MuCoSim Introduction (Part II)

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High Performance Computing

Preparation:
Copy **~unrz139/mucosim** to your home
(WARNING: may overwrite existing files!)

Let‘s start with some recap:
Go to **mucosim/stream** and compile the code with latest **Intel** suite

Run code with **OMP_NUM_THREADS=4** a few times and determine min. and max. bandwidth for the **copy** kernel.

MuCoSim Introduction

COMPILERS

Compilers @ RRZE

- We provide GCC, Intel C/C++ Compiler (and PGI and others)
- On warmup also arm-clang (/opt/arm/… license up-on-request)
- Provided through **`module`** system
- Common compiler names:
  - GCC: **`gcc`** and **`gfortran`**
  - Intel: **`icc`** and **`ifort`**

Library names
`libtest.so` → **`-ltest`**

Location(s) of headers

Location(s) of libs

```
gcc -O3 -fopenmp -I<INCDIR> -L<LIBDIR> test.c -o test -llib
gfortran -O3 -fopenmp -I<INCDIR> -L<LIBDIR> test.f90 -o test -llib
```

Compiler options

Input file(s)

Output file

Compilers @ RRZE

- Common compiler switches:

Meaning	GCC	Intel compilers
General optimization level	`-O1`, `-O2`, `-O3` (some vendor specific options like `-Ofast`)	
Hardware feature flags	`-m` like `-mavx2`	`-x` like `-xCORE-AVX2`
Compiler feature flag	`-f` **like** `-fopenmp`	`-q` **like** `-qopenmp`

- In many cases, the Intel compiler
  - produces „better“ code and often better performing
  - provides fallbacks for GCC flags (`-fopenmp` accepted by ICC)

- CUDA compilers only available at nodes with GPUs

Compile **`compile/get_cpuflags.c`** with GCC and run it

What is the widest SIMD the system supports?

(MMX → SSE → SSE2 → SSE3 → SSE4 → AVX → AVX2 → AVX512)

SSE → SSE2 → SSE3 → SSE4: 128 bit vectors (2 doubles, 4 floats)

AVX → AVX2: 256 bit vectors (4 doubles, 8 floats)

AVX512: 512 bit vectors (8 doubles, 16 floats)

Compile **`compile/triad.c`** with recent GCC and ICC and …

What‘s the minimum runtime you can achieve on the compute node?

Single hardware thread? Do optimization flags help?

All hardware threads?

> Remember: Copy folder to your home/workdir/…
> **`cp -r ~unrz139/mucosim $HOME`**

MuCoSim Introduction

PERFORMANCE and TIMING

How to measure performance?

- Performance = WORK / TIME

- WORK
  - 1 : Time-to-solution, carefully define problem
  - Flops : Floating-point operations (specify single-prec. or dbl.-prec.)
  - Particles|LatticeUpdates|Whatever : Algorithm related work

- TIME
  - UNIX **`time`** command can be confusing! Use **`real`** time
    Sometimes, **`time`** is a builtin, use **`/usr/bin/time`**

```
$ time <cmd>
<output>
real     0m0.008s
user     0m0.002s
sys      0m0.002s
```

  - Best practice: Use high-resolution timers around region of interest

How to measure performance? *Inside applications*

- Check **`snippets`** folder for helpful headers
  - **`walltime.h`**: **`timestamp()`** returns the current time in seconds
  - **`cycletime.h`**: **`cyclestamp()`** returns the number of cycles since boot
- For time measurements: endstamp - startstamp
- Careful when measuring small intervals:
  - Might be below resolution!
  - **`walltime.h`**: **`resolution()`** to check the current timer
- Check out **`test_times.c`** for example usage

MuCoSim Introduction

LIKWID

On emmy: Close interactive session and open a new one with :likwid property

On testfront: Keep your session

High Performance Computing

What is LIKWID?

