

Multicore Performance and Tools

Part 2: Performance Analysis with hardware metrics



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`

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 frequency of cores
DATA: Load to store ratio
FLOPS_DP: Double Precision MFlops/s
FLOPS_SP: Single Precision 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
ENERGY: Power and energy consumption

likwid-perfctr wrapper mode

```
$ likwid-perfctr -g L2 -C S1:0-3 ./a.out
```

```
-----  
CPU name: Intel(R) Xeon(R) Platinum 8360Y CPU @ 2.40GHz[...]  
-----
```

```
<<<< PROGRAM OUTPUT >>>>
```

```
-----  
Group 1: L2
```

Event	Counter	HWThread 36	HWThread 37	HWThread 38	HWThread 39
INSTR_RETIRED_ANY	FIXC0	1409713380	1393263859	1394342491	1388917034
CPU_CLK_UNHALTED_CORE	FIXC1	2095261718	2088036330	2075539220	2058287996
CPU_CLK_UNHALTED_REF	FIXC2	2103679392	2121235200	2100479808	2075658144
TOPDOWN_SLOTS	FIXC3	10476308590	10440181650	10377696100	10291439980
L1D_REPLACEMENT	PMC0	142720376	142481840	142482162	142434419
L2_TRANS_L1D_WB	PMC1	54986306	54864382	54868339	54815549
TCACHE_64B_IPTAG_MISS	PMC2	381869	2094	7399	7718

Always measured for Intel CPUs

Configured metrics (this group)

```
[... statistics output omitted ...]
```

Metric	HWThread 36	HWThread 37	HWThread 38	HWThread 39
Runtime (RDTSC) [s]	1.0092	1.0092	1.0092	1.0092
Runtime unhalted [s]	0.8751	0.8721	0.8669	0.8597
Clock [MHz]	2384.7406	2356.8484	2365.8917	2374.2844
CPI	1.4863	1.4987	1.4885	1.4819
L2D load bandwidth [MBytes/s]	9050.5857	9035.4589	9035.4794	9032.4518
L2D load data volume [GBytes]	9.1341	9.1188	9.1189	9.1158
L2D evict bandwidth [MBytes/s]	3486.9462	3479.2144	3479.4653	3476.1177
L2D evict data volume [GBytes]	3.5191	3.5113	3.5116	3.5082
L2 bandwidth [MBytes/s]	12561.7480	12514.8061	12515.4139	12509.0589
L2 data volume [GBytes]	12.6777	12.6303	12.6309	12.6245

