

OpenMP Threads Affinity

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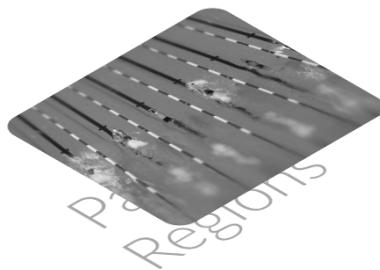
“Foundation of HPC” course



DATA SCIENCE &
SCIENTIFIC COMPUTING
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OpenMP Outline



Advanced
Parallelism



NUMA
AWARENESS



NUMA Outline

OpenMP



- The problem: “Where? Who? What?”
- Touch-first and touch-by-all policy
- Threads affinity

Remind: get back to [The typical NUMA architecture](#)



| Where do the threads run ?



As we have seen when we discussed the modern architectures, a unique central memory with a fixed bandwidth would be a major bottleneck in a system with a fast growing number of cores/sockets and sockets.

The problem is avoided by physically disjointing the memory in separated units (*the memory banks*) each of which is connected to a socket; All the sockets are inter-connected so that each core can access all the memory and a cache-coherency system “glues” the data.

This way, the resulting aggregated bandwidth scales as the number of sockets (although, we know, the cache-coherency becomes the new limiting factor).

However, the major drawback is that the access time is no more uniform. This has severe consequences on how you have to write and run your codes.



| Where do the threads run ?



OpenMP and the OS offer the capability to decide where each thread have to run, i.e. on which core and/or how the threads have to distribute on the available cores.

We know that each core may have the capability of running more than one thread, which is called (*) Simultaneous MultiThreading (SMT).

In the next slides, let's call *strands* or *hwthreads* (hardware threads) the different threads that a physical core could run, as opposed to "swthreads" (software threads) that indicates the OpenMP threads.

The placement of OpenMP threads on cores is called “threads affinity”.

(*)The Hyper-Threading is the proprietary technology, and trademark, of Intel's SMT



| Threads affinity



The *Threads affinity* is defined as the mapping of the threads on the underlying cores. The goal is to maximize the efficiency of the memory access on a strongly hierarchical memory system.

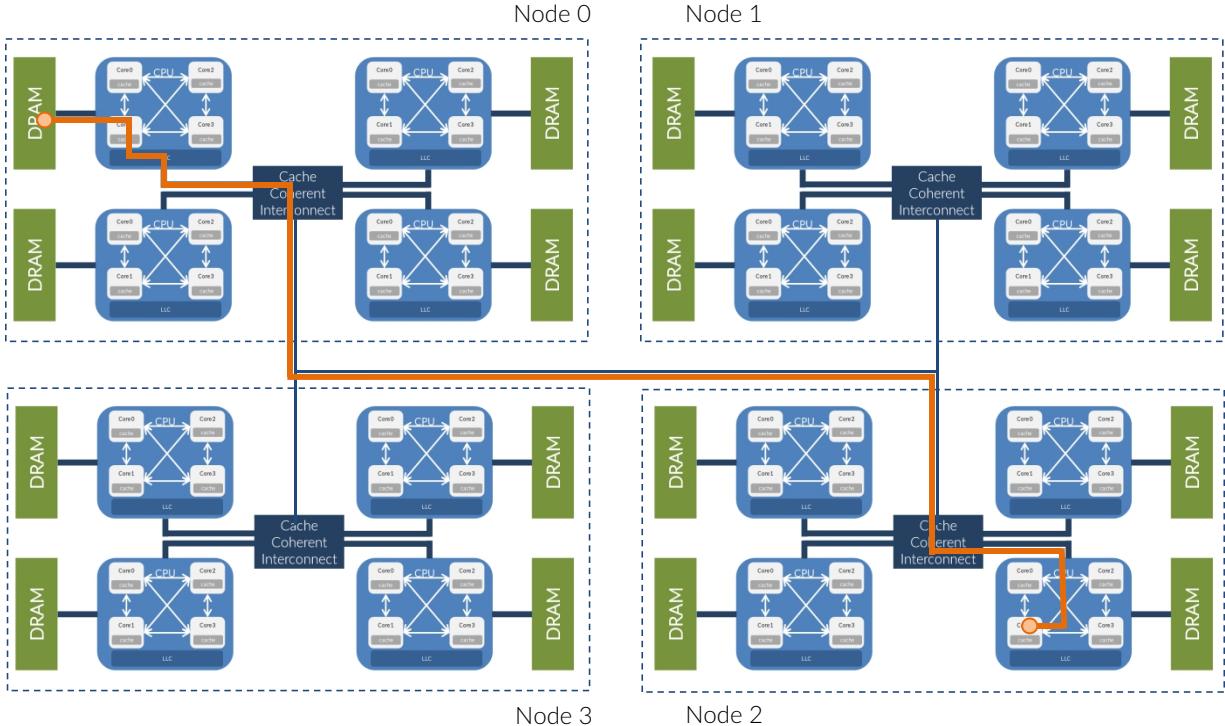
As usual, what “efficient” is depends on the details of each specific case.

For instance, if n threads work on shared data, it would be more efficient if they share the L2 cache – or in other words, they run on the same socket – so that frequently used data are at hands for all of them.

Conversely, if n threads work on independent memory segments, the most efficient choice is to maximize the memory bandwidth over the shortest core-to-ram path.



Where? Who? What?



The aim is to have as few *remote memory accesses* as possible. That depends on

- **Where:** i.e. in what memory bank the data are;
- **Who:** is accessing them, i.e. which thread → how are the threads distributed on the cores;
- **What:** how is the work-load distributed among the threads;



In principle, you want to be able to distribute the work in an optimal way, i.e. without any resource (computational power, caches and memory) contention.