- A toolset for performance-oriented developers/users

- Get system topology
- Place threads according system topology (affinity domains)
- Run micro-benchmarks to check system features
- Measure hardware events during application runs
- Determine energy consumption
- Manipulate CPU/Uncore frequencies and prefetchers

How to use LIKWID on FAU systems

- LIKWID is available in the module system
  `$ module avail likwid`
- Always use newest version (currently 5.2.0)
- Disabled on production systems:
  - **`likwid-setFrequencies`**
  - **`likwid-features`**

Changes settings for all following jobs on that system! Reset yourself at end of job

- Module sets environment variables (**`module show likwid/<version>`**):
  `LIKWID_LIBDIR`, **`LIKWID_INCDIR`**

```
gcc –I$LIKWID_INCDIR –LLIKWID_LIBDIR … -llikwid
```

System topology with LIKWID

$ likwid-topology -g

- Thread topology
- Cache topology
- NUMA topology
- Graphical topology

```
Socket 0:                              Intel Xeon CPU E5-2660 v2 @ 2.20GHz)
+-------------------------------------------------------------------------+
| +---------+ +---------+ +---------+ +-+ +---------+ +---------+ +---------+ |
| |  0 20   | |  1 21   | |  2 22   | | | |  7 27   | |  8 28   | |  9 29   | |
| +---------+ +---------+ +---------+ +-+ +---------+ +---------+ +---------+ |
| +---------+ +---------+ +---------+ +-+ +---------+ +---------+ +---------+ |
| |  32 kB | |  32 kB | |  32 kB | | | |  32 kB | |  32 kB | |  32 kB | |
| +---------+ +---------+ +---------+ +-+ +---------+ +---------+ +---------+ |
| +---------+ +---------+ +---------+ +-+ +---------+ +---------+ +---------+ |
| | 256 kB | | 256 kB | | 256 kB | | | | 256 kB | | 256 kB | | 256 kB | |
| +---------+ +---------+ +---------+ +-+ +---------+ +---------+ +---------+ |
| +-----------------------------------------------------------------------+ |
| |                      25                   MB                          | |
| +-----------------------------------------------------------------------+ |
+-------------------------------------------------------------------------+
```

System topology with LIKWID

```
$ likwid-topology
CPU name: Intel(R) Xeon(R) CPU E5-2697 v4 @ 2.30GHz
*************************************************************
Hardware Thread Topology
*************************************************************
Sockets:      2
Cores per socket:   18
Threads per core:   2
[…]
*************************************************************
NUMA Topology
*************************************************************
NUMA domains:       4
```

Product name

SMT active!

ClusterOnDie / SNC active (NUMA > Sockets)

System topology with LIKWID

```
$ likwid-topology
*************************************************
Cache Topology
*************************************************
Level:            1
Size:             32 kB
Cache groups:     ( 0 36 ) ( 1 37 ) ( 2 38 ) …

Level:            2
Size:             256 kB
Cache groups:     ( 0 36 ) ( 1 37 ) ( 2 38 ) …

Level:            3
Size:             22 MB
Cache groups:     ( 0 36 1 37 2 38 3 39 4 40 5 41 6 42 7 43 8 44
```

L1 Cache

Cache size

Hardware threads sharing a cache

`likwid-topology -c`: more infos about caches like cache line size, associativity, …

How many HW threads does your compute node provide?

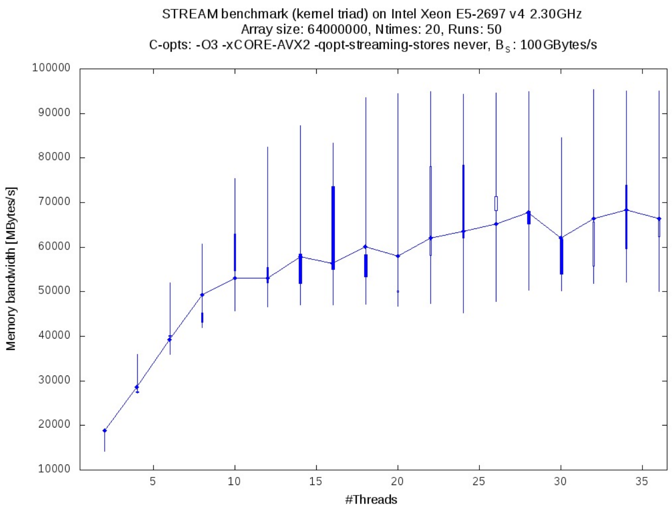
Does you system has CoD/SNC active?

