Performance analysis with hardware metrics

Likwid-perfctr

Best practices

Energy consumption

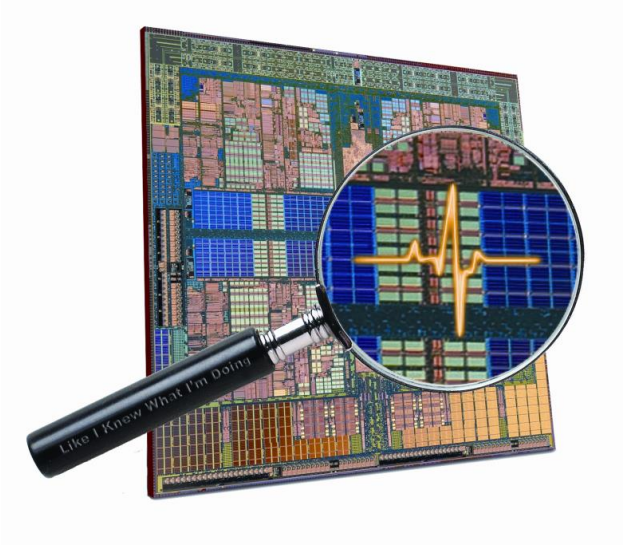
Hardware performance metrics

- … 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

} **"Performance pattern"**



Using hardware performance metrics

likwid-perfctr

Probing performance behavior

- **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

```
$ likwid-perfctr -g L2 -C S1:0-3 ./a.out
--------------------------------------------------------------------------------
CPU name:       Intel(R) Xeon(R) CPU E5-2695 v3 @ 2.30GHz [...]
--------------------------------------------------------------------------------
<<<< PROGRAM OUTPUT >>>>
--------------------------------------------------------------------------------
Group 1: L2
+----------------------+---------+------------+------------+------------+------------+
|        Event         | Counter |   Core 14  |   Core 15  |   Core 16  |   Core 17  |
+----------------------+---------+------------+------------+------------+------------+
|   INSTR_RETIRED_ANY  |  FIXC0  | 1298031144 | 1965945005 | 1854182290 | 1862521357 |
| CPU_CLK_UNHALTED_CORE|  FIXC1  | 2353698512 | 2894134935 | 2894645261 | 2895023739 |
| CPU_CLK_UNHALTED_REF |  FIXC2  | 2057044629 | 2534405765 | 2535218217 | 2535560434 |
|    L1D_REPLACEMENT   |   PMC0  |  212900444 |  200544877 |  200389272 |  200387671 |
|    L2_TRANS_L1D_WB   |   PMC1  |  112464863 |  99931184  |  99982371  |  99976697  |
|     ICACHE_MISSES    |   PMC2  |    21265   |    26233   |    12646   |    12363   |
+----------------------+---------+------------+------------+------------+------------+
[... statistics output omitted ...]
+------------------------------+------------+------------+------------+------------+
|            Metric            |   Core 14  |   Core 15  |   Core 16  |   Core 17  |
+------------------------------+------------+------------+------------+------------+
|       Runtime (RDTSC) [s]    |   1.1314   |   1.1314   |   1.1314   |   1.1314   |
|      Runtime unhalted [s]    |   1.0234   |   1.2583   |   1.2586   |   1.2587   |
|           Clock [MHz]        | 2631.6699  | 2626.4367  | 2626.0579  | 2626.0468  |
|               CPI            |   1.8133   |   1.4721   |   1.5611   |   1.5544   |
|  L2D load bandwidth [MBytes/s] | 12042.7388 | 11343.8446 | 11335.0428 | 11334.9523 |
|  L2D load data volume [GBytes] |   13.6256  |   12.8349  |   12.8249  |   12.8248  |
| L2D evict bandwidth [MBytes/s] |  6361.5883 |  5652.6192 |  5655.5146 |  5655.1937 |
| L2D evict data volume [GBytes] |   7.1978   |   6.3956   |   6.3989   |   6.3985   |
|     L2 bandwidth [MBytes/s]  | 18405.5299 | 16997.9477 | 16991.2728 | 16990.8453 |
|     L2 data volume [GBytes]  |   20.8247  |   19.2321  |   19.2246  |   19.2241  |
+------------------------------+------------+------------+------------+------------+
```