To do that, you must be able to place each OpenMP *swthread* to a dedicated computational resource, and to grant it the fastest possible access to “its own” data.

So, you need to:

- explicitly bind the threads to “cores”, i.e. *hwthreads*
- explicitly allocate memory on the best suited physical memory
- minimize the remote memory access
- In case, to migrate memory and/or *swthreads* to one NUMA node to another, or to one *hwthreads* to another respectively



What is the “optimal” way to place the swthreads in a node depends on the nature of the algorithm and the data you are dealing with.

Having the swthreads “**distant**” from each other:

- may increase the aggregate bandwidth – i.e. each hwthread could fully exploit its available bandwidth – if the data are placed accordingly;
- may result in a better utilization of each core’s cache, because it would be reserved to a single swthread’s data;
- may worsen the performance of synchronization constructs.
- may dispel the cache advantage if the swthreads are reading the same data

Symmetrically, having the swthreads “**close**” to each other:

- may decrease the latency of synchronization constructs;
- may decrease the aggregated bandwidth;
- may worsen/enhance the cache performance depending on what operations are performed on the data.



| Threads affinity



OpenMP offers 2 basic concepts to set and control the affinity:



PLACES

i.e. to what physical entities (*hwthread*) we are referring to with our affinity request: “where” the threads run.

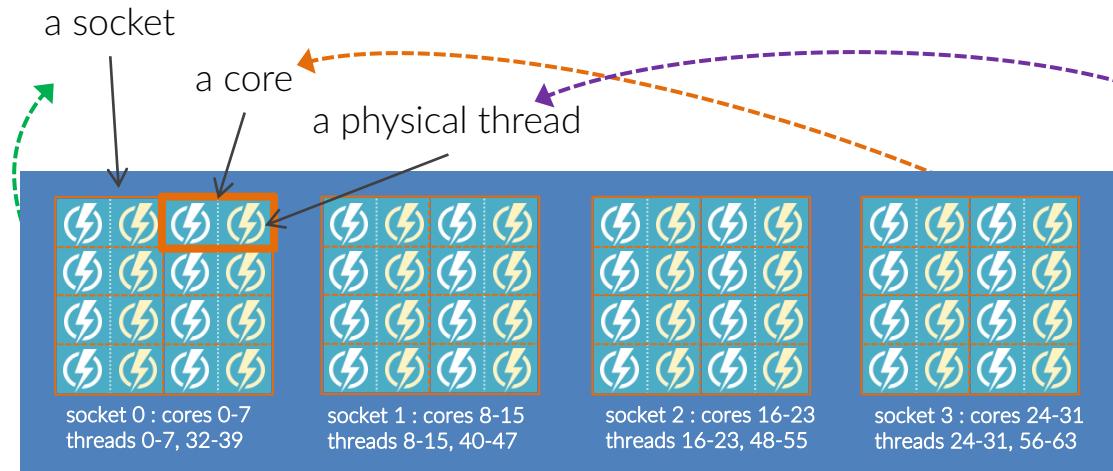


BINDING

i.e. whether there is some request about the relationship between threads and PLACES (in other words: between swthreads and hwthreads), and what that request is.



Threads affinity - PLACES



A typical example of configuration for a multicore, multisocket node: 4 sockets, each with 8 cores, each with 2 hwthreads.

Physical threads are exposed as “cores”, numbered in a round robin fashion.

PLACES are where swthreads run.

The names for PLACES are:

- **THREADS** each place corresponds to a hwthread, or strand, on cores
- **CORES** each place corresponds to a single core (which may have more strands) on sockets
- **SOCKETS** each place corresponds to a physical socket, with its multiple cores



Threads affinity - examples



Architecture: x86_64
CPU op-mode(s): 32-bit, 64-bit
Byte Order: Little Endian
CPU(s): 96
On-line CPU(s) list: 0-95
Thread(s) per core: 2
Core(s) per socket: 12
Socket(s): 4
NUMA node(s): 4
Vendor ID: GenuineIntel
CPU family: 6
Model: 85
Model name: Intel(R) Xeon(R) Gold 5118 CPU @ 2.30GHz
Stepping: 4
CPU MHz: 1000.073
CPU max MHz: 3200.0000
CPU min MHz: 1000.0000
BogoMIPS: 4600.00
Virtualization: VT-x
L1d cache: 32K
L1i cache: 32K
L2 cache: 1024K
L3 cache: 16896K
NUMA node0 CPU(s): 0-11,48-59
NUMA node1 CPU(s): 12-23,60-71
NUMA node2 CPU(s): 24-35,72-83
NUMA node3 CPU(s): 36-47,84-95

First hardware threads on sockets.
Do exist also when SMT is switched off

Second hardware threads.
Depends on SMT being active

Socket 0

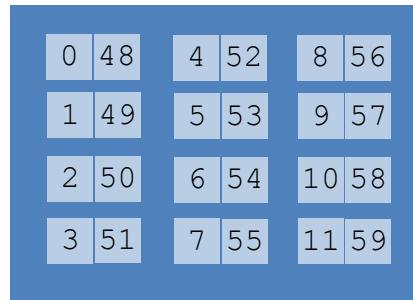
Socket 1

Socket 2

Socket 3

The following examples will refer to a node like the one reported here on the left:

4 sockets
12 cores / socket
2 hwthreads / core





| Threads affinity - examples



0 48	4 52	8 56
1 49	5 53	9 57
2 50	6 54	10 58
3 51	7 55	11 59

Socket 0

12 60	16 64	20 68
13 61	17 65	21 69
14 62	18 66	22 70
15 63	19 67	23 71

Socket 1

24 72	28 76	32 80
25 73	29 77	33 81
26 74	30 78	34 82
27 75	31 79	35 83

Socket 2

36 84	40 88	44 92
37 85	41 89	45 93
38 86	42 90	46 94
39 87	43 91	47 95

Socket 3

On a node the computational resources are identified as the physical threads numbered in a round-robin way.