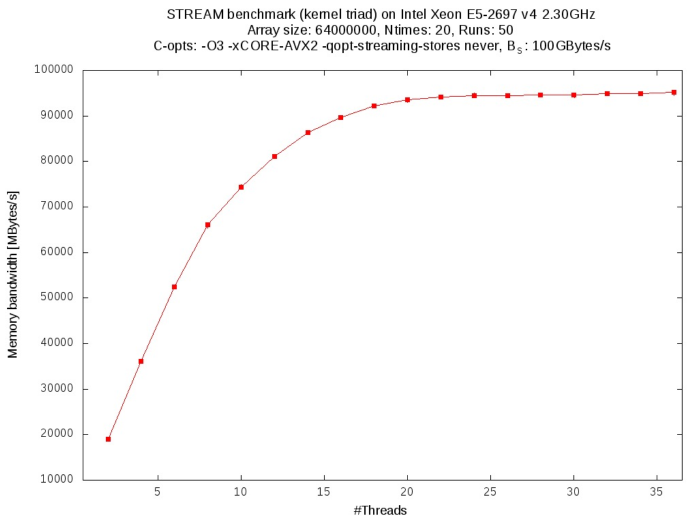
Is SMT active?

What‘s the L3 cache size?

Task Affinity

- OS task scheduler places tasks (=processes/threads) on HW threads
- OS scheduler moves tasks to different cores from time to time
- STREAM benchmark:





This is how it looks when you saturate a shared resource

Task Affinity

- Limiting set of possible HW threads per process/thread
- There are several reasons for caring about affinity:
  - Eliminating performance variation
  - Making use of architectural features
  - Avoiding resource contention
- Many tools/methods for affinity:
  - **`taskset:`** Limit set of HW threads (threads can be moved around)
  - **`sched.h:`** Application threads pin themselves
  - OpenMP/MPI-specific: Vendor-specific, often not portable
  - **`numactl:`** Limit application threads to NUMA domain (can be moved around)
  - **`likwid-pin`**
- Choose what fits best! Remember to set thread count!

Task Affinity - `numactl`

- **`numactl -C <cpulist> <executable>`**
  - Same like **`taskset`** -> no real pinning!
- numactl provides more features regarding memory allocation
  - Bind memory to specific NUMA domains (**`-m <nodelist>`**)
  - Interleave memory in specific NUMA domains (**`-i <nodelist>`**)
- Some output functionality
  (**`-s`** for current settings and **`-H`** for NUMA hardware inventory)

Commonly not the way to do CPU pinning! But the right way for memory pinning!

Task Affinity - `likwid-pin`

- Pin processes/threads without touching application code
- Supports most threading solutions
- Requirement: Application must be dynamically linked
- Support for multiple CPU selection syntaxes:
  - Physical: 0,4,5 or 0,4-5 → CPUs with ID 0,4 and 5
  - Logical: S0:0-3 → First four phy. cores on Socket 0
  - Expression based: E:N:20:1:2 → 20 threads, one out of two
- **`likwid-pin -c <cpusel> ./a.out`**

N: node
Sx: socket
My: NUMA domain
Cz: LLC

Skipping SMT threads

Combine CPU selections with @

How many affinity domains does your system provide? (**--help**)

Compile **pin/hello_pthread.c** (**-pthread**)
Run it a few times, how often do threads share a CPU?

Pin **hello_pthread** (5 threads)

Pin **hello_pthread** to the first two physical HW threads of all sockets

What happens? Who wins?