Always measured

Configured metrics (this group)

Derived metrics

Things to look at (in roughly this order)

- Load balance (flops, instructions, BW)
- In-socket memory BW saturation
- Shared cache BW saturation
- Flop/s, loads and stores per flop metrics
- SIMD vectorization
- CPI metric
- Clock speed
- # of instructions, branches, mispredicted branches

Caveats

- Load imbalance may not show in CPI or # of instructions
  - Spin loops in OpenMP barriers/MPI blocking calls
  - Looking at “top” or the Windows Task Manager does not tell you anything useful
- In-socket performance saturation may have various reasons
- Cache miss metrics are overrated
  - If I really know my code, I can often *calculate* the misses
  - Runtime and resource utilization is much more important

- likwid-perfctr counts events on cores; it has no notion of what kind of code is running (if any)

  This allows you to “listen” to what is currently happening, without any overhead:

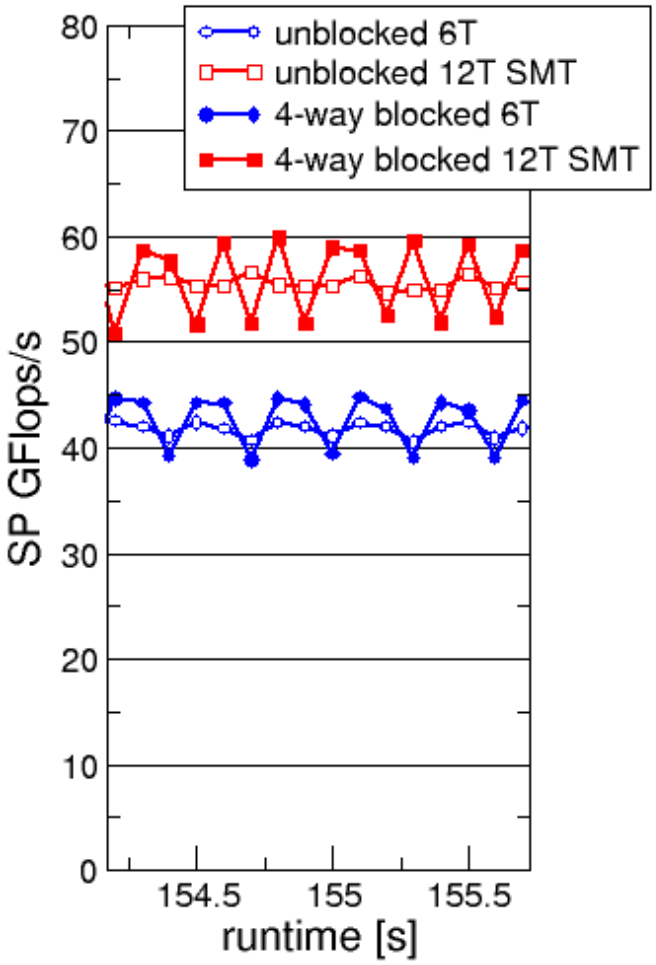
```
likwid-perfctr -c N:0-11 -g FLOPS_DP sleep 10
```

