Erlangen Regional Computing Center

FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG

Multicore Performance and Tools

Part 1: Topology, affinity control, clock speed

High Performance Computing

Tools for Node-level Performance Engineering

- **Node Information**
  */proc/cpuinfo, numactl, hwloc, **likwid-topology**, likwid-powermeter*

- **Affinity control** and data placement
  *OpenMP and MPI runtime environments, hwloc, numactl, **likwid-pin***

- **Runtime Profiling**
  Compilers, gprof, perf, HPC Toolkit, Intel Amplifier, …

- **Performance Analysis**
  *Intel VTune, **likwid-perfctr**, PAPI-based tools, HPC Toolkit, Linux perf*

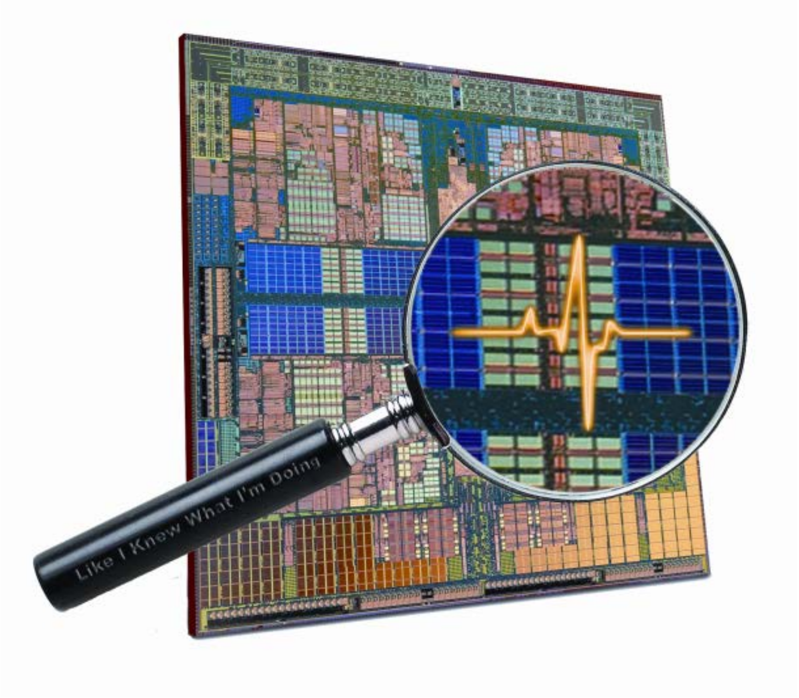
- **Microbenchmarking**
  *STREAM, **likwid-bench**, lmbench, uarch-bench*

LIKWID performance tools

https://youtu.be/6uFl1HPq-88

LIKWID tool suite:

Like
I
Knew
What
I'm
Doing



Open source tool collection (developed at RRZE):

J. Treibig, G. Hager, G. Wellein: *LIKWID: A lightweight performance-oriented tool suite for x86 multicore environments.* PSTI2010, Sep 13-16, 2010, San Diego, CA. DOI: [10.1109/ICPPW.2010.38](https://doi.org/10.1109/ICPPW.2010.38)