OMP_NUM_THREADS=10 likwid-pin -c 0-4 ./hello_pthread

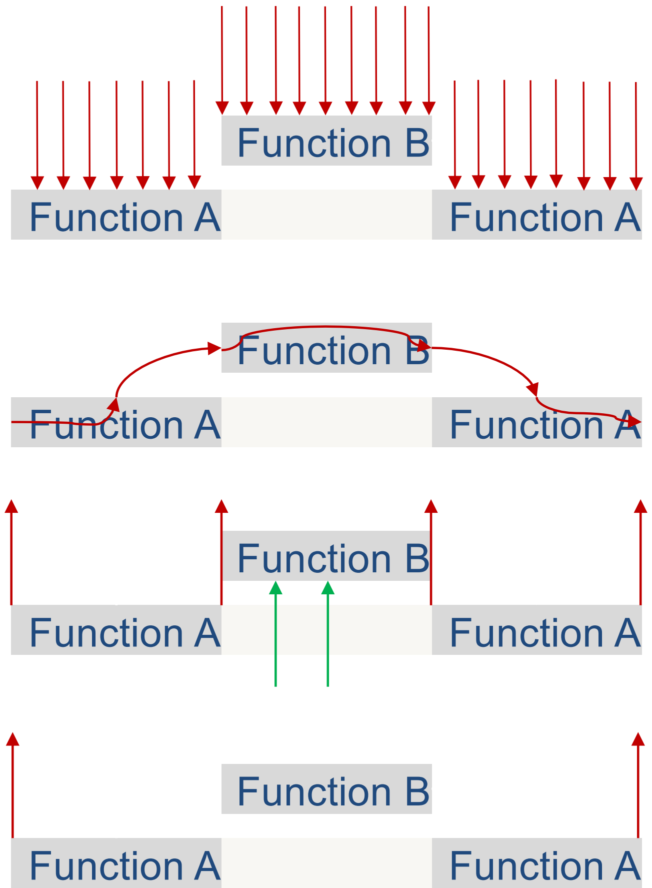
Run **stream** with 4 threads pinned differently (**N:0-3**, **S0:0-1@S1:0-1**).
What‘s the fastest CPU selection for **triad**?

MuCoSim Introduction

Analysis of applications

Measurement techniques

- Sampling
- Tracing
- Instrumentation
- Profiling



gprof, xray, perf, …

- Read state periodically
- Follow the execution path
- Add **`read_state()`** where desired
- Create an overview what happened

Runtime profile - Find out hotspots in the code

- Many tools available: **`gprof`**, **`xray`**, **`perf`**, …
- For **`gprof`** build with **`-pg`**
- Creates XML and tabular output files with fields:
  - Time and time share for function
  - Call and exit count
  - File and line of function
- Run application like normal
- Afterwards: **`gprof <exec> gmon.out`**

Runtime profile

Inclusive timing — Exclusive timing

Time(%)	Self (sec)	Call count	Function
44.52	2.47	100	`triad()`
25.96	1.44	100	`add()`
16.94	0.94	100	`copy()`
100.00	0.00	1	`main()`

Call count: How often a function was called

Besides function runtime, how can we measure resource usage?

So, how to restrict measurements to the `triad()` function?

Compile **`stream`** in **`runtime_profile`** with runtime profiling
(use `*.c` and include header path **`-I.`**)

Look at the hotspots in the code.
Can you name a reason for the runtime difference?

What is hardware performance monitoring?
Overview about HPM

- Performance monitoring units (PMUs) at hardware level
- Introduced for x86 with Intel Pentium (1994)
- Originally used by CPU vendors for hardware validation
- No additional CPU work to handle hardware events in PMUs
- Accessing PMUs requires CPU work → Overhead
- Limited number of counters per PMU (x86: 4 per unit)

Hardware Performance Monitoring with LIKWID - `likwid-perfctr`

- **`likwid-perfctr`** sets up system topology and perfmon
- Setup, start, read and stop PMUs
- Execute application on given CPU set (**`-C`**)
- Evaluate counter values

```
likwid-perfctr -C 0 -g INST_RETIRED_ANY:FIXC0 <app>
```

- LIKWID needs you to specify which counter runs which event
- Combine multiple (event+counter)s with ','
- For advanced usage, the events can be enriched with options **`threshold`**, **`invert`**, **`count_kernel`**, **`edge_detect`**,

LIKWID - HPM with `likwid-perfctr`

```
$ likwid-perfctr -C 0,1 -g L2_TRANS_L1D_WB:PMC0 ./app
+-----------------------+---------+--------------+--------------+
|         Event         | Counter |    Core 0    |    Core 1    |
+-----------------------+---------+--------------+--------------+
|  Runtime (RDTSC) [s]  |   TSC   | 2.573182e+00 | 2.573182e+00 |
|    L2_TRANS_L1D_WB    |   PMC0  |    281176518 |    281240170 |
+-----------------------+---------+--------------+--------------+
```

- Event names (in many cases) not intuitive
- Events are architecture-specific
- Some sound promising but return bad counts, others are broken
- More interest in real metrics like volume of loaded/stored data