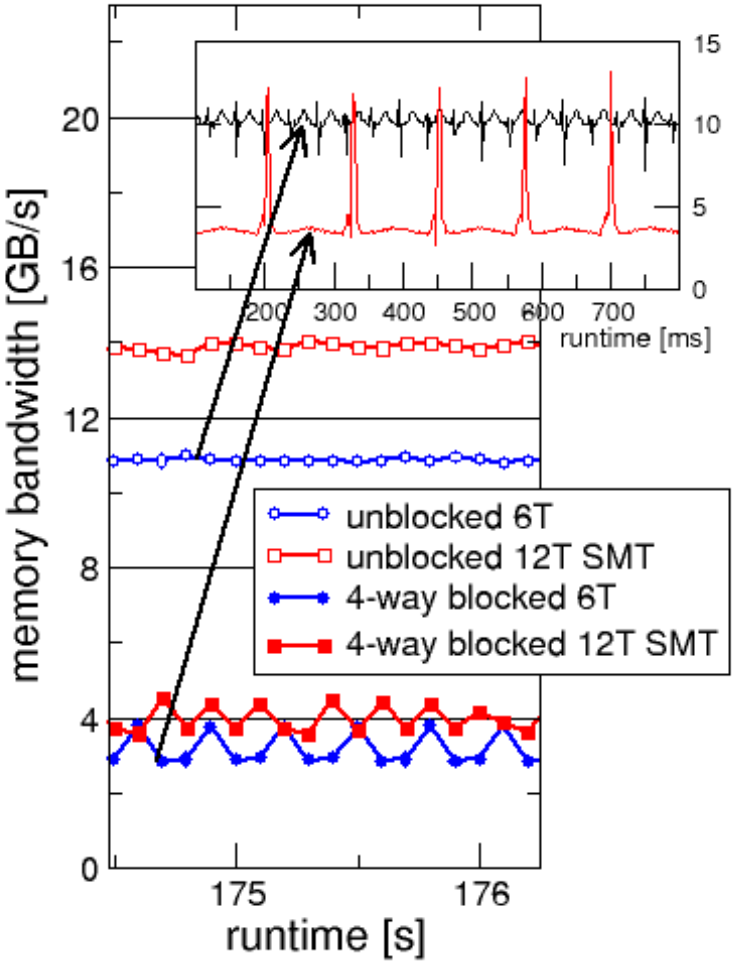
- It can be used as cluster/server monitoring tool

- A frequent use is to measure a certain part of a long running parallel application from outside

likwid-perfctr supports time-resolved measurements of full node:

```
$ likwid-perfctr -c N:0-11 -g MEM -t 50ms  > out.txt
```





likwid-perfctr
Marker API

- The marker API can restrict measurements to code regions
- The API only turns counters on/off. The configuration of the counters is still done by likwid-perfctr
- Multiple named regions support, accumulation over multiple calls
- Inclusive and overlapping regions allowed

```
#include <likwid.h>
. . .
LIKWID_MARKER_INIT;                    // must be called from serial region
#pragma omp parallel
{
  LIKWID_MARKER_THREADINIT;            // only reqd. if measuring multiple threads
}
. . .
LIKWID_MARKER_START("Compute");
. . .
LIKWID_MARKER_STOP("Compute");
. . .
LIKWID_MARKER_START("Postprocess");
. . .
LIKWID_MARKER_STOP("Postprocess");
. . .
LIKWID_MARKER_CLOSE;                   // must be called from serial region
```

- Activate macros with `-DLIKWID_PERFMON`
- Run `likwid-perfctr` with `-m` switch to enable marking
- See https://github.com/RRZE-HPC/likwid/wiki/TutorialMarkerF90 for Fortran example

Compile:

```
cc -I /path/to/likwid.h -DLIKWID_PERFMON -c program.c
```

Link:

```
cc -L /path/to/liblikwid program.o -llikwid
```

Run:

```
likwid-perfctr -C <MASK> -g <GROUP> -m ./a.out
```

- One separate block of output for every marked region
- Caveat: marker API can cause overhead; do not call too frequently!
  See also https://blogs.fau.de/hager/archives/8189

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 recompilation of likwid
- **`likwid-perfctr -a`** prints a list of groups
- An extended documentation (help text) is available for every group

Example: triangular dense MVM

Multiplication of upper triangular matrix with vector

```
#define N 10000 // large enough to use memory
#define ROUNDS 10

[...]

// Calculation loop
#pragma omp parallel
{
    for (int k = 0; k < ROUNDS; k++) {
        #pragma omp for private(current,j)
        for (int i = 0; i < N; i++) {
            current = 0;
            for (int j = i; j < N; j++)
                current += mat[(i*N)+j] * bvec[j];
            cvec[i] = current;
        }
        while (cvec[N>>1] < 0) {dummy();break;}
    }
}
```