If there are n_{sockets} with $n_{\text{cores-per-socket}}$ then there are

$$n_{\text{cores}} = n_{\text{sockets}} \times n_{\text{cores-per-socket}}$$

$$n_{\text{threads}} = n_{\text{cores}} \times n_{\text{SMT-threads}}$$

The n_{threads} are the computational resources available on the node; in the following examples we do refer to these IDs



| Threads affinity - examples



To clarify the numbering: if the same system shown in the previous slide had $n_{SMT\text{-}threads} = 4$ instead of 2 the numbering would have been as in the right instead of as in the left, here below.

SMT 2

NUMA node0 CPU(s) : 0-11, 48-59

NUMA node1 CPU(s) : 12-23, 60-71

NUMA node2 CPU(s) : 24-35, 72-83

NUMA node3 CPU(s) : 36-47, 84-95

SMT 4

NUMA node0 CPU(s) : 0-11, 48-59, 96-107, 144-155

NUMA node1 CPU(s) : 12-23, 60-71, 108-119, 156-167

NUMA node2 CPU(s) : 24-35, 72-83, 120-131, 168-179

NUMA node3 CPU(s) : 36-47, 84-95, 132-143, 180-191



| Threads affinity - PLACES



A “place” can be defined by an **unordered** set of comma-separated non-negative numbers enclosed in braces (*the numbers are the IDs of the smallest unit of execution on that hardware, a hwthread*).

“unordered” means that the OS and OpenMP are free to use all the resources specified in the set without any specific priority.

- | | |
|--------------------|--|
| { 0, 1 } | this defines a place made by hwt 0 and hwt 1
<i>in the frame of the previous examples, these are the hwt on core 0 and core 1 of socket 0</i> |
| { 0, 48 } | this defines a place made by hwt 0 and hwt 48
<i>in the frame of the previous examples, these are the hwt and the SMT hwt on core 0 of socket 0</i> |
| { 0, 12, 24, 36 } | this defines a place made by hwt 0, 12, 24, 36
<i>in the frame of the previous examples, these are the hwt on cores 0 of sockets 0, 1, 2 and 3</i> |
| { 0,1 }, { 1 ,49 } | A list with two places |



| Threads affinity - PLACES



OMP_PLACES can be defined as an explicit **ordered** list of comma-separated places (see the previous slide for a definition of “places”).

Intervals can also be used, specified as `start:counter:stride` which results in the serie

`start, start+stride, start + 2×stride, ..., start + (counter-1)×stride`

`OMP_PLACES =
{ 0, 48 }, {1, 49}`

sets OMP_PLACES to 2 places
in the frame of the previous examples, these are the hwt and SMT hwt on cores 0 and 1, respectively, of socket 0

`OMP_PLACES =
{ 0:2:48}, {1:2:48}`

the same than previous line

`OMP_PLACES =
{ 0, 12, 24, 36 }`

SET OMP_PLACES to 1 place
in the frame of the previous examples, these are the hwt on cores 0 of sockets 0, 1, 2 and 3

`OMP_PLACES =
{ 0:4:12 }`

the same than previous line



Other examples of places definition by intervals:

{ 0 }:4:12 → { 0 }, { 12 }, { 24 }, { 36 }

$\{ O:4:1 \}:4:12 \rightarrow \{ 0,1,2,3 \}, \{ 12,13,14,15 \}, \{ 24,25,26,27 \}, \{ 36,37,38,39 \}$

$$\{0:4\}:4:4 \rightarrow \{0,1,2,3\}, \{4,5,6,7\}, \{8,9,10,11\}, \{12,13,14,15\}$$

$$\{0:4\}, \{4:4\}, \{8:4\}, \{12:4\}$$

{ 0:12 }:4:12 → Equivalent to OMP_PLACES=sockets on a system with 4 sockets with 12 cores each

The ! Operator can be used to exclude intervals.

The places are *static*: there is no way to change it while the program is running. If some of the specified places is not available, the behaviour is implementation dependent.



| Threads affinity - PLACES



HOW TO PASS TO OPENMP YOUR PLACES DEFINITION:

through the env. variable **OMP_PLACES**

```
:> export OMP_PLACES = { sockets | cores | threads }

:> export OMP_PLACES = "{0}:4:12"

:> export OMP_PLACES = "{0:11,48:11},{24:12,72:12}"
```



| Threads affinity - PLACES



RESUMÉ:

We have just learnt how to define the *places* the swthreads will run during execution.

Each place is composed by 1 or more physical resources that are pretty equivalent from the point of view of the OS or OpenMP (i.e. all the resources in a place are equivalently good/"legal" for the placement of a swthread).

The next fundamental question is how the swthreads are placed among the available places ?

That is decided upon the **threads affinity policy**, which is defined through the "thread binding" on places: once the destination place for running has been decided, the swthreads are not allowed to move out of that place (it may be rescheduled on a different resource in the same place, but still in the same place)



| Threads affinity - BINDING



The **BINDING** defines how the swthreads are mapped onto the **PLACES**.

