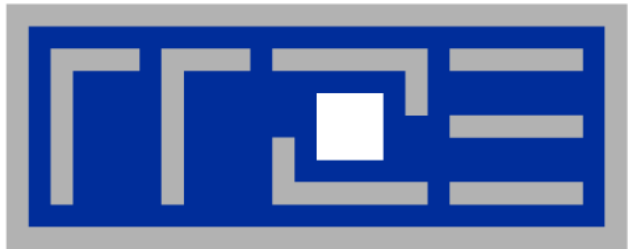


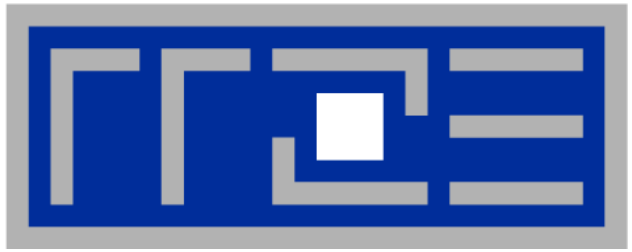
Multicore Performance and Tools

Part 1: Topology, affinity, clock speed

Likwid Tool Suite

- **Command line tools for Linux:**
  - easy to install
  - works with standard linux kernel
  - simple and clear to use
  - supports Intel and AMD CPUs

- **Current tools:**
  - **likwid-topology**: Print thread and cache topology
  - **likwid-pin**: Pin threaded application without touching code
  - **likwid-perfctr:** Measure performance counters
  - **likwid-powermeter**: Measure energy consumption
  - **likwid-bench**: Microbenchmarking tool and environment
  - … some more



Reporting topology

likwid-topology

Output of `likwid-topology -g`

on one node of Intel Haswell-EP

```
--------------------------------------------------------------------------------
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

```
********************************************************************************
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 of likwid-topology continued