Example: triangular dense MVM

LIKWID marker API

```
#include <likwid.h>
[…]
LIKWID_MARKER_INIT;
#pragma omp parallel
{
    LIKWID_MARKER_THREADINIT;
}
#pragma omp parallel
{
    for (int k = 0; k < ROUNDS; k++) {
        LIKWID_MARKER_START("Compute");
        #pragma omp for private(current,j)
        for (int i = 0; i < N; i++) {
            current = 0;
            for (int j = i; j < N; j++)
                current += mat[(i*N)+j] * bvec[j];
            cvec[i] = current;
        }
        LIKWID_MARKER_STOP("Compute");
        while (cvec[N>>1] < 0) {dummy();break;}
    }
}
LIKWID_MARKER_CLOSE;
```

Expectation: less work for high thread IDs

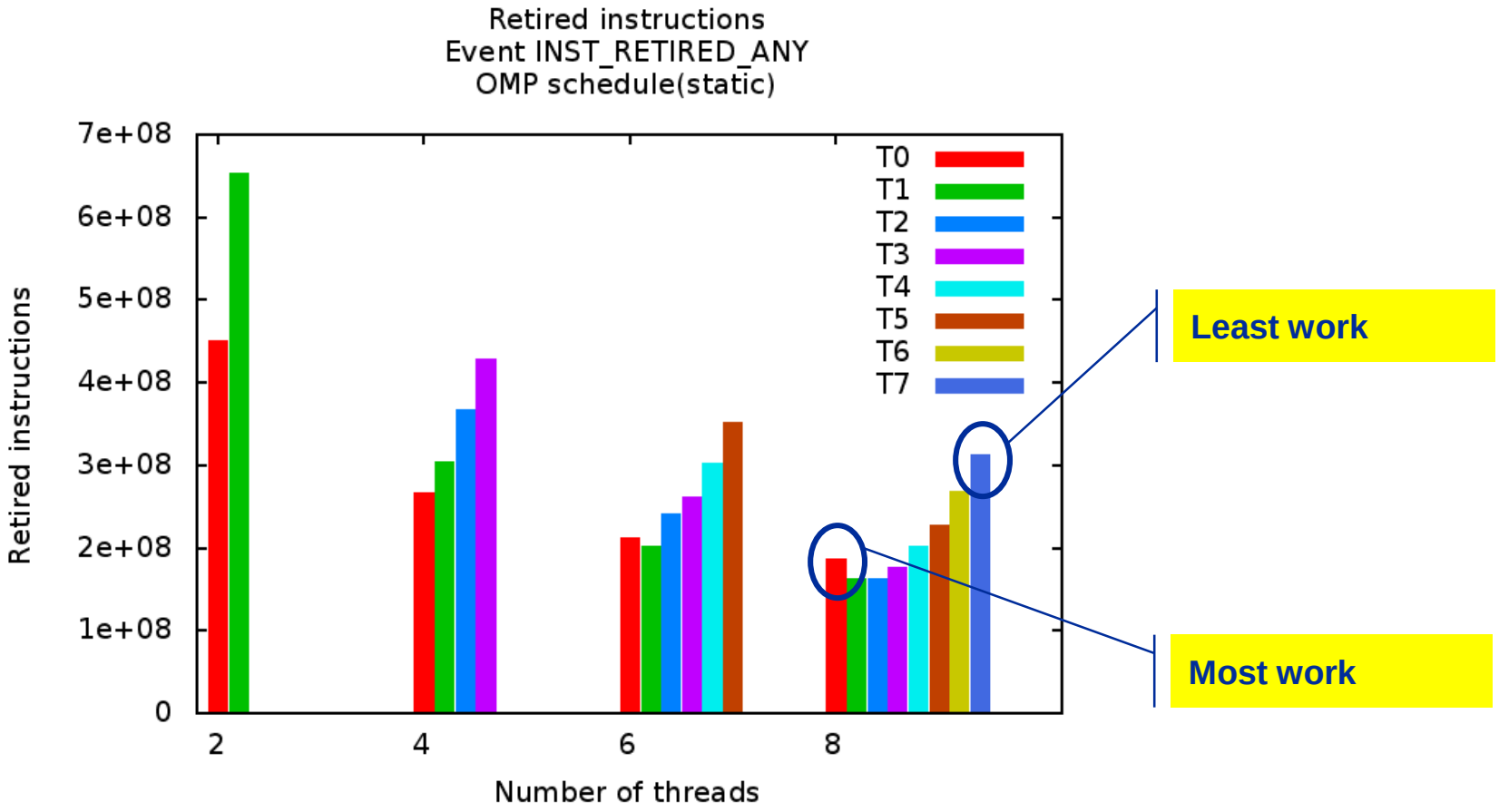
Example: triangular dense MVM

```
$ likwid-perfctr -C 0,1,2 -g L2 -m ./a.out
--------------------------------------------------------------------------------
CPU type:       Intel Core SandyBridge EN/EP processor
CPU clock:      3.09 GHz
--------------------------------------------------------------------------------
=======================
Group 1: Region Compute
=======================