Derived metrics

likwid-perfctr stethoscope mode

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

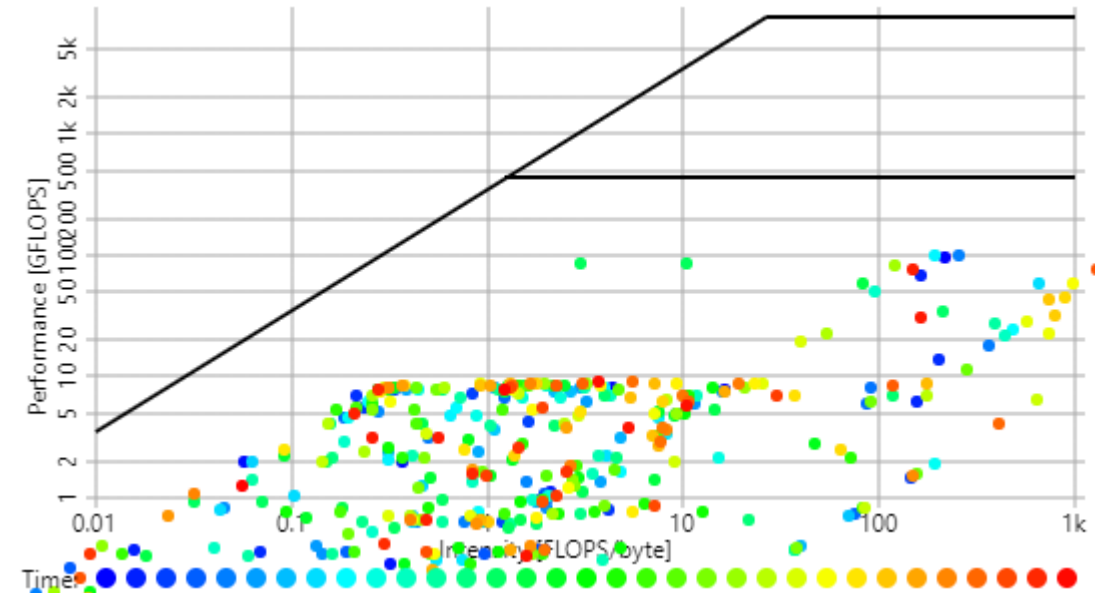
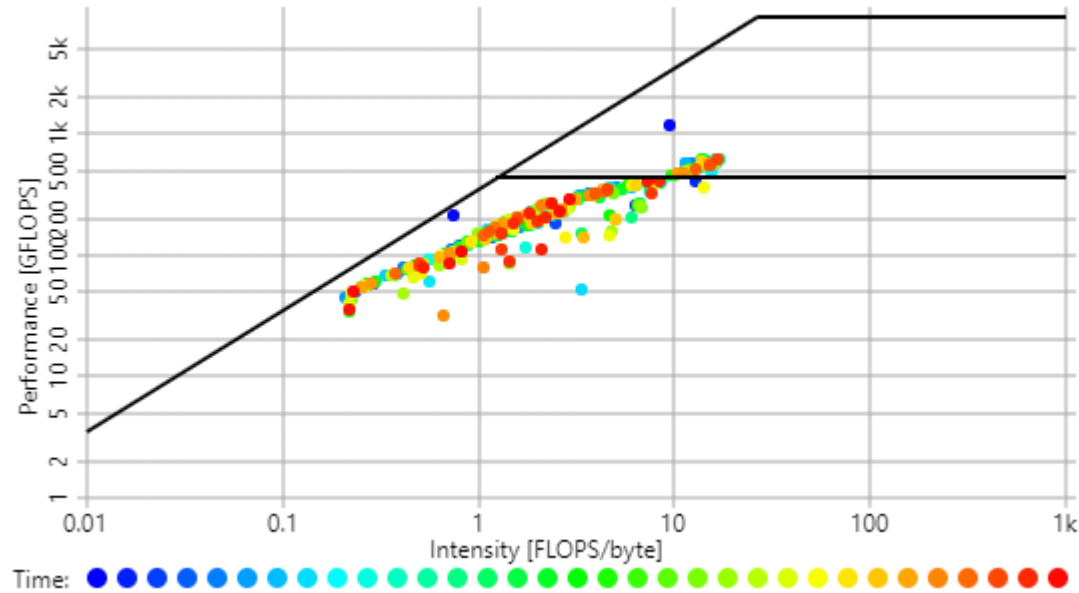
This allows you to “listen” to what is currently happening, **without any overhead:**

```
$ likwid-perfctr -c N:0-11 -g FLOPS_DP -S 10s
```

- Can be used as cluster/server monitoring tool
- Frequent use: monitor a long-running parallel application from outside

Cluster monitoring with likwid-perfctr

Two jobs on the NHR@FAU “Fritz” cluster



<https://github.com/ClusterCockpit>

likwid-perfctr with MarkerAPI

- The MarkerAPI can restrict measurements to **code regions**
- The API only reads counters.
The configuration of the counters is still done by `likwid-perfctr`
- Multiple named regions allowed, accumulation over multiple calls
- Inclusive and overlapping regions allowed

