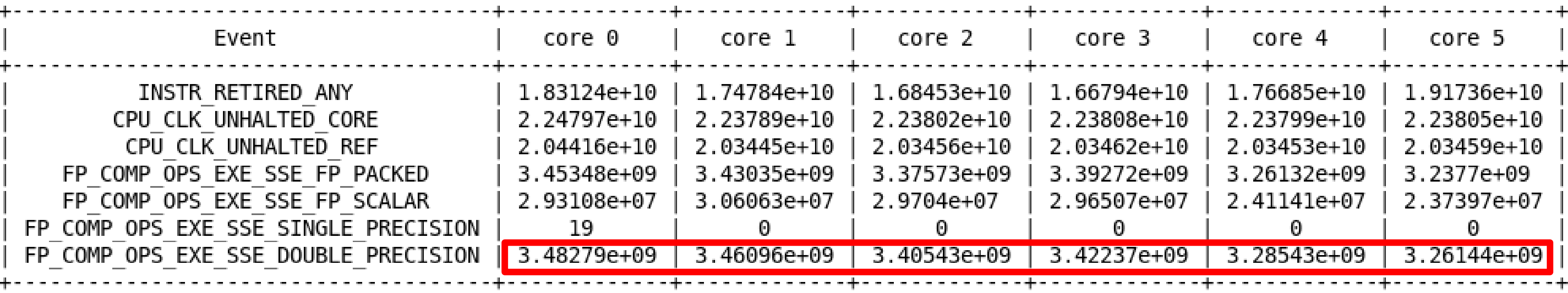
- **Instructions retired / CPI may not be a good indication of useful workload – at least for numerical / FP intensive codes….**
- **Floating Point Operations Executed is often a better indicator**
- **Waiting / “Spinning” in barrier generates a high instruction count**

```
+-------------------------------------------------------------------------------------------------------------------+
|              Event               |    core 0    |    core 1    |    core 2    |    core 3    |    core 4    |    core 5    |
+-------------------------------------------------------------------------------------------------------------------+
|         INSTR_RETIRED_ANY        | 2.10045e+10  | 1.90983e+10 |  1.729e+10   | 1.60898e+10 | 1.67958e+10 | 1.84689e+10 |
|       CPU_CLK_UNHALTED_CORE      | 1.82569e+10  | 1.81203e+10 | 1.81802e+10 | 1.82084e+10 | 1.82334e+10 | 1.82484e+10 |
|        CPU_CLK_UNHALTED_REF      | 1.66053e+10  | 1.6473e+10  | 1.65274e+10 | 1.65531e+10 | 1.65758e+10 | 1.65894e+10 |
|   FP_COMP_OPS_EXE_SSE_FP_PACKED  | 2.77016e+08  | 7.83476e+08 | 1.39355e+09 | 1.94365e+09 | 2.38059e+09 | 2.85981e+09 |
|   FP_COMP_OPS_EXE_SSE_FP_SCALAR  | 1.70802e+08  | 2.64065e+08 | 2.23153e+08 | 2.60835e+08 | 2.30434e+08 | 2.07293e+08 |
| FP_COMP_OPS_EXE_SSE_SINGLE_PRECISION |    19     |      0      |      0      |      0      |      0      |      0      |
| FP_COMP_OPS_EXE_SSE_DOUBLE_PRECISION | 4.47818e+08 | 1.04754e+09 | 1.61671e+09 | 2.20448e+09 | 2.61102e+09 | 3.0671e+09 |
+-------------------------------------------------------------------------------------------------------------------+
```

```
+-------------+-----------+----------+----------+----------+----------+----------+
|    Metric   |  core 0   |  core 1  |  core 2  |  core 3  |  core 4  |  core 5  |
+-------------+-----------+----------+----------+----------+----------+----------+
| Runtime [s] |  6.84594  | 6.79471  | 6.81716  | 6.82773  | 6.83711  | 6.84274  |
| Clock [MHz] |  2932.07  | 2933.51  | 2933.51  | 2933.51  | 2933.51  | 2933.51  |
|     CPI     |  0.869191 | 0.948789 | 1.05148  | 1.13167  | 1.08559  | 0.988061 |
| DP MFlops/s |  109.192  | 275.833  | 453.48   | 624.893  | 751.96   | 892.857  |
```