+-------------------+----------+----------+----------+
|    Region Info    |  Core 0  |  Core 1  |  Core 2  |
+-------------------+----------+----------+----------+
| RDTSC Runtime [s] | 0.161382 | 0.161365 | 0.161365 |
|     call count    |    10    |    10    |    10    |
+-------------------+----------+----------+----------+
+----------------------+---------+-------------+-------------+-------------+
|         Event        | Counter |    Core 0   |    Core 1   |    Core 2   |
+----------------------+---------+-------------+-------------+-------------+
|   INSTR_RETIRED_ANY  |  FIXC0  | 2.626800e+08 | 3.187585e+08 | 3.780255e+08 |
| CPU_CLK_UNHALTED_CORE |  FIXC1  | 4.972802e+08 | 4.961411e+08 | 4.933711e+08 |
|  CPU_CLK_UNHALTED_REF |  FIXC2  | 4.972801e+08 | 4.961404e+08 | 4.933714e+08 |
|    L1D_REPLACEMENT   |   PMC0  | 5.490278e+07 | 3.927353e+07 | 2.364295e+07 |
|      L1D_M_EVICT     |   PMC1  | 2.920200e+04 | 2.876600e+04 | 2.861000e+04 |
|     ICACHE_MISSES    |   PMC2  | 4.649000e+03 | 4.984000e+03 | 5.321000e+03 |
+----------------------+---------+-------------+-------------+-------------+
```