https://github.com/RRZE-HPC/likwid

Reporting topology

DEMO

likwid-topology https://youtu.be/mxMWjNe73SI

Output of `likwid-topology -g`

on one node of Intel Haswell-EP

optional

```
--------------------------------------------------------------------------------
CPU name:     Intel(R) Xeon(R) CPU E5-2695 v3 @ 2.30GHz
CPU type:     Intel Xeon Haswell EN/EP/EX processor
CPU stepping: 2
********************************************************************************
Hardware Thread Topology
********************************************************************************
Sockets:                    2
Cores per socket:           14
Threads per core:           2
--------------------------------------------------------------------------------
HWThread      Thread        Core          Socket        Available
0               0           0             0             *
1               0           1             0             *
…
43              1           1             1             *
44              1           2             1             *
--------------------------------------------------------------------------------
Socket 0:     ( 0 28 1 29 2 30 3 31 4 32 5 33 6 34 7 35 8 36 9 37 10 38 11 39 12 40 13 41 )
Socket 1:     ( 14 42 15 43 16 44 17 45 18 46 19 47 20 48 21 49 22 50 23 51 24 52 25 53 26 54 27 55 )
--------------------------------------------------------------------------------
********************************************************************************
Cache Topology
********************************************************************************
Level:                      1
Size:                       32 kB
Cache groups:               ( 0 28 ) ( 1 29 ) ( 2 30 ) ( 3 31 ) ( 4 32 ) ( 5 33 ) ( 6 34 ) ( 7 35 ) ( 8 36 ) ( 9 37 ) ( 10 38 )
( 11 39 ) ( 12 40 ) ( 13 41 ) ( 14 42 ) ( 15 43 ) ( 16 44 ) ( 17 45 ) ( 18 46 ) ( 19 47 ) ( 20 48 ) ( 21 49 ) ( 22 50 ) ( 23
51 ) ( 24 52 ) ( 25 53 ) ( 26 54 ) ( 27 55 )
--------------------------------------------------------------------------------
Level:                      2
Size:                       256 kB
Cache groups:               ( 0 28 ) ( 1 29 ) ( 2 30 ) ( 3 31 ) ( 4 32 ) ( 5 33 ) ( 6 34 ) ( 7 35 ) ( 8 36 ) ( 9 37 ) ( 10 38 )
( 11 39 ) ( 12 40 ) ( 13 41 ) ( 14 42 ) ( 15 43 ) ( 16 44 ) ( 17 45 ) ( 18 46 ) ( 19 47 ) ( 20 48 ) ( 21 49 ) ( 22 50 ) ( 23
51 ) ( 24 52 ) ( 25 53 ) ( 26 54 ) ( 27 55 )
--------------------------------------------------------------------------------
Level:                      3
Size:                       17 MB
Cache groups:               ( 0 28 1 29 2 30 3 31 4 32 5 33 6 34 ) ( 7 35 8 36 9 37 10 38 11 39 12 40 13 41 ) ( 14 42 15 43 16
44 17 45 18 46 19 47 20 48 ) ( 21 49 22 50 23 51 24 52 25 53 26 54 27 55 )
--------------------------------------------------------------------------------
```

All physical processor IDs

Output of `likwid-topology` continued

optional

```
********************************************************************************
NUMA Topology
********************************************************************************
NUMA domains:           4
--------------------------------------------------------------------------------
Domain:                 0
Processors:             ( 0 28 1 29 2 30 3 31 4 32 5 33 6 34 )
Distances:              10 21 31 31
Free memory:            13292.9 MB
Total memory:           15941.7 MB
--------------------------------------------------------------------------------
Domain:                 1
Processors:             ( 7 35 8 36 9 37 10 38 11 39 12 40 13 41 )
Distances:              21 10 31 31
Free memory:            13514 MB
Total memory:           16126.4 MB
--------------------------------------------------------------------------------
Domain:                 2
Processors:             ( 14 42 15 43 16 44 17 45 18 46 19 47 20 48 )
Distances:              31 31 10 21
Free memory:            15025.6 MB
Total memory:           16126.4 MB
--------------------------------------------------------------------------------
Domain:                 3
Processors:             ( 21 49 22 50 23 51 24 52 25 53 26 54 27 55 )
Distances:              31 31 21 10
Free memory:            15488.9 MB
Total memory:           16126 MB
--------------------------------------------------------------------------------
```

Output similar to `numactl --hardware`

Output of `likwid-topology` continued

optional

Cluster on Die (CoD) mode and SMT enabled!

```
********************************************************************************
Graphical Topology
********************************************************************************
Socket 0:
+-----------------------------------------------------------------------------------------------------------------------------------------------------------+
| +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ |
| |  0 28  | |  1 29  | |  2 30  | |  3 31  | |  4 32  | |  5 33  | |  6 34  | |  7 35  | |  8 36  | |  9 37  | | 10 38  | | 11 39  | | 12 40  | | 13 41  | |
| +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ |
| +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ |
| |  32kB  | |  32kB  | |  32kB  | |  32kB  | |  32kB  | |  32kB  | |  32kB  | |  32kB  | |  32kB  | |  32kB  | |  32kB  | |  32kB  | |  32kB  | |  32kB  | |
| +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ |
| +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ |
| |  256kB | |  256kB | |  256kB | |  256kB | |  256kB | |  256kB | |  256kB | |  256kB | |  256kB | |  256kB | |  256kB | |  256kB | |  256kB | |  256kB | |
| +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ |
| +--------------------------------------------------------------------------+ +--------------------------------------------------------------------------+ |
| |                                   17MB                                   | |                                   17MB                                   | |
| +--------------------------------------------------------------------------+ +--------------------------------------------------------------------------+ |
+-----------------------------------------------------------------------------------------------------------------------------------------------------------+
Socket 1:
+-----------------------------------------------------------------------------------------------------------------------------------------------------------+
| +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ |
| | 14 42  | | 15 43  | | 16 44  | | 17 45  | | 18 46  | | 19 47  | | 20 48  | | 21 49  | | 22 50  | | 23 51  | | 24 52  | | 25 53  | | 26 54  | | 27 55  | |
| +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ |
| +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ |
| |  32kB  | |  32kB  | |  32kB  | |  32kB  | |  32kB  | |  32kB  | |  32kB  | |  32kB  | |  32kB  | |  32kB  | |  32kB  | |  32kB  | |  32kB  | |  32kB  | |
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| +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ |
| |  256kB | |  256kB | |  256kB | |  256kB | |  256kB | |  256kB | |  256kB | |  256kB | |  256kB | |  256kB | |  256kB | |  256kB | |  256kB | |  256kB | |
| +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ |
| +--------------------------------------------------------------------------+ +--------------------------------------------------------------------------+ |
| |                                   17MB                                   | |                                   17MB                                   | |
| +--------------------------------------------------------------------------+ +--------------------------------------------------------------------------+ |
+-----------------------------------------------------------------------------------------------------------------------------------------------------------+
```