Cluster on die 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  | |
| +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ |
| |  256kB | |  256kB | |  256kB | |  256kB | |  256kB | |  256kB | |  256kB | |  256kB | |  256kB | |  256kB | |  256kB | |  256kB | |  256kB | |  256kB | |
| +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ +--------+ |
| +-------------------------------------------------------------------------+ +-------------------------------------------------------------------------+ |
| |                                  17MB                                   | |                                  17MB                                   | |
| +-------------------------------------------------------------------------+ +-------------------------------------------------------------------------+ |
+-----------------------------------------------------------------------------------------------------------------------------------------------------------------------+
```

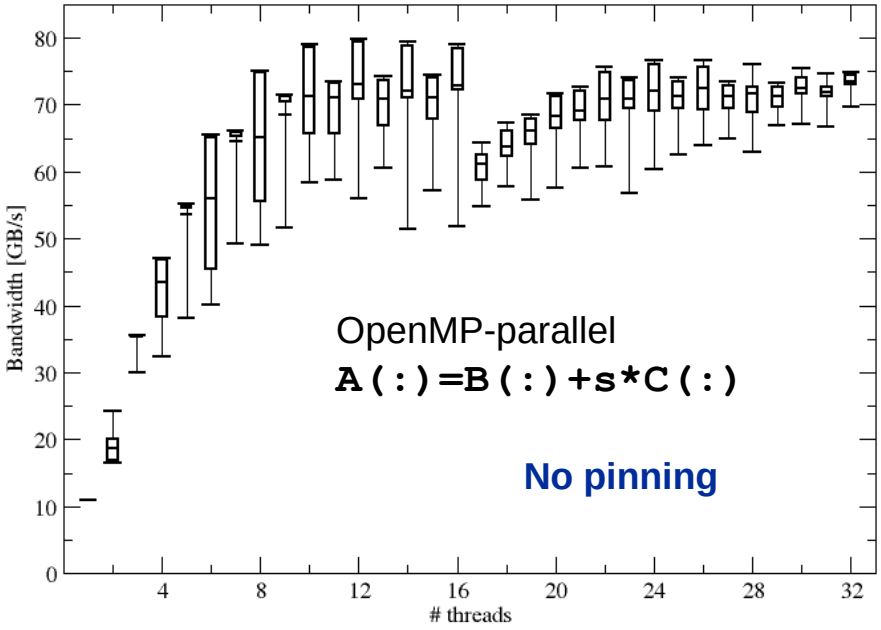
Enforcing thread/process-core affinity under the Linux OS

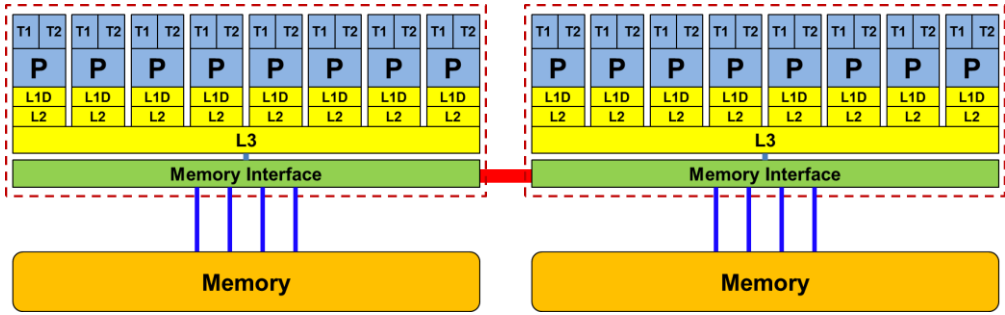
The case for enforcing affinity

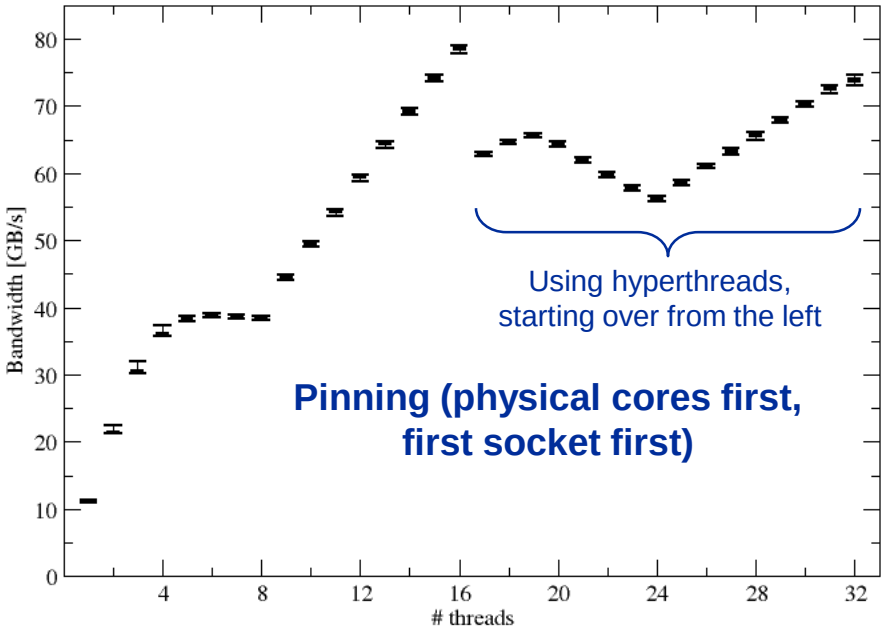
likwid-pin

Standard OpenMP affinity mechanism

Example: 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**