????

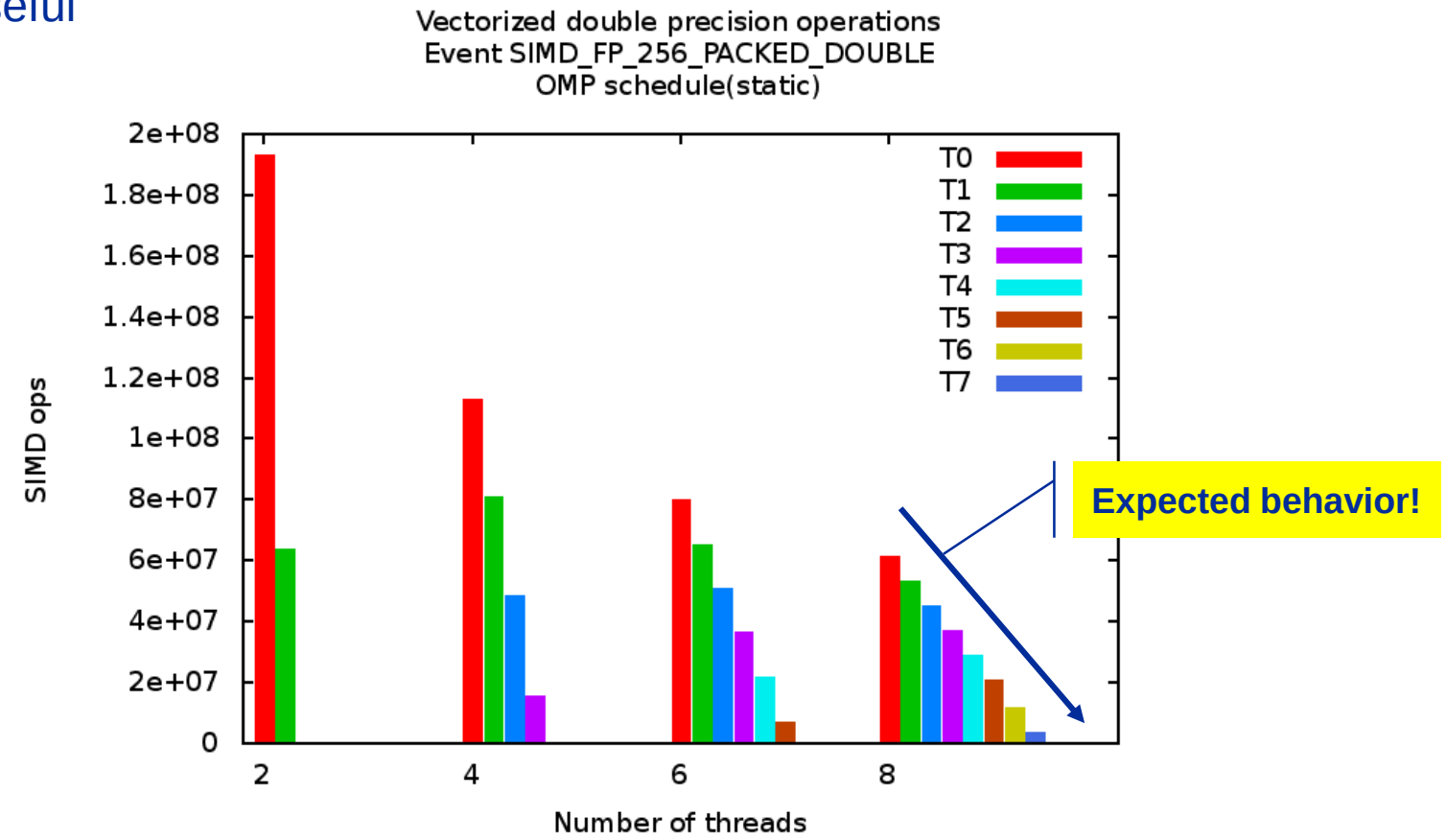
Example: triangular dense MVM

- Retired instructions are misleading
- Waiting in implicit OpenMP barrier issues many instructions