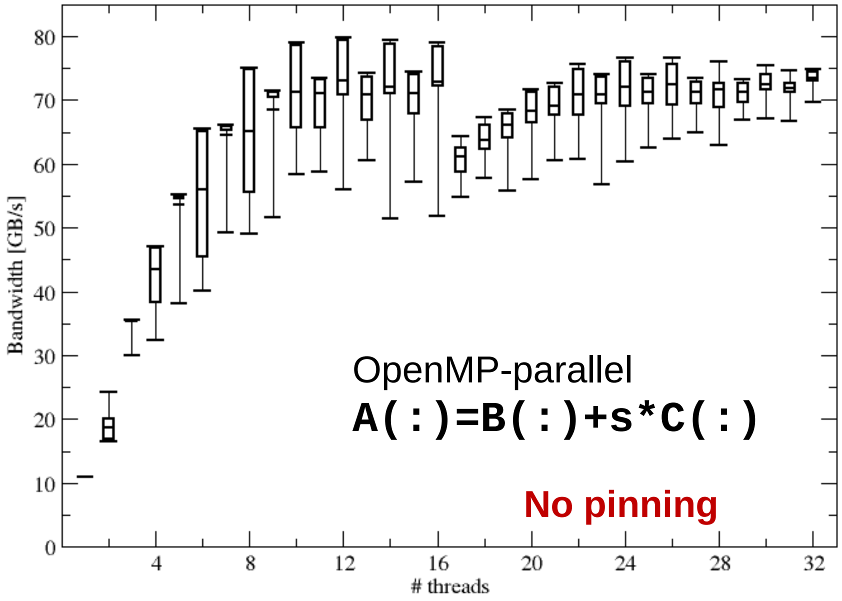
Enforcing thread/process affinity under the Linux OS