- **Caveat:** Marker API can cause overhead; do not call too frequently!

```
#include <likwid-marker.h>

LIKWID_MARKER_INIT; // must be called from serial region
. . .
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
```

likwid-perfctr with MarkerAPI: OpenMP code (C)

```
#include <likwid-marker.h>

int main(...) {
    LIKWID_MARKER_INIT;
    #pragma omp parallel
    {
        LIKWID_MARKER_REGISTER("MatrixAssembly");
    }
    ...
    #pragma omp parallel
    {
        LIKWID_MARKER_START("MatrixAssembly");
        #pragma omp for
        for(int i=0; i<N; ++i) { /* Loop */ }
        LIKWID_MARKER_STOP("MatrixAssembly");
    }
    ...
    LIKWID_MARKER_CLOSE;
}
```

Optional: Prepare data structures (reduced overhead on 1st marker call)

Call markers in parallel region if data should be taken on all threads

<https://github.com/RRZE-HPC/likwid/wiki/TutorialMarkerC>

likwid-perfctr with MarkerAPI: OpenMP code (Fortran)

```
program p
  use likwid
  call likwid_markerInit
  !$omp parallel
    call likwid_markerRegisterRegion("MatrixAssembly")
  !$omp end parallel
  ...
  !$omp parallel
    call likwid_markerStartRegion("MatrixAssembly")
    !$omp do
      do i=1,N
        ! Loop
      enddo
    !$omp end do
    call likwid_markerStopRegion("MatrixAssembly")
  !$omp end parallel
  ...
  call likwid_markerClose
end program p
```

Optional: Prepare data structures (reduced overhead on 1st marker call)

Call markers in parallel region if data should be taken on all threads

<https://github.com/RRZE-HPC/likwid/wiki/TutorialMarkerF90>

likwid-perfctr with MarkerAPI: source code transformations

```
#pragma omp parallel for  
  <loop>
```



```
#pragma omp parallel  
{  
  LIKWID_MARKER_START("Compute");  
  #pragma omp for  
  <loop>  
  LIKWID_MARKER_STOP("Compute");  
}
```

```
some_parallel_f()
```



```
#pragma omp parallel  
{  
  LIKWID_MARKER_START("foo");  
}  
some_parallel_f()  
#pragma omp parallel  
{  
  LIKWID_MARKER_STOP("foo");  
}
```

Compiling, linking, and running with marker API

Compile:

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

Activate LIKWID
macros (C only)

Link:

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

Run:

```
likwid-perfctr -C <CPULIST> -g <GROUP> -m ./program
```

Activate
markers

MPI:

```
likwid-mpirun -np 4 -pin <PINEXPR> -g <GROUP> -m ./program
```

→ One separate block of output for every marked region

So... what should I look at first?

Focus on **resource utilization** and **instruction decomposition**!

Metrics to measure:

- Operation throughput (Flops/s)
- Overall instruction throughput (IPC,CPI)
- **Instruction breakdown**:
 - FP instructions
 - loads and stores
 - branch instructions
 - other instructions
- Instruction breakdown to **SIMD width** (scalar, SSE, AVX, AVX512 for x86)
- **Data volumes** and **bandwidths** to main memory (GB and GB/s)
- Data volumes and bandwidth to different cache levels (GB and GB/s)

Useful diagnostic metrics are:

- Clock frequency (GHz)
- Power (W)

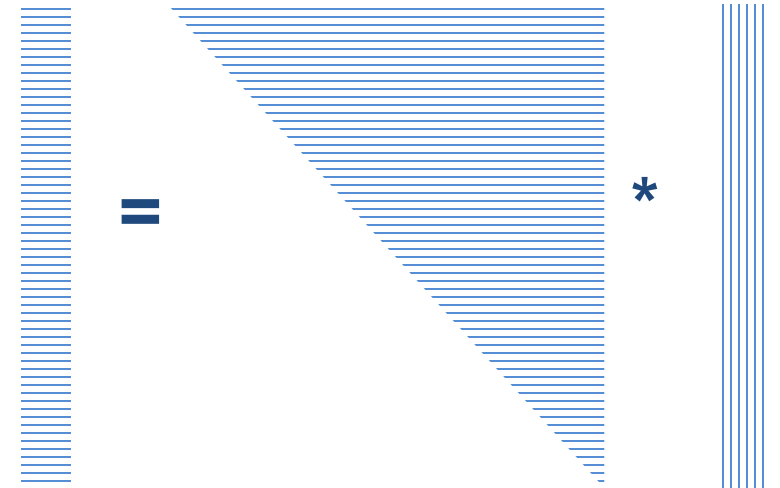
All the above metrics can be acquired using performance groups:

MEM_DP, MEM_SP, BRANCH, DATA, L2, L3

Example: triangular matrix-vector multiplication

```
#define N 10000 // matrix in memory
#define ROUNDS 10
// Initialization
fillMatrix(mat, N*N, M_PI);
fillMatrix(bvec, N, M_PI);

// 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;}
    }
}
```



Prevent smart compilers from eliminating benchmark if `cvec` not used afterwards

Example: triangular matrix-vector multiplication

```
#include <likwid-marker.h>
[...] // defines, fillMatrix, init data
LIKWID_MARKER_INIT;
#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;
```



Example: triangular matrix-vector multiplication

```
$ likwid-perfctr -C 0,1,2 -g L2 -m ./a.out
```

```
-----  
CPU type: Intel Icelake SP processor  
CPU clock: 2.39 GHz  
-----
```

```
<<<< PROGRAM OUTPUT >>>>
```

```
Region Compute, Group 1: L2
```

Region Info	HWThread 0	HWThread 1	HWThread 2
RDTSC Runtime [s]	0.198263	0.198364	0.198246
call count	10	10	10

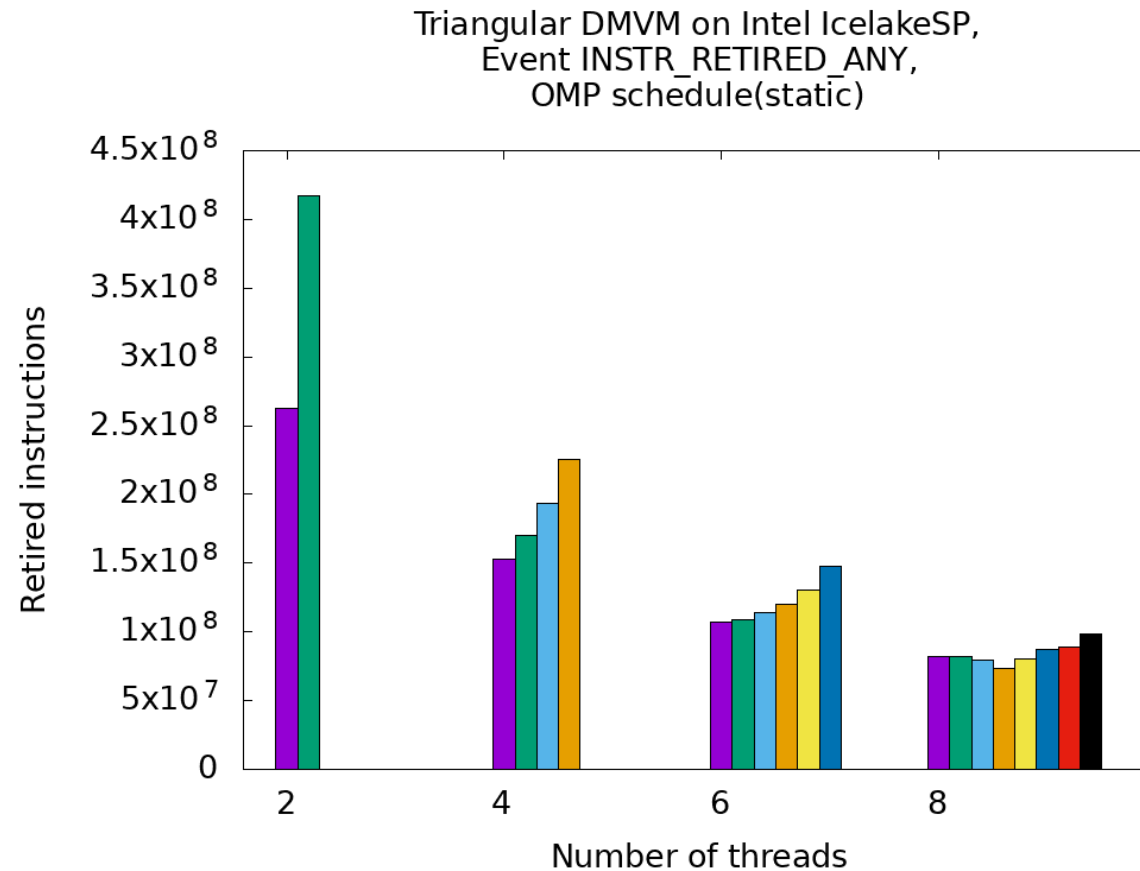
Event	Counter	HWThread 0	HWThread 1	HWThread 2
INSTR_RETIRED_ANY	FIXC0	194399400	269695800	341470000
CPU_CLK_UNHALTED_CORE	FIXC1	458193600	464605300	433236300
CPU_CLK_UNHALTED_REF	FIXC2	473442400	469863600	465054300
TOPDOWN_SLOTS	FIXC3	2290968000	2323026000	2166181000
L1D_REPLACEMENT	PMC0	69660770	41754150	7610321
L2_TRANS_L1D_WB	PMC1	43768	263047	442018
ICACHE_64B_IFTAG_MISS	PMC2	9698	11399	11571