The names for BINDING are listed here on the right

- **NONE** the placement is up to the OS
- **CLOSE** the swthreads are placed onto places as close as possible to each other (assigned to consecutive places in a round-robin way)
- **SPREAD** the swthreads are placed onto places as evenly as possible, then the places are filled in a round-robin fashion
- **MASTER** the swthreads run onto the same place than master thread



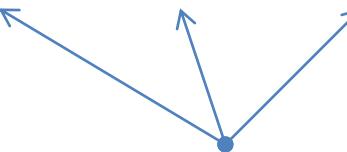
HOW TO PASS TO OPENMP YOUR BINDING REQUEST:

(1) through the env. variable **OMP_PROC_BIND**

```
:> export OMP_PROC_BIND = { false | true | master | close | spread }
```

this amounts to ask no policy (i.e. "none"), so that the O.S. will decide the placement, and to allow the O.S. to migrate the threads.

this amounts to ask no policy (i.e. "none"), so that the O.S. will decide the placement, BUT forbid the O.S. to migrate the threads.



these 3 options amount to ask a precise policy and forbid the O.S. to migrate the threads.



(2) The binding can be specified in a non-persistent way for each parallel region *inside* the code:

```
#pragma omp parallel proc_bind(policy)
```

Once a swthread has been assigned to a hwthread, it is not allowed to migrate. If you have *nested parallelism*, you may define different behaviour for the nested regions

```
#pragma omp parallel proc_bind(spread)
{
    #pragma omp parallel for proc_bind(close)
    for ( int ii = 0; ii < local_N; ii++ )
}
```



- $T \leq P$: there are sufficient places for a unique assignment.
swthreads are assigned to consecutive places by their thread ID.
The first place is the master's place.
“consecutive” must be intended in physical sense, so that if the places is “threads” the hwthreads on a same core are the closest to each other.

CLOSE

- $T > P$: at least one place executes more than one swthread.
swthread are splitted in P subsets St_i , so that

$$\text{floor}(T/P) \leq St_i \leq \text{ceiling}(T/P)$$

St_0 includes swt 0 and is assigned to the master's place.



| Threads affinity - BINDING



- $T \leq P$: place list is splitted in τ subpartitions; each subpartition contains at least $\text{floor}(P/T)$ and at most $\text{ceiling}(P/T)$ consecutive places. A thread is then assigned to a subpartition, starting from the master thread. Then, assignment proceeds by thread ID, and the threads are placed in the first place of the next subpartition.

SPREAD

- $T > P$: place list is splitted in P subpartitions, each of which contains only 1 place and st_i threads with consecutive IDs. The number of threads st_i in each subpartition is chosen so that:
$$\text{floor}(T/P) \leq st_i \leq \text{ceiling}(T/P)$$
At least one place has more than one thread assigned to it. The first subset with st_0 contains thread 0 and runs on the place that hosts the master thread.



Threads affinity - examples



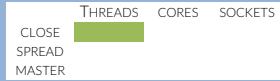
places binding	THREADS	CORES	SOCKETS
CLOSE	swt are placed on close hwt, saturating all the SMT hwt in each core before using new cores	swt are placed on close hwt, using 1 hwt/core before starting to use SMT	swt are placed round-robin per socket, 1/core; after saturation, SMT is used by round-robin +1 hwt/socket
SPREAD	swt are placed round-robin sockets, onto free cores in sockets	similar to ← SMT is avoided until saturation	similar to ← swt are placed by round-robin sockets and hwt
MASTER	all swt are placed on the same hwt on the same core on the same socket	all swt are placed on the same core on the same socket, using all its hwt	all swt are placed on the same socket, saturing all hwt starting from SMT ones

Using the **abstract names** for places

note:
swt = software threads
hwt = hardware threads



| Threads affinity - examples



OMP_PLACES = threads
OMP_PROC_BIND = close

There are 96 places.
swt are placed on close hwt, saturating
all the siblings SMT hwt in each core
before using new cores

4 swthreads

0 48	4 52	8 56
1 49	5 53	9 57
2 50	6 54	10 58
3 51	7 55	11 59

Socket 0

7 swthreads

0 48	4 52	8 56
1 49	5 53	9 57
2 50	6 54	10 58
3 51	7 55	11 59

Socket 0

18 swthreads

0 48	4 52	8 56
1 49	5 53	9 57
2 50	6 54	10 58
3 51	7 55	11 59

Socket 0

25 swthreads

12 60	16 64	20 68
13 61	17 65	21 69
14 62	18 66	22 70
15 63	19 67	23 71

Socket 1 (SO saturated)



| Threads affinity - examples



```
OMP_PLACES = threads  
OMP_PROC_BIND = close
```

There are 96 places.
swt are placed on close hwt, saturating
all the siblings SMT hwt in each core
before using new cores

4 swthreads

	hwthreads	swthreads
node 0	00-11 , 48-59	0,48,1,49 ●●○○
node 1	12-23 , 60-71	
node 2	24-35 , 72-83	
node 3	36-47 , 84-95	

swthreads places are reported by ID order.

- means hwthread
 - means SMT hwthread

7 swthreads

	hwthreads	swthreads
node 0	00-11 , 48-59	0,48,1,49,2,50,3 ●●●●○○○
node 1	12-23 , 60-71	
node 2	24-35 , 72-83	
node 3	36-47 , 84-95	

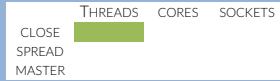
18 swthreads

	hwthreads	swthreads
node 0	00-11 , 48-59	0,48,1,49,2,50, 3,51,4,52,5,53, 6,54,7,55,8,56
node 1	12-23 , 60-71	
node 2	24-35 , 72-83	
node 3	36-47 , 84-95	





| Threads affinity - examples



OMP_PLACES = threads
OMP_PROC_BIND = close

There are 96 places.
swt are placed on close hwt, saturating
all the siblings SMT hwt in each core
before using new cores