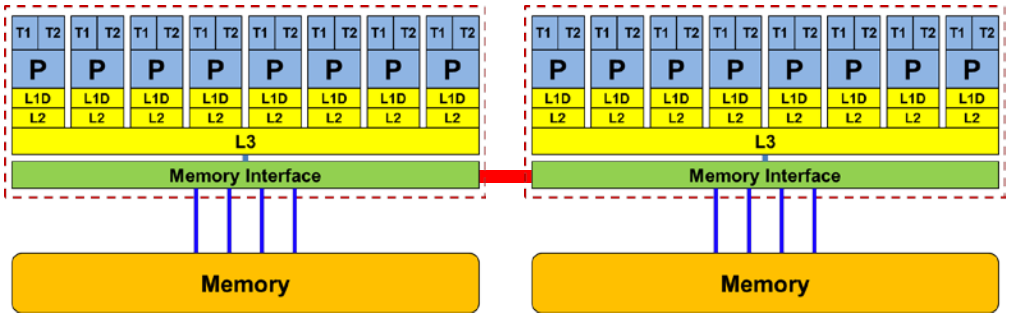
DEMO

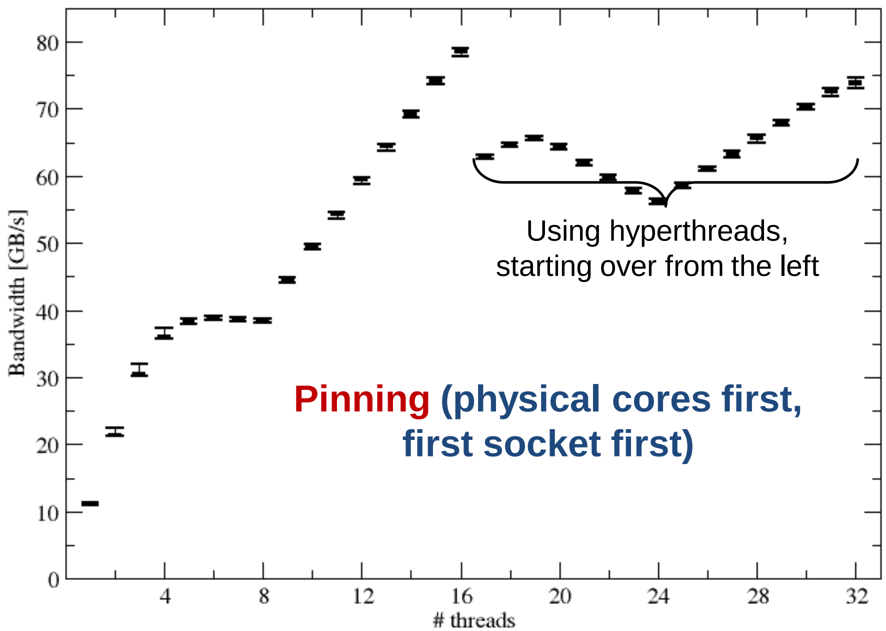
likwid-pin https://youtu.be/PSJKNQaqwB0

STREAM benchmark on 16-core Sandy Bridge

Anarchy vs. thread pinning



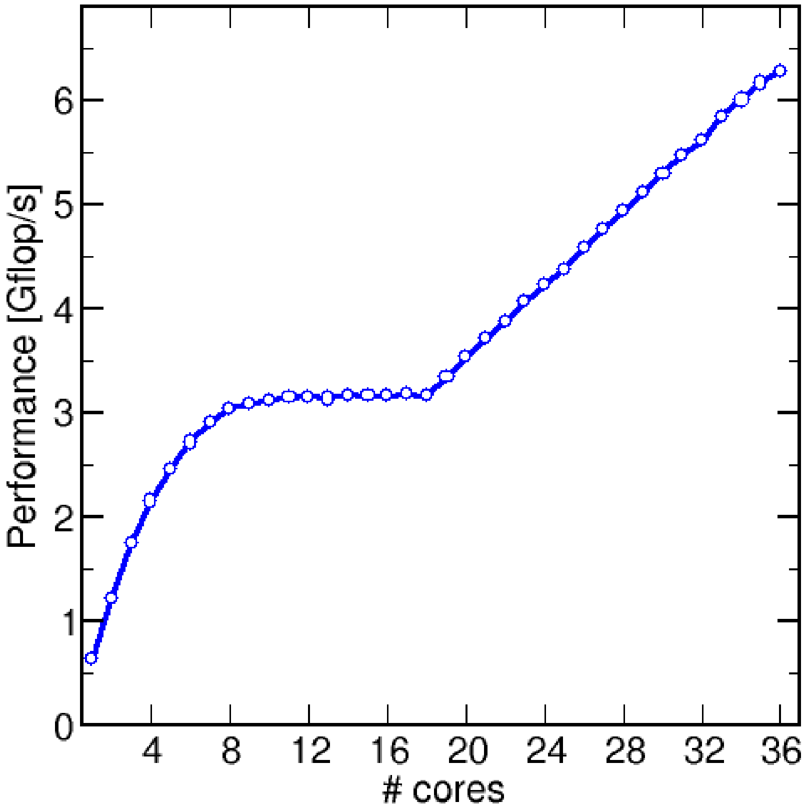




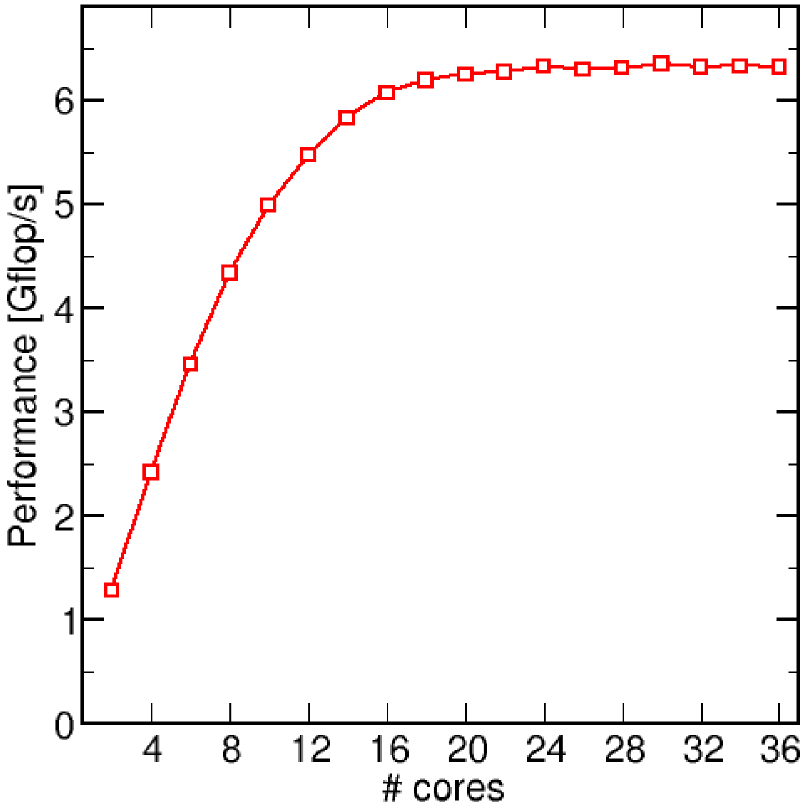
There are several reasons for caring about affinity:

- Eliminating performance variation
- Making use of architectural features
- Avoiding resource contention

Vector triad on dual-socket 18-core node



Filling cores from left to right (“compact” pinning)



Filling both sockets simultaneously (“scattered” or “spread” pinning)

More thread/process affinity (“pinning”) options

- Highly OS-dependent system calls
  But available on all systems
  - Linux: **`sched_setaffinity()`**
  - Windows: **`SetThreadAffinityMask()`**
- Hwloc project (**`http://www.open-mpi.de/projects/hwloc/`**)
- Support for “semi-automatic” pinning
  - All modern compilers with OpenMP support
  - Generic Linux: **`taskset`**, **`numactl`**, **`likwid-pin`** (see below)
  - OpenMP 4.0 (**`OMP_PLACES`**, **`OMP_PROC_BIND`**)
  - Slurm Batch scheduler
- Affinity awareness in MPI libraries
  - OpenMPI
  - Intel MPI …

`https://youtu.be/IKW0kRLnhyc`

Overview `likwid-pin`

- Pins processes and threads to specific cores without touching code
- Directly supports pthreads, gcc OpenMP, Intel OpenMP
- Based on combination of wrapper tool together with overloaded pthread library → binary must be dynamically linked!
- Supports logical core numbering within topological entities (thread domains)

- Simple usage with physical (kernel) core IDs:

```
$ likwid-pin -c 0-3,4,6  ./myApp parameters
$ OMP_NUM_THREADS=4 likwid-pin -c 0-9 ./myApp params
```

- Simple usage with logical IDs (“thread groups expressions”):

```
$ likwid-pin -c S0:0-7  ./myApp params
$ likwid-pin –c C1:0-2 ./myApp params
```

LIKWID terminology: Thread group syntax

- The OS numbers all processors (hardware threads) on a node
- The numbering is enforced at boot time by the BIOS

- LIKWID introduces **thread domains** consisting of HWthreads sharing a topological entity (e.g. socket or shared cache)
- A **thread domain** is defined by a single **character + index**

- Example for likwid-pin:
  `$ likwid-pin –c S1:0-3 ./a.out`

Physical cores first!