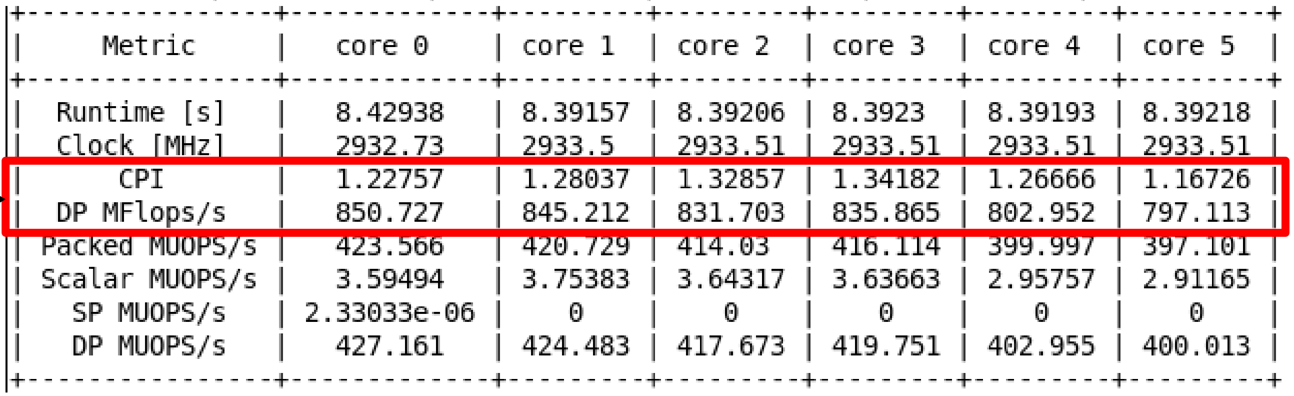
```
!$OMP PARALLEL DO
DO I = 1, N
  DO J = 1, I
    x(I) = x(I) + A(J,I) * y(J)
  ENDDO
ENDDO
!$OMP END PARALLEL DO
```

# The problem of instructions retired (2)



```
+--------------------------------------+-------------+-------------+-------------+-------------+-------------+-------------+
|                Event                 |   core 0    |   core 1    |   core 2    |   core 3    |   core 4    |   core 5    |
+--------------------------------------+-------------+-------------+-------------+-------------+-------------+-------------+
|           INSTR_RETIRED_ANY          | 1.83124e+10 | 1.74784e+10 | 1.68453e+10 | 1.66794e+10 | 1.76685e+10 | 1.91736e+10 |
|         CPU_CLK_UNHALTED_CORE        | 2.24797e+10 | 2.23789e+10 | 2.23802e+10 | 2.23808e+10 | 2.23799e+10 | 2.23805e+10 |
|          CPU_CLK_UNHALTED_REF        | 2.04416e+10 | 2.03445e+10 | 2.03456e+10 | 2.03462e+10 | 2.03453e+10 | 2.03459e+10 |
|      FP_COMP_OPS_EXE_SSE_FP_PACKED   | 3.45348e+09 | 3.43035e+09 | 3.37573e+09 | 3.39272e+09 | 3.26132e+09 | 3.2377e+09  |
|      FP_COMP_OPS_EXE_SSE_FP_SCALAR   | 2.93108e+07 | 3.06063e+07 | 2.9704e+07  | 2.96507e+07 | 2.41141e+07 | 2.37397e+07 |
| FP_COMP_OPS_EXE_SSE_SINGLE_PRECISION |     19      |      0      |      0      |      0      |      0      |      0      |
| FP_COMP_OPS_EXE_SSE_DOUBLE_PRECISION | 3.48279e+09 | 3.46096e+09 | 3.40543e+09 | 3.42237e+09 | 3.28543e+09 | 3.26144e+09 |
+--------------------------------------+-------------+-------------+-------------+-------------+-------------+-------------+
```

Higher CPI but better performance



```
+-----------------+-------------+---------+---------+---------+---------+---------+
|     Metric      |    core 0   | core 1  | core 2  | core 3  | core 4  | core 5  |
+-----------------+-------------+---------+---------+---------+---------+---------+
|   Runtime [s]   |   8.42938   | 8.39157 | 8.39206 | 8.3923  | 8.39193 | 8.39218 |
|   Clock [MHz]   |   2932.73   | 2933.5  | 2933.51 | 2933.51 | 2933.51 | 2933.51 |
|       CPI       |   1.22757   | 1.28037 | 1.32857 | 1.34182 | 1.26666 | 1.16726 |
|   DP MFlops/s   |   850.727   | 845.212 | 831.703 | 835.865 | 802.952 | 797.113 |
|  Packed MUOPS/s |   423.566   | 420.729 | 414.03  | 416.114 | 399.997 | 397.101 |
|  Scalar MUOPS/s |   3.59494   | 3.75383 | 3.64317 | 3.63663 | 2.95757 | 2.91165 |
|    SP MUOPS/s   | 2.33033e-06 |    0    |    0    |    0    |    0    |    0    |
|    DP MUOPS/s   |   427.161   | 424.483 | 417.673 | 419.751 | 402.955 | 400.013 |
+-----------------+-------------+---------+---------+---------+---------+---------+
```

```
!$OMP PARALLEL DO
DO I = 1, N
  DO J = 1, N
    x(I) = x(I) + A(J,I) * y(J)
  ENDDO
ENDDO
!$OMP END PARALLEL DO
```