25 swthreads

	hwthreads	swthreads
node 0	00-11 , 48-59	SATURATED
node 1	12-23 , 60-71	12 ●
node 2	24-35 , 72-83	
node 3	36-47 , 84-95	

50 swthreads

	hwthreads	swthreads
node 0	00-11 , 48-59	SATURATED
node 1	12-23 , 60-71	SATURATED
node 2	24-35 , 72-83	24, 72 ●○
node 3	36-47 , 84-95	



| Threads affinity - examples



THREADS CORES SOCKETS

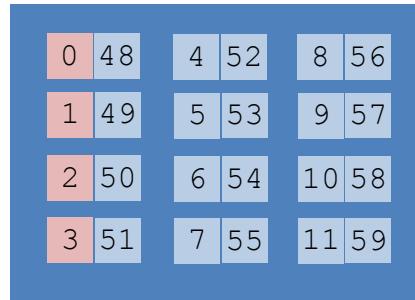
CLOSE
SPREAD
MASTER

OMP_PLACES = cores
OMP_PROC_BIND = close

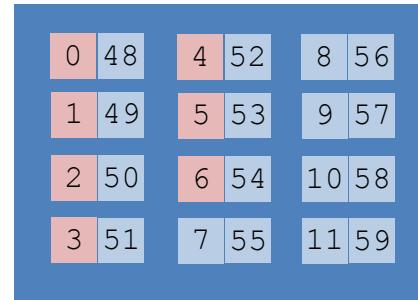
There are 48 places now.
swt are placed on close hwt, using 1
hwt/core.
When a socket is full, placement
continues with the next socket.

numa_awareness/
00_where_I_am.c

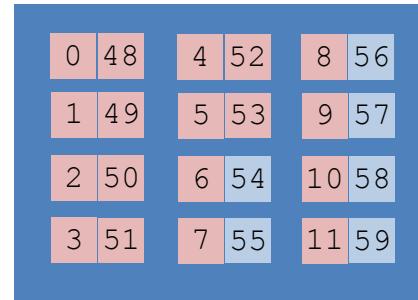
4 swthreads



7 swthreads



18 swthreads



Socket 0

Socket 0

Socket 0



| Threads affinity - examples



THREADS CORES SOCKETS
CLOSE SPREAD MASTER

OMP_PLACES = sockets
OMP_PROC_BIND = close

There are 4 places.
swt are placed round-robin per socket,
1/core; after saturation, SMT is used by
round-robin +1 hwt/socket



numa_awareness/
00_where_I_am.c

4 swthreads

0 48	4 52	8 56
1 49	5 53	9 57
2 50	6 54	10 58
3 51	7 55	11 59

Socket 0

12 60	16 64	20 68
13 61	17 65	21 69
14 62	18 66	22 70
15 63	19 67	23 71

Socket 1

24 72	28 76	32 80
25 73	29 77	33 81
26 74	30 78	34 82
27 75	31 79	35 83

Socket 2

36 84	40 88	44 92
37 85	41 89	45 93
38 86	42 90	46 94
39 87	43 91	47 95

Socket 3



| Threads affinity - examples



OMP_PLACES = sockets

OMP_PROC_BIND = close

There are 4 places.
swt are placed round-robin per socket,
1/core; after saturation, SMT is used by
round-robin +1 hwt/socket

4 swthreads

NOTE: for the sake of clarity in the previous slide we picked-up the first hwthread on each socket; however, since the place is the entire socket your threads may be placed wherever in each socket, like in this example

0 48	4 52	8 56
1 49	5 53	9 57
2 50	6 54	10 58
3 51	7 55	11 59

Socket 0

12 60	16 64	20 68
13 61	17 65	21 69
14 62	18 66	22 70
15 63	19 67	23 71

Socket 1

24 72	28 76	32 80
25 73	29 77	33 81
26 74	30 78	34 82
27 75	31 79	35 83

Socket 2

36 84	40 88	44 92
37 85	41 89	45 93
38 86	42 90	46 94
39 87	43 91	47 95

Socket 3



| Threads affinity - examples

In this case ($T=P$) the close and spread policies produce the same distribution.
To further clarify the difference between the two, let's examine the case $T < P$ with $T=2$

0 48	4 52	8 56
1 49	5 53	9 57
2 50	6 54	10 58
3 51	7 55	11 59

Socket 0

12 60	16 64	20 68
13 61	17 65	21 69
14 62	18 66	22 70
15 63	19 67	23 71

Socket 1

24 72	28 76	32 80
25 73	29 77	33 81
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27 75	31 79	35 83

Socket 2

36 84	40 88	44 92
37 85	41 89	45 93
38 86	42 90	46 94
39 87	43 91	47 95

Socket 3



| Threads affinity - examples



PLACES = sockets; BINDING = spread (two subpartitions {0,1} and {2,3}, a thread on each)

0 48	4 52	8 56
1 49	5 53	9 57
2 50	6 54	10 58
3 51	7 55	11 59

Socket 0

12 60	16 64	20 68
13 61	17 65	21 69
14 62	18 66	22 70
15 63	19 67	23 71

Socket 1

24 72	28 76	32 80
25 73	29 77	33 81
26 74	30 78	34 82
27 75	31 79	35 83

Socket 2

36 84	40 88	44 92
37 85	41 89	45 93
38 86	42 90	46 94
39 87	43 91	47 95

Socket 3

PLACES = sockets; BINDING = close (threads assigned to consecutive places by their thread id)