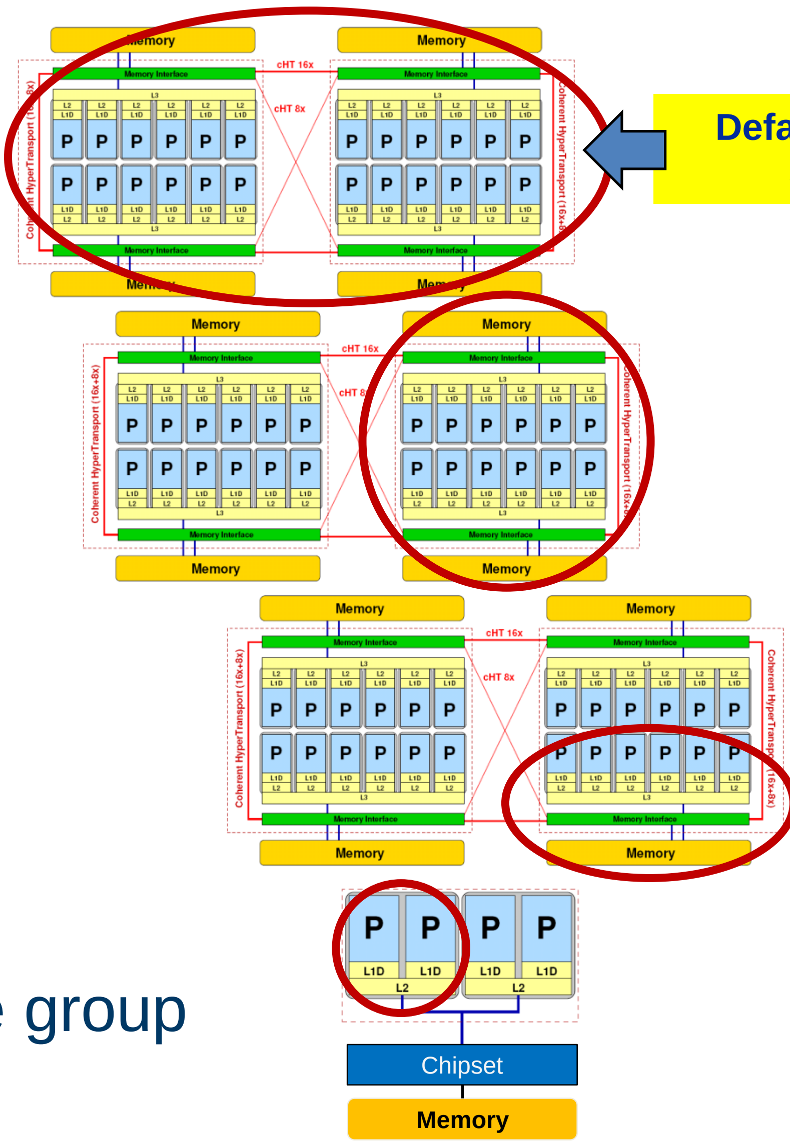
```
+-------------------------------------+
| +------+ +------+ +------+ +------+ |
| |  0  4| |  1  5| | 2  6 | | 3  7 | |
| +------+ +------+ +------+ +------+ |
| +------+ +------+ +------+ +------+ |
| |  32kB| |  32kB| |  32kB| |  32kB| |
| +------+ +------+ +------+ +------+ |
| +------+ +------+ +------+ +------+ |
| | 256kB| | 256kB| | 256kB| | 256kB| |
| +------+ +------+ +------+ +------+ |
| +---------------------------------+ |
| |               8MB               | |
| +---------------------------------+ |
+-------------------------------------+
```

- Thread group expressions may be chained with @:
  `$ likwid-pin –c S0:0-3@S1:0-3 ./a.out`

LIKWID Currently available thread domains

Possible unit prefixes

- **N** node
- **S** socket
- **M** NUMA domain
- **C** outer level cache group



Default if –c is not specified!

Advanced options for pinning: Expression syntax

optional

- The Expression syntax is more powerful in situations where the pin mask would be very long or clumsy

  Compact pinning (counting through HW threads):

```
$ likwid-pin -c E:<thread domain>:\
    <number of threads>\
    [:<chunk size>:<stride>] ...
```

  Scattered pinning across all domains of the designated type:

```
$ likwid-pin -c <domaintype>:scatter
```

- Examples:

```
$ likwid-pin -c E:N:8:1:2 ...
$ likwid-pin -c E:N:120:2:4 ...
```

- Scatter across all NUMA domains:

```
$ likwid-pin -c M:scatter
```

"Compact" placement!

```
+-------------------------------------+
| +------+ +------+ +------+ +------+ |
| | 0   1| |  2  3| | 4  5 | | 6  7 | |
| +------+ +------+ +------+ +------+ |
| +------+ +------+ +------+ +------+ |
| |  32kB| |  32kB| |  32kB| |  32kB| |
| +------+ +------+ +------+ +------+ |
| +------+ +------+ +------+ +------+ |
| | 256kB| | 256kB| | 256kB| | 256kB| |
| +------+ +------+ +------+ +------+ |
| +---------------------------------+ |
| |               8MB               | |
| +---------------------------------+ |
+-------------------------------------+
```

OMP_PLACES and Thread Affinity

optional

Processor: smallest entity able to run a thread or task (hardware thread)

Place: one or more processors → thread pinning is done place by place

Free migration of the threads on a place between the processors of that place.

abstract name

OMP_PLACES	Place ==
threads	Hardware thread (hyper-thread)
cores	All HW threads of a single core
sockets	All HW threads of a socket
abstract_name(num_places)	Restrict # of places available

Or use explicit numbering, e.g. 8 places, each consisting of 4 processors:

- `OMP_PLACES="{0,1,2,3},{4,5,6,7},{8,9,10,11}, … {28,29,30,31}"`
- `OMP_PLACES="{0:4},{4:4},{8:4}, … {28:4}"`
- `OMP_PLACES="{0:4}:8:4"`

<lower-bound>:<number of entries>[:<stride>]

Caveat: Actual behavior is implementation defined!