LIKWID - HPM with **likwid-perfctr**

- LIKWID defines performance groups
  ≈ eventlist + derived metrics + documentation
- List all groups: **likwid-perfctr -a**

You can also define own performance groups!

```
$ likwid-perfctr -C 0,1 -g L2 ./app
+-----------------------------------+-----------+-----------+
|              Metric               |  Core 0   |  Core 1   |
+-----------------------------------+-----------+-----------+
|        Runtime (RDTSC) [s]        |    2.6439 |    2.6439 |
|   L2D load bandwidth [MBytes/s]   | 6744.8121 | 6743.6037 |
|   L2D load data volume [GBytes]   |   17.8325 |   17.8293 |
|   L2D evict bandwidth [MBytes/s]  | 3372.4061 | 3371.8019 |
|   L2D evict data volume [GBytes]  |    8.9163 |    8.9147 |
```

LIKWID - Performance groups

- **FLOPS_AVX: Packed AVX MFlops/s**
- **FLOPS_DP: Double Precision MFlops/s**
- **FLOPS_SP: Single Precision MFlops/s**
- **DATA: Load to store ratio**
- **L2: L2 cache bandwidth in MBytes/s**
- **L3: L3 cache bandwidth in MBytes/s**
- **MEM: Main memory bandwidth in MBytes/s**
- **ENERGY: Power and Energy consumption**
- **MEM_DP: Memory & DP FLOP/s & Energy**
- **MEM_SP: Memory & SP FLOP/s & Energy**

Overcounting on Intel SandyBridge & IvyBridge. No **FLOPS_*** groups on Intel Haswell.

Hardware Performance Monitoring with LIKWID - `likwid-perfctr`

- **`$ likwid-perfctr -C 0,1 -g FLOPS_DP ./a.out`**
  Measure DP FLOP/s of the whole application run of on CPUs 0, 1
- **`$ likwid-perfctr -c 0,1 -g DATA ./a.out`**
  Measure load/store ratio on CPUs 0,1. Application is not pinned!
- **`$ likwid-perfctr -g MEM_DP -H`**
  Get help for performance group MEM_DP
- **`$ likwid-perfctr -e (| less)`**
  List all events and counters, search with **`-E <searchstr>`**

Compile **`perfctr/triad.c`**
Measure the memory bandwidth (**`MEM`**)
from 1 to number of phys. cores per socket
At which core count does it saturate?

Compile **`perfctr/pi.c`**
Measure the FLOP rate from 4 to 10 processes on one socket
Does it have a saturation point?
How well is it vectorized? What is the max. vectorization ratio you can achieve? Are all operations done with „best“ vectorization?

LIKWID - *HPM of functions*

- LIKWID offers MarkerAPI for code region measurements

```
#include <likwid-marker.h>
LIKWID_MARKER_INIT; // in serial region
LIKWID_MARKER_REGISTER("Compute"); // in parallel region
LIKWID_MARKER_START("Compute");
<code>
LIKWID_MARKER_STOP("Compute");
LIKWID_MARKER_CLOSE;  // in serial region
```

Older version use `<likwid.h>`

Reduces startup overhead

Multiple regions and nesting allowed

- Compile with **`-DLIKWID_PERFMON`**

Add marker API to code (restructure loops)

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

→

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

LIKWID_MARKER_STOP("Compute");
}
```

Add marker API to code (closed-source library calls)

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

LIKWID - *HPM of functions*

Defined by LIKWID module at RRZE

Compile @ RRZE:

```
$CC -DLIKWID_PERFMON $LIKWID_INC $LIKWID_LIB code.c -o code -llikwid
```

```
likwid-perfctr -C <cpustr> -g <group> -m ./a.out
```

Use capital C
MarkerAPI requires pinned threads

Tells `likwid-perfctr` to use MarkerAPI mode

Copy **`perfctr/pi.c`** to **`marker/pi.c`**

Add MarkerAPI calls around loop for each OpenMP thread & compile

Measure the FLOP rate from 4 to number of phys. cores per socket

Compile **`marker/stream.c`** (use **`-I. *.c`**)

What are the read and write memory bandwidths of each hotspot for 4 threads?

Compare results to the application output of stream.

Is there a difference and if yes, why?

Thank you for your attention!

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