0 48	4 52	8 56
1 49	5 53	9 57
2 50	6 54	10 58
3 51	7 55	11 59

Socket 0

12 60	16 64	20 68
13 61	17 65	21 69
14 62	18 66	22 70
15 63	19 67	23 71

Socket 1

24 72	28 76	32 80
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Socket 2

36 84	40 88	44 92
37 85	41 89	45 93
38 86	42 90	46 94
39 87	43 91	47 95

Socket 3



| Threads affinity - examples



THREADS CORES SOCKETS
CLOSE SPREAD MASTER

OMP_PLACES = sockets
OMP_PROC_BIND = close

There are 4 places.
swt are placed round-robin per socket,
1/core; after saturation, SMT is used by
round-robin +1 hwt/socket



numa_awareness/
00_where_I_am.c

14 swthreads

0 48	4 52	8 56
1 49	5 53	9 57
2 50	6 54	10 58
3 51	7 55	11 59

Socket 0

12 60	16 64	20 68
13 61	17 65	21 69
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15 63	19 67	23 71

Socket 1

24 72	28 76	32 80
25 73	29 77	33 81
26 74	30 78	34 82
27 75	31 79	35 83

Socket 2

36 84	40 88	44 92
37 85	41 89	45 93
38 86	42 90	46 94
39 87	43 91	47 95

Socket 3



| Threads affinity - examples



OMP_PLACES = threads

OMP_PROC_BIND = spread

swt are placed round-robin sockets, onto free cores in sockets



numa_awareness/
00_where_I_am.c

4 swthreads

0 48	4 52	8 56
1 49	5 53	9 57
2 50	6 54	10 58
3 51	7 55	11 59

Socket 0

12 60	16 64	20 68
13 61	17 65	21 69
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Socket 1

24 72	28 76	32 80
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27 75	31 79	35 83

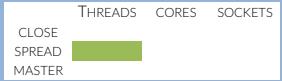
Socket 2

36 84	40 88	44 92
37 85	41 89	45 93
38 86	42 90	46 94
39 87	43 91	47 95

Socket 3



| Threads affinity - examples



OMP_PLACES = threads
OMP_PROC_BIND = spread

swt are placed round-robin sockets, onto free cores in sockets



numa_awareness/
00_where_I_am.c

14 swthreads

0 48	4 52	8 56
1 49	5 53	9 57
2 50	6 54	10 58
3 51	7 55	11 59

Socket 0

12 60	16 64	20 68
13 61	17 65	21 69
14 62	18 66	22 70
15 63	19 67	23 71

Socket 1

24 72	28 76	32 80
25 73	29 77	33 81
26 74	30 78	34 82
27 75	31 79	35 83

Socket 2

36 84	40 88	44 92
37 85	41 89	45 93
38 86	42 90	46 94
39 87	43 91	47 95

Socket 3



| Threads affinity - examples



OMP_PLACES = cores

OMP_PROC_BIND = spread



OMP_PLACES = sockets

OMP_PROC_BIND = spread

Similar to (thread, spread), just infer the differences from the [table](#) description.
And, run on your own `00_where_I_am` to check what is happening.



numa_awareness/
`00_where_I_am.c`



| Threads affinity - examples



THREADS CORES SOCKETS
CLOSE SPREAD MASTER

OMP_PLACES = threads
OMP_PROC_BIND = master

4 swthreads

• 4 swthreads are running on this same hwthread

0	48	4	52	8	56
1	49	5	53	9	57
2	50	6	54	10	58
3	51	7	55	11	59

Socket 0

12	60	16	64	20	68
13	61	17	65	21	69
14	62	18	66	22	70
15	63	19	67	23	71

Socket 1

24	72	28	76	32	80
25	73	29	77	33	81
26	74	30	78	34	82
27	75	31	79	35	83

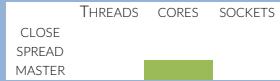
Socket 2

36	84	40	88	44	92
37	85	41	89	45	93
38	86	42	90	46	94
39	87	43	91	47	95

Socket 3



| Threads affinity - examples



OMP_PLACES = cores

OMP_PROC_BIND = master

4 swthreads

2 swthreads are running on each of these 2 hwthreads

0	48	4	52	8	56
1	49	5	53	9	57
2	50	6	54	10	58
3	51	7	55	11	59

Socket 0

12	60	16	64	20	68
13	61	17	65	21	69
14	62	18	66	22	70
15	63	19	67	23	71

Socket 1

24	72	28	76	32	80
25	73	29	77	33	81
26	74	30	78	34	82
27	75	31	79	35	83

Socket 2

36	84	40	88	44	92
37	85	41	89	45	93
38	86	42	90	46	94
39	87	43	91	47	95

Socket 3



| Threads affinity - examples



THREADS CORES SOCKETS
CLOSE SPREAD MASTER

OMP_PLACES = sockets
OMP_PROC_BIND = master

4 swthreads

0 48	4 52	8 56
1 49	5 53	9 57
2 50	6 54	10 58
3 51	7 55	11 59

Socket 0

12 60	16 64	20 68
13 61	17 65	21 69
14 62	18 66	22 70
15 63	19 67	23 71

Socket 1

24 72	28 76	32 80
25 73	29 77	33 81
26 74	30 78	34 82
27 75	31 79	35 83

Socket 2

36 84	40 88	44 92
37 85	41 89	45 93
38 86	42 90	46 94
39 87	43 91	47 95

Socket 3



| Threads affinity - examples



THREADS CORES SOCKETS
CLOSE SPREAD MASTER

OMP_PLACES = sockets
OMP_PROC_BIND = master

20 swthreads

0 48	4 52	8 56
1 49	5 53	9 57
2 50	6 54	10 58
3 51	7 55	11 59

Socket 0

12 60	16 64	20 68
13 61	17 65	21 69
14 62	18 66	22 70
15 63	19 67	23 71

Socket 1

24 72	28 76	32 80
25 73	29 77	33 81
26 74	30 78	34 82
27 75	31 79	35 83

Socket 2

36 84	40 88	44 92
37 85	41 89	45 93
38 86	42 90	46 94
39 87	43 91	47 95

Socket 3



| Threads affinity - examples



OMP_PLACES = sockets
OMP_PROC_BIND = master

35 swthreads

When all the hwthreads are saturated, more than 1 swthread is placed on hwthreads by round-robin, on the same socket