OMP_PROC_BIND variable / proc_bind() clause

optional

Determines how places are used for pinning:

OMP_PROC_BIND	Meaning
FALSE	Affinity disabled
TRUE	Affinity enabled, implementation defined strategy
CLOSE	Threads bind to consecutive places
SPREAD	Threads are evenly scattered among places
MASTER	Threads bind to the same place as the master thread that was running before the parallel region was entered

If there are more threads than places, consecutive threads are put into individual places ("balanced")

Some simple OMP_PLACES examples

optional

Intel Xeon w/ SMT, 2x10 cores, 1 thread per physical core, fill 1 socket

```
OMP_NUM_THREADS=10
OMP_PLACES=cores
OMP_PROC_BIND=close
```

Always prefer abstract places instead of HW thread IDs!

Intel Xeon Phi with 72 cores,
32 cores to be used, 2 threads per physical core

```
OMP_NUM_THREADS=64
OMP_PLACES=cores(32)
OMP_PROC_BIND=close    # spread will also do
```

Intel Xeon, 2 sockets, 4 threads per socket (no binding within socket!)

```
OMP_NUM_THREADS=8
OMP_PLACES=sockets
OMP_PROC_BIND=close    # spread will also do
```

Intel Xeon, 2 sockets, 4 threads per socket, binding to cores

```
OMP_NUM_THREADS=8
OMP_PLACES=cores
OMP_PROC_BIND=spread
```

MPI startup and hybrid pinning: `likwid-mpirun`

- How do you manage affinity with MPI or hybrid MPI/threading?
- In the long run a unified standard is needed
- Till then, likwid-mpirun provides a portable/flexible solution
- The examples here are for Intel MPI/OpenMP programs, but are also applicable to other threading models

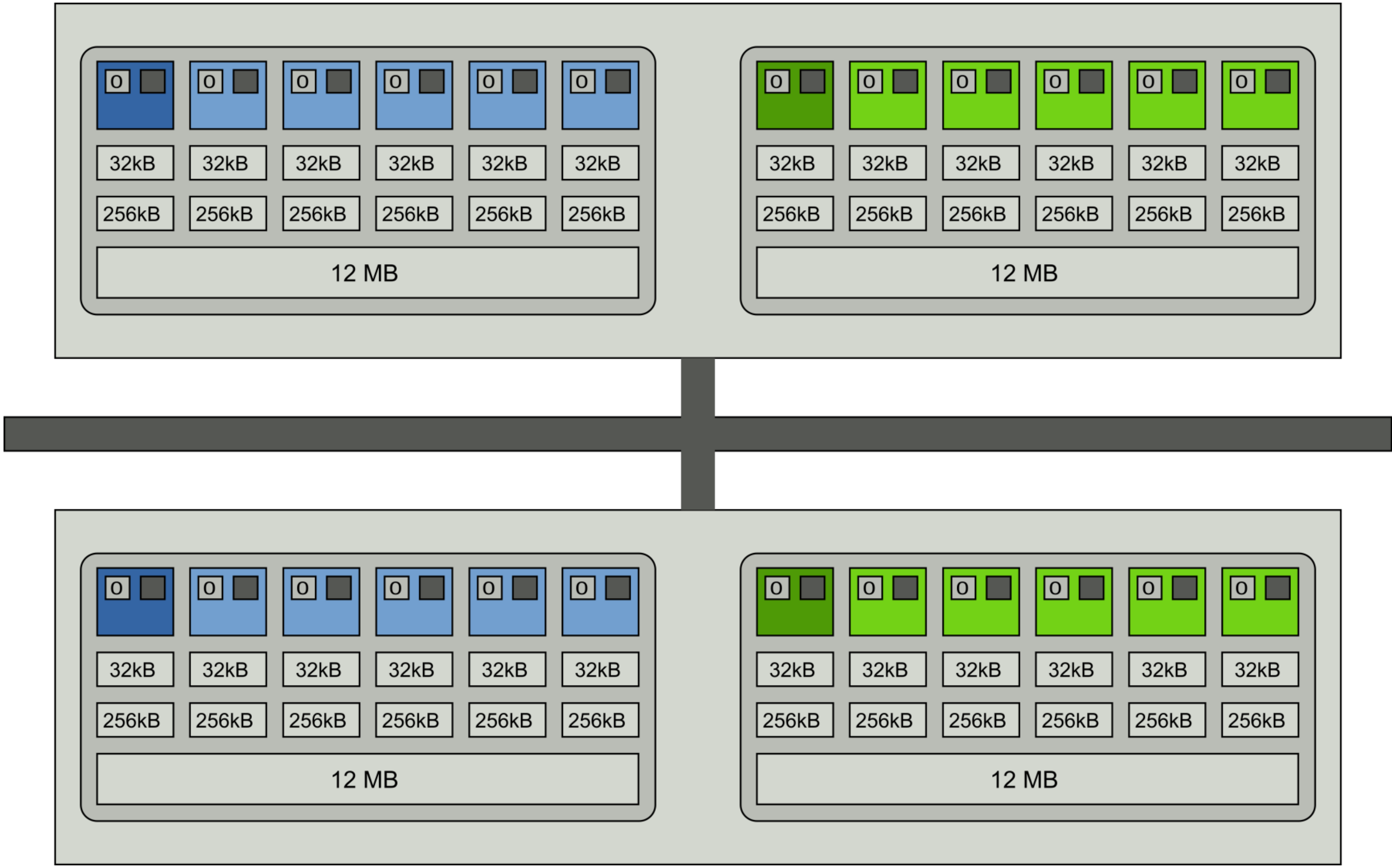
Pure MPI:

```
$likwid-mpirun -np 16 -nperdomain S:2 ./a.out
```