## Example 1:
*Abstraction penalties in C++ code*

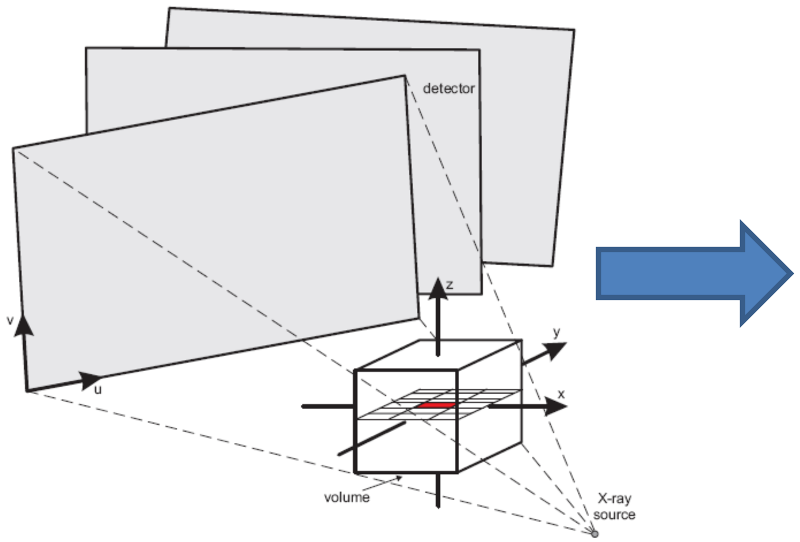
C++ codes which suffer from overhead (inlining problems, complex abstractions) need a lot more overall instructions related to the arithmetic instructions.

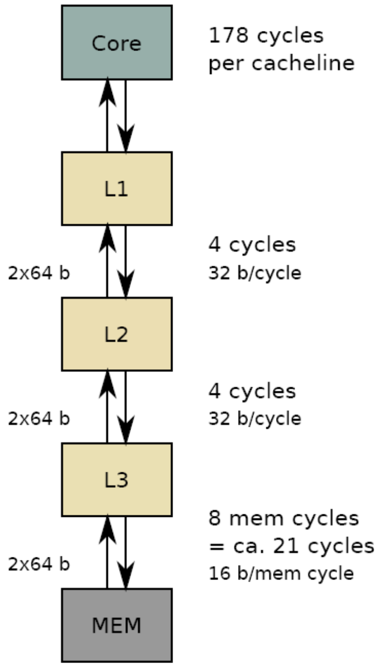
- Often (but not always) “good” (i.e., low) CPI → “Bad instruction mix” pattern
- Lower bandwidth
- Instruction throughput limited
- High-level optimizations complex or impossible → “Strided access” pattern

Example: Matrix-matrix multiply with expression template frameworks on a 2.93 GHz Westmere core

| | Total retired instructions [$10^{11}$] | CPI | Memory Bandwidth [MB/s] | MFlops/s |
|---|---|---|---|---|
| Classic | **12.5** | **0.44** | **5300** | **1250** |
| **Boost uBLAS** | **10.1** | **4.6** | **630** | **156** |
| Eigen3 | **2.1** | **0.41** | **371** | **8555** |
| Blaze/DGEMM | **2.0** | **0.32** | **531** | **11260** |

## Example 2:
## Image reconstruction by backprojection





- **Simple roofline analysis**
  **→ Memory-bound algorithm → "Memory BW saturation" pattern**
- **Closer look via `likwid-perfctr` MEM group and IACA tool**
  **→ "Limited instruction throughput" pattern**
- **Work reduction optimization**
  **→ "Load imbalance" pattern identified by `likwid-perfctr` FLOPS_SP group → corrected by round-robin schedule**

## Conclusions

- **Automatic analysis is useful for the beginner, but will never match an experienced analyst**

- **Performance patterns are more than simple numbers**
  - Scaling behavior
  - Bottleneck saturation
  - HPM signatures

- **The set presented here is just a suggestion; it will have to be tested against more codes**

- **Power/energy patterns are still missing, but will have to be included**

## Thank you.

OMI4papps

## References

- J. Treibig, G. Hager and G. Wellein: *LIKWID: A lightweight performance-oriented tool suite for x86 multicore environments.* Proceedings of PSTI2010, the First International Workshop on Parallel Software Tools and Tool Infrastructures, San Diego CA, September 13, 2010. DOI: 10.1109/ICPPW.2010.38
- K. Iglberger, G. Hager, J. Treibig, and U. Rüde: *Expression Templates Revisited: A Performance Analysis of Current ET Methodologies.* SIAM Journal on Scientific Computing **34**(2), C42-C69 (2012). DOI: 10.1137/110830125
- J. Treibig, G. Hager, H. G. Hofmann, J. Hornegger, and G. Wellein: *Pushing the limits for medical image reconstruction on recent standard multicore processors.* International Journal of High Performance Computing Applications, (online first) DOI: 10.1177/1094342012442424