0	48	4	52	8	56
1	49	5	53	9	57
2	50	6	54	10	58
3	51	7	55	11	59

Socket 0

12	60	16	64	20	68
13	61	17	65	21	69
14	62	18	66	22	70
15	63	19	67	23	71

Socket 1

24	72	28	76	32	80
25	73	29	77	33	81
26	74	30	78	34	82
27	75	31	79	35	83

Socket 2

36	84	40	88	44	92
37	85	41	89	45	93
38	86	42	90	46	94
39	87	43	91	47	95

Socket 3



| Threads affinity



If you compile `00_where_I_am.c` with `-DSPY`, it will load the hwthreads with some amount of work so that meanwhile you can inspect what is happening by using the either the htop or the top utility:

On my laptop
using
2 swthreads { {

```
top - 14:11:56 up 5:29, 4 users, load average: 3.01, 2.10, 1.81
Threads: 899 total, 3 running, 828 sleeping, 0 stopped, 0 zombie
%Cpu0 : 16.4 us, 7.0 sy, 0.0 ni, 76.6 id, 0.0 wa, 0.0 hi, 0.0 si, 0.0 st
%Cpu1 : 100.0 us, 0.0 sy, 0.0 ni, 0.0 id, 0.0 wa, 0.0 hi, 0.0 si, 0.0 st
%Cpu2 : 100.0 us, 0.0 sy, 0.0 ni, 0.0 id, 0.0 wa, 0.0 hi, 0.0 si, 0.0 st
%Cpu3 : 9.8 us, 3.9 sy, 0.0 ni, 86.3 id, 0.0 wa, 0.0 hi, 0.0 si, 0.0 st
KiB Mem : 27.7/16241208 [███████████] 
KiB Swap: 0.0/35639292 [
```

PID	PPID	UID	USER	RUSER	TTY	TIME+	%CPU	%MEM	S	COMMAND
20037	15584	1000	luca	luca	pts/1	1:17.54	99.9	0.0	R	00_where_I_am_s
20036	15584	1000	luca	luca	pts/1	1:14.71	99.9	0.0	R	00_where_I_am_s
3271	3240	1000	luca	luca	?	5:24.05	5.3	0.7	S	kwin_x11
2660	2656	0	root	root	tty1	11:13.78	4.3	1.0	S	Xorg
4181	3223	1000	luca	luca	?	4:05.04	3.9	1.8	S	Wavebox
3279	1	1000	luca	luca	?	3:20.64	3.0	3.0	S	plasmashell



The OpenMP standard offers several `omp_` library functions to deal with the affinity.

You can study their usage in the source files that are in the `day17/examples/` folder



`numa_awareness/`
`01_where_I_am_omp.c`

Setting the affinity

`proc_bind` clause

Get the affinity

`omp_get_proc_bind()`

Get details on places

`omp_get_num_places()`

`omp_get_place_num()`

`omp_get_place_num_procs()`

`omp_get_place_proc_ids()`

Display affinity

`omp_display_affinity()`

`omp_get_affinity_format(...)`

`omp_set_affinity_format(...)`

`omp_capture_affinity(...)`



It is possible to control on what physical memory your data will reside by:

1. By carefully touching data
2. By changing default memory allocation with `numactl`
3. By explicit memory migration



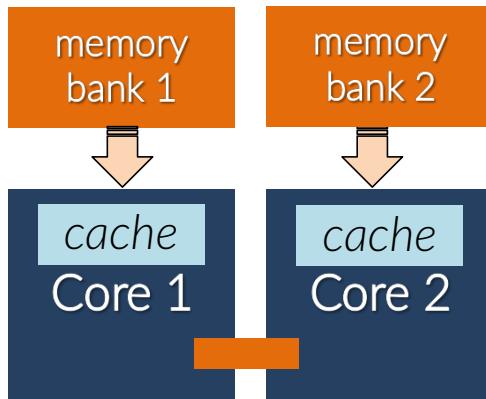
*We're **not** gonna cover this*



1. Careful data touching



“touch-first” policy



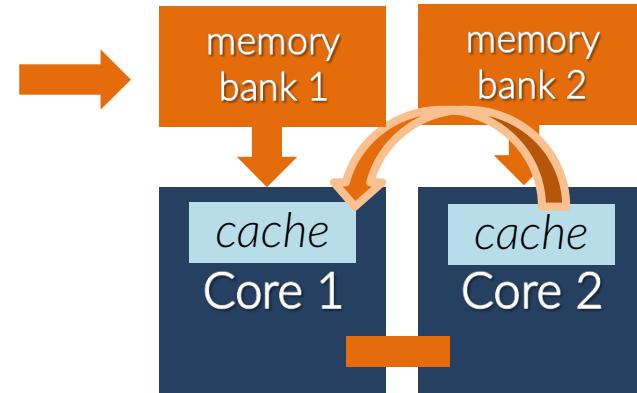
Suppose that you are operating on a SMP system similar to the one depicted here on the left.

Each socket is physically connected to a RAM bank, and then physically connected to other socket. This way, the memory access is *not uniform*: the bandwidth for a core to access a memory bank not physically connected to it is likely to be significantly smaller than that to access the closest bank.