More thread/Process-core 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 in some compilers/environments**
  - All modern compilers with OpenMP support
  - Generic Linux: **`taskset`**, **`numactl`**, **`likwid-pin`** (see below)
  - OpenMP 4.0 (**`OMP_PLACES`**, **`OMP_PROC_BIND`**)
- **Affinity awareness in MPI libraries**
  - OpenMPI
  - Intel MPI
  - …

Likwid-pin

Overview

- 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!
- Can also be used as a superior replacement for taskset
- Supports logical core numbering within a node

- 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 parameters`

- Simple usage with logical core IDs (“thread groups”):
  - `likwid-pin -c S0:0-7  ./myApp parameters`
  - `likwid-pin -c C1:0-2 ./myApp parameters`

Likwid

Currently available thread domains

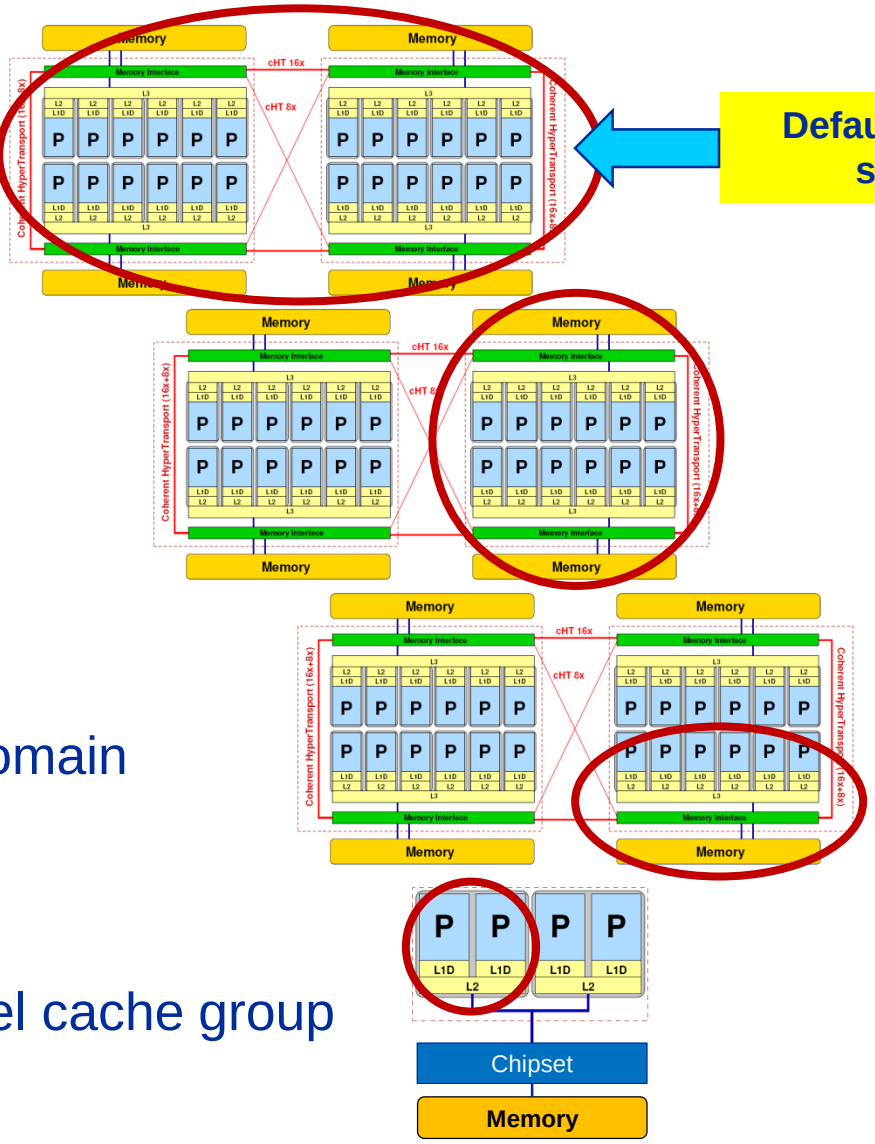
- Possible unit prefixes

N node

S socket

M NUMA domain

C outer level cache group



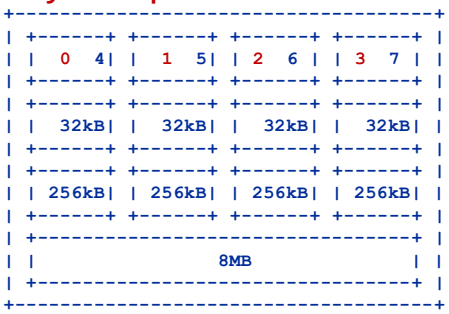
LIKWID terminology
Thread group syntax

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

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

- Example for likwid-pin:
  `likwid-pin -c S1:0-3,6,7 ./a.out`

Physical processors first!



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

Running the STREAM benchmark with likwid-pin:

```
$ likwid-pin -c S0:0-3 ./stream
[likwid-pin] Main PID -> core 0 - OK
-------------------------------------------------
 Double precision appears to have 16 digits of accuracy
 Assuming 8 bytes per DOUBLE PRECISION word
-------------------------------------------------
 Array size =   20000000
 Offset     =         32
 The total memory requirement is  457 MB
 You are running each test  10 times
 --
 The *best* time for each test is used
 *EXCLUDING* the first and last iterations
[pthread wrapper] [pthread wrapper] PIN_MASK: 0->1  1->2  2->3
[pthread wrapper] SKIP MASK: 0x1
        threadid 140370139711232 -> SKIP
        threadid 140370117211968 -> core 1 - OK
        threadid 140370113013632 -> core 2 - OK
        threadid 140369974597568 -> core 3 - OK

  [... rest of STREAM output omitted ...]
```

Main PID always pinned

Skip shepherd thread (if present)

Pin all spawned threads in turn

OMP_PLACES and Thread Affinity

A *place* consists of one or more *processors*.
Pinning is done on the level of *places*.
Free migration of the threads on a place between the *processors* of that place.

processor is the smallest unit to run a thread or task

- **`OMP_PLACES=threads`** *abstract_name*
  - Each place corresponds to the single processor of a single hardware thread (hyper-thread)
- **`OMP_PLACES=cores`**
  - Each place corresponds to the processors (one or more hardware threads) of a single core
- **`OMP_PLACES=sockets`**
  - Each place corresponds to the processors of a single socket (consisting of all hardware threads of one or more cores)
- **`OMP_PLACES=`*abstract_name(num_places)***
  - In general, the number of places may be explicitly defined

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

- **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"`**

OMP_PROC_BIND variable / proc_bind() clause

- 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

- 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
```

Clock speed under the Linux OS

likwid-powermeter

likwid-setFrequencies

Which clock speed steps are there?

likwid-powermeter

Uses the Intel RAPL (Running average power limit) 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
```

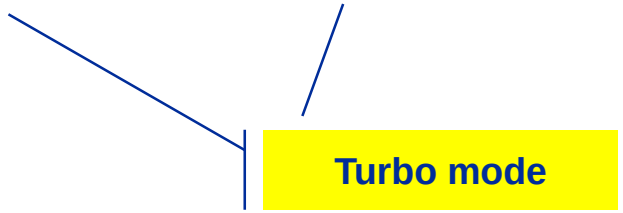
Likwid-powermeter can also measure energy consumption,
but likwid-perfctr can do it better (see later)

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 2.301
$ 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
$
```



Uncore clock frequency

Starting with Intel Haswell, the Uncore (L3, memory controller, UPI) sits in its own clock domain

```
$ likwid-setFrequencies -p
[...]
CPU 68: governor  performance min/cur/max 2.3/2.301/2.301 GHz Turbo 1
CPU 69: governor  performance min/cur/max 2.3/2.301/2.301 GHz Turbo 1
CPU 70: governor  performance min/cur/max 2.3/2.301/2.301 GHz Turbo 1
CPU 71: governor  performance min/cur/max 2.3/2.301/2.301 GHz Turbo 1

Current Uncore frequencies:
Socket 0: min/max 1.2/3.0 GHz
Socket 1: min/max 1.2/3.0 GHz

$ likwid-setFrequencies --umin 2.3 --umax 2.3
```

- Uncore has considerable impact on power consumption
  - J. Hofmann et al.: *An analysis of core- and chip-level architectural features in four generations of Intel server processors*. Proc. ISC High Performance 2017. DOI: 10.1007/978-3-319-58667-0_16.
  - J. Hofmann et al.: *On the accuracy and usefulness of analytic energy models for contemporary multicore processors*. Proc. ISC High Performance 2018. DOI: 10.1007/978-3-319-92040-5_2