Hybrid:

```
$likwid-mpirun -np 16 -pin S0:0,1_S1:0,1 ./a.out
```

```
$ likwid-mpirun –np 4 -pin S0:0-5_S1:0-5 ./a.out
```



Intel MPI+compiler:

```
OMP_NUM_THREADS=6 mpirun –ppn 2 –np 4 \
     –env I_MPI_PIN_DOMAIN socket –env KMP_AFFINITY scatter ./a.out
```

Clock speed under the Linux OS

Turbo steps and likwid-powermeter

likwid-setFrequencies

Which clock speed steps are there?

Uses the Intel RAPL interface (Sandy Bridge++)

```
$ likwid-powermeter -i
--------------------------------------------------------------------------
CPU name:        Intel(R) Xeon(R) CPU E5-2695 v3 @ 2.30GHz
CPU type:        Intel Xeon Haswell EN/EP/EX processor
CPU clock:       2.30 GHz
--------------------------------------------------------------------------
Base clock:      2300.00 MHz
Minimal clock:   1200.00 MHz
Turbo Boost Steps:
C0 3300.00 MHz
C1 3300.00 MHz
C2 3100.00 MHz
C3 3000.00 MHz
C4 2900.00 MHz
[...]
C13 2800.00 MHz
---------------------------------
```

Note: AVX code on HSW+ may execute even slower than base freq.

```
Info for RAPL domain PKG:
Thermal Spec Power: 120 Watt
Minimum Power: 70 Watt
Maximum Power: 120 Watt
Maximum Time Window: 46848 micro sec

Info for RAPL domain DRAM:
Thermal Spec Power: 21.5 Watt
Minimum Power: 5.75 Watt
Maximum Power: 21.5 Watt
Maximum Time Window: 44896 micro sec
```

`likwid-powermeter` can also measure energy consumption, but **`likwid-perfctr`** can do it better (see later)

Setting the clock frequency

- The "Turbo Mode" feature makes reliable benchmarking harder

  CPU can change clock speed at its own discretion
- Clock speed reduction may save a lot of energy
- So how do we set the clock speed?

  → LIKWID to the rescue!

```
$ likwid-setFrequencies –l
Available frequencies:
1.2 1.3 1.4 1.5 1.6 1.7 1.8 1.9 2 2.1 2.2 2.3
$ likwid-setFrequencies –p
Current CPU frequencies:
CPU 0: governor  performance min/cur/max 2.3/2.301/2.301 GHz Turbo 1
CPU 1: governor  performance min/cur/max 2.3/2.301/2.301 GHz Turbo 1
CPU 2: governor  performance min/cur/max 2.3/2.301/2.301 GHz Turbo 1
CPU 3: governor  performance min/cur/max 2.3/2.301/2.301 GHz Turbo 1
[...]
$ likwid-setFrequencies –f 2.0   # min=max=2.0
[...]
$ likwid-setFrequencies –turbo 0 # turbo off
```

Turbo mode