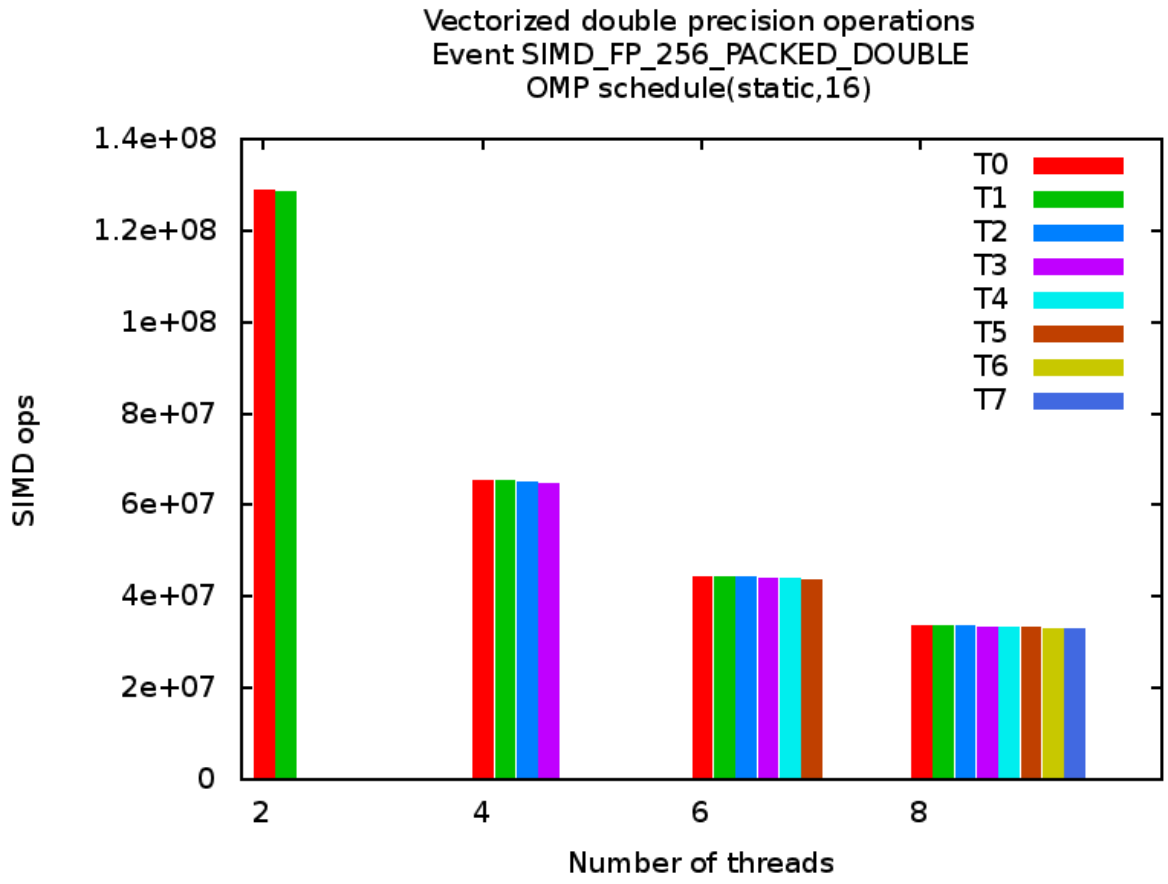
Example: triangular dense MVM

- **Floating point instructions are reliable ↔ useful work metric!**
- **But floating point instr. counters suffer from miscounting since SandyBridge (corrected in Broadwell)**
  - Still useful



Example: triangular dense MVM

- Changing `static` schedule to `static,16` → load balanced



Energy with likwid-perfctr in wrapper mode

```
$ likwid-perfctr -g ENERGY -C S0:0-1 ./a.out

[...]
+----------------------+-------------+-------------+
|        Metric        |    Core 0   |    Core 1   |
+----------------------+-------------+-------------+
|  Runtime (RDTSC) [s] | 2.362547e+01 | 2.362547e+01 |
| Runtime unhalted [s] | 3.347379e+01 | 3.348318e+01 |
|      Clock [MHz]     | 3.284280e+03 | 3.284278e+03 |
|          CPI         | 6.105052e-01 | 6.116845e-01 |
|    Temperature [C]   |      33      |      33      |
|      Energy [J]      | 1.423615e+03 |       0      |
|       Power [W]      | 6.025761e+01 |       0      |
|    Energy PP0 [J]    |       0      |       0      |
|     Power PP0 [W]    |       0      |       0      |
|    Energy DRAM [J]   |   89.424216  |       0      |
|    Power DRAM [W]    | 3.785076e+00 |       0      |
+----------------------+-------------+-------------+
[...]
```

Package (socket)

Cores only (if available)

DRAM (DIMMs)

Summary of hardware performance monitoring

- **Useful only of you know what you are looking for**
  - PM bears potential of acquiring massive amounts of data for nothing!
- **Resource-based metrics are most useful**
  - Cache lines transferred, work executed, loads/stores, cycles
  - Instructions, CPI, cache misses may be misleading
- **Caveat: Processor work != user work**
  - Waiting time in libraries (OpenMP, MPI) may incur lots of instructions
  - → distorted application characteristic
- **Another very useful application of PM: validating performance models!**
  - Roofline is data centric → measure data volume through memory hierarchy