???

Example: triangular matrix-vector multiplication

Retired instructions are misleading!

Waiting in implicit OpenMP barrier executes many instructions



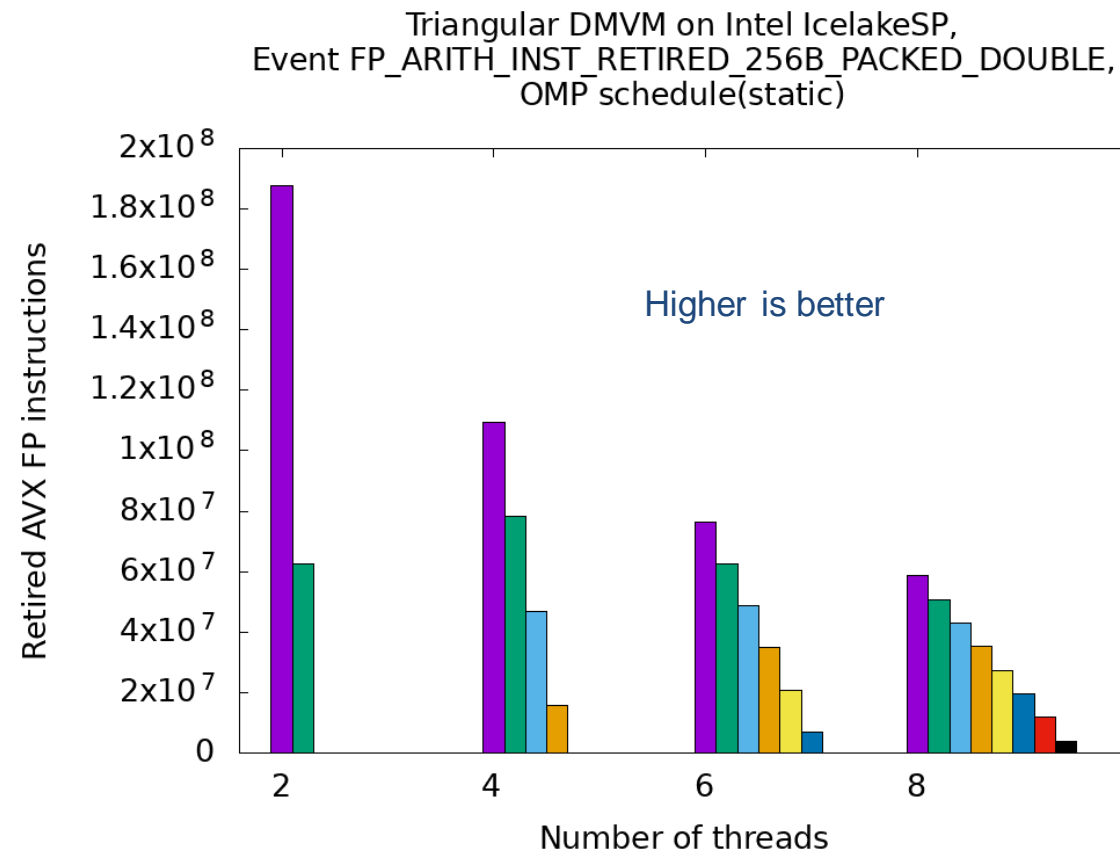
We need to measure actual work (or use a tool that can separate user from runtime lib instructions)

Example: triangular matrix-vector multiplication

Floating-point instructions reliable ↔ useful work metric

Caveats:

- FP instruction counters from SandyBridge to Haswell are only qualitatively correct
- Masked SIMD lanes cannot be counted directly on x86



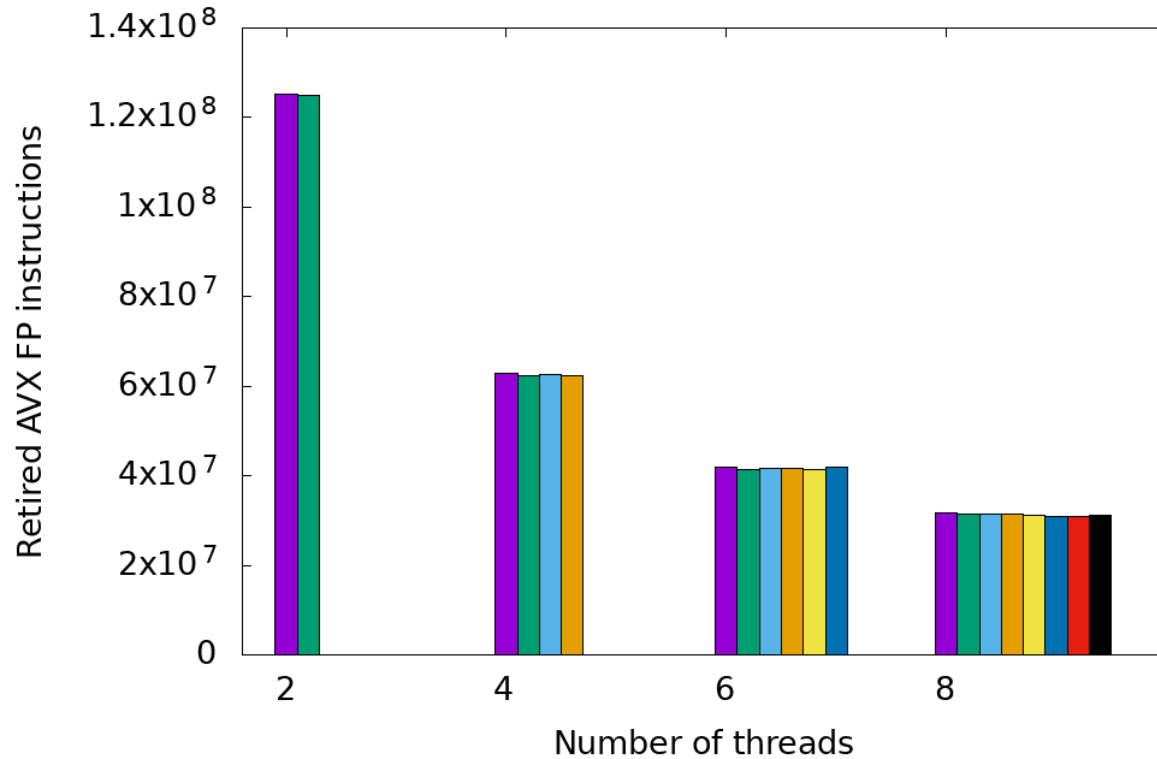
Example: triangular matrix-vector multiplication

Changing OMP schedule to **static** with **chunk size 16** → smaller work packages per thread

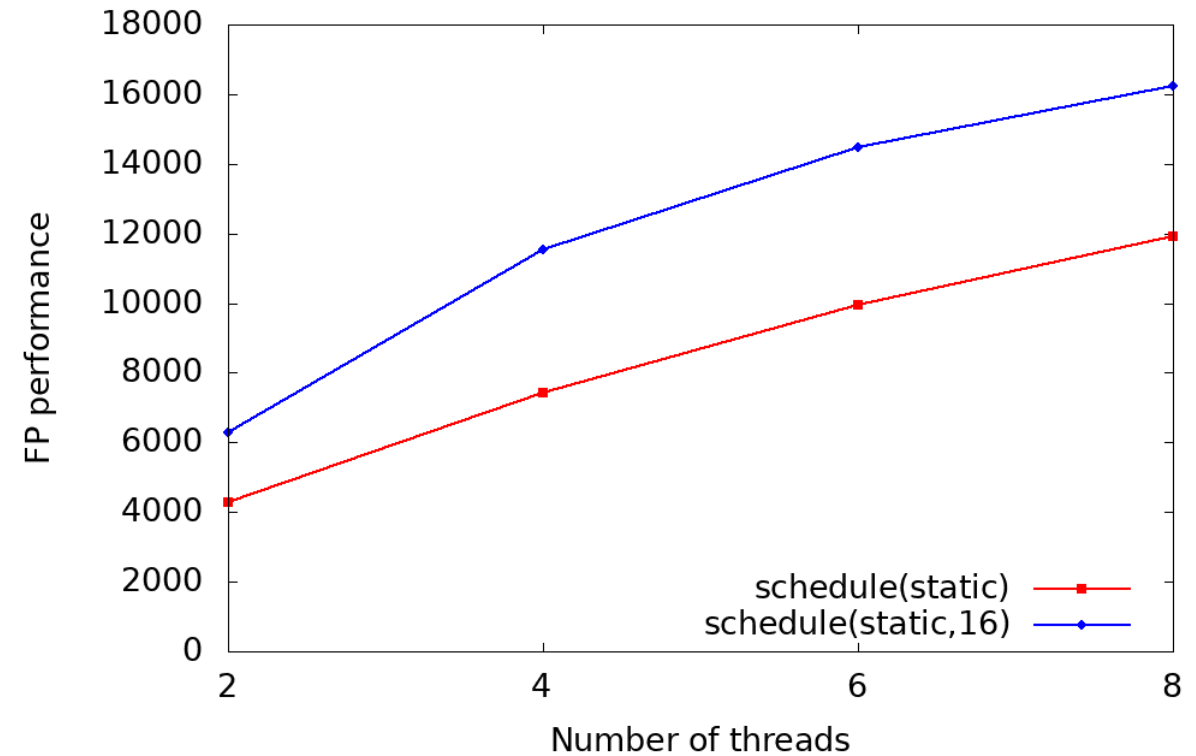
No imbalance anymore!

Is it also faster?

Triangular DMVM on Intel IcelakeSP,
Event FP_ARITH_INST_RETIRED_256B_PACKED_DOUBLE,
OMP schedule(static,16)



Triangular DMVM on Intel IcelakeSP,
Double-precision MFLOPS/s,
OMP schedule(static) vs schedule(static,16)



Summary of hardware performance monitoring

- Useful **only if you know what you are looking for**
 - Hardware event counting bears the 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 cause lots of instructions
 - → distorted application characteristic
 - Some tools can distinguish runtime instructions from user code instructions
- Another very useful application of PM: **validating performance models!**
 - Roofline is data centric → measure data volume through memory hierarchy