The matter is: who “owns” the data?

```
double *a = (double*)calloc( N, sizeof(double);  
  
for ( int i = 0; ii < N; ii++ ) {  
    a[i] = initialize(i);  
  
#pragma omp parallel for reduction(+: sum)  
for ( int i = 0; i < N; i++ )  
    sum += a[i];
```



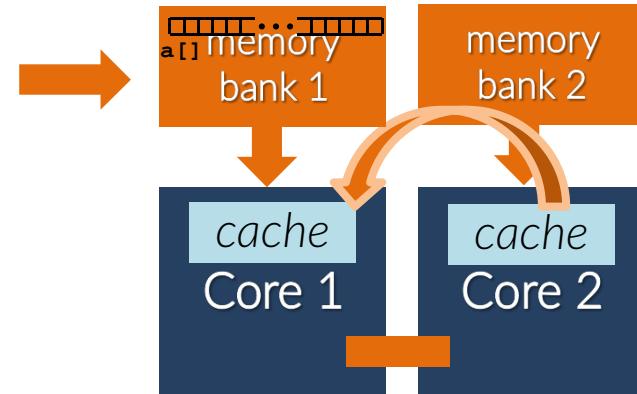
In this way, *all* the data are physically paged in the memory bank of the core on which the master thread runs; its cache is also warmed-up; the other thread must access the memory bank1 which is not the most suited for the bandwidth



“touch-first” policy

parallel_loops/
01_array_sum.c

```
double *a = (double*)calloc( N, sizeof(double);  
  
for ( int i = 0; ii < N; ii++ ) {  
    a[i] = initialize(i);  
  
#pragma omp parallel for reduction(+: sum)  
for ( int i = 0; i < N; i++ )  
    sum += a[i];
```



In this way, the cache of the thread that initialize (first touch) the data is warmed-up and the data are allocated in the memory connected to it.



“touch-first” policy



In the “touch-first” policy, the data pages are allocated in the physical memory that is the closest to the physical core which is running the thread that access the data first.

If a single thread is initializing all the data, then all the data will reside in its memory and the number of remote accesses will be maximized.



“touch-by-all” policy

The matter is: who “owns” the data?



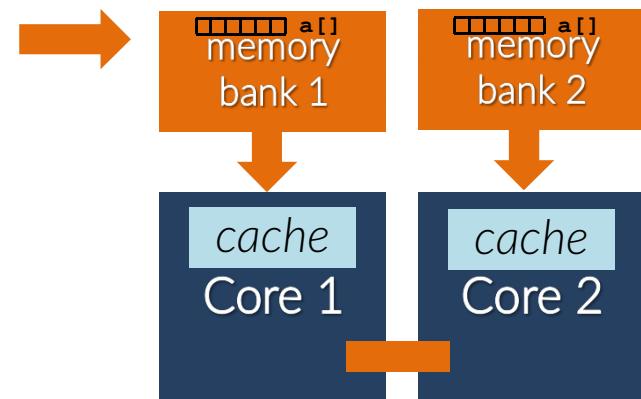
parallel_loops/
06_touch_by_all.c

```
double *a = (double*)malloc(N*sizeof(double));
```

why did I change from `calloc` to `malloc`?

```
#pragma omp parallel for
for ( int i = 0; ii < N; ii++ ) {
    a[i] = initialize(i);

#pragma omp parallel for reduction(+: sum)
for ( int i = 0; i < N; i++ )
    sum += a[i];
```



In this way, the cache of each thread is warmed-up with the data it will use afterwards **and the data are allocated into each thread's memory** (the scheduling must be the same!)



“touch-by-all” policy



The matter is: who “owns” the data?



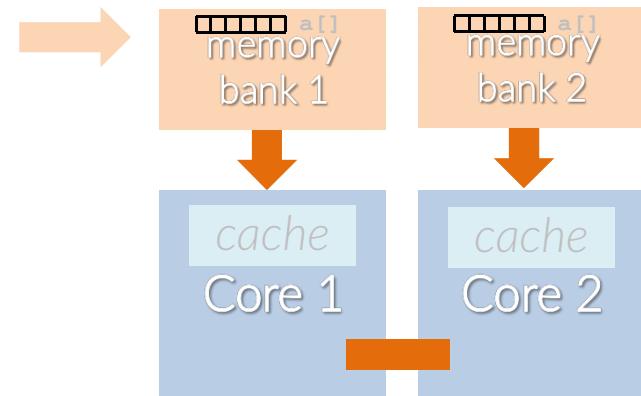
parallel_loops/
06_touch_by_all.c

```
double *a = (double*)malloc(N*sizeof(double));
```

why did I change from *calloc* to *malloc*?

```
#pragma omp parallel for
for ( int i = 0; ii < N; ii++ ) {
    a[i] = initialize(i);

#pragma omp parallel for reduction(+: sum)
for ( int i = 0; i < N; i++ )
    sum += a[i];
```



In this way, the cache of each thread is warmed-up with the data it will use afterwards and the data are allocated into each thread's memory (the scheduling must be the same!)



“touch-by-all” policy



malloc

The difference between malloc and calloc

Notifies that the required amount of memory will be used, and the memory occupancy of the process in the heap is grown accordingly.

However, the actual mapping of the memory pages into the physical memory does not happen until the pages are actually “touched” (i.e. read or written). Moreover, the mapping is done only for the touched pages, not for the entire amount of memory.

calloc

As for malloc, but with two fundamental differences:

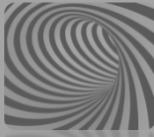
- (1) the memory is required to be *physically contiguous* (that is what the starting “c” means), and hence entirely on the same physical location;
- (2) all the memory is initialized to zero as a way to immediately “touch” it so that it is mapped onto a physical bank as soon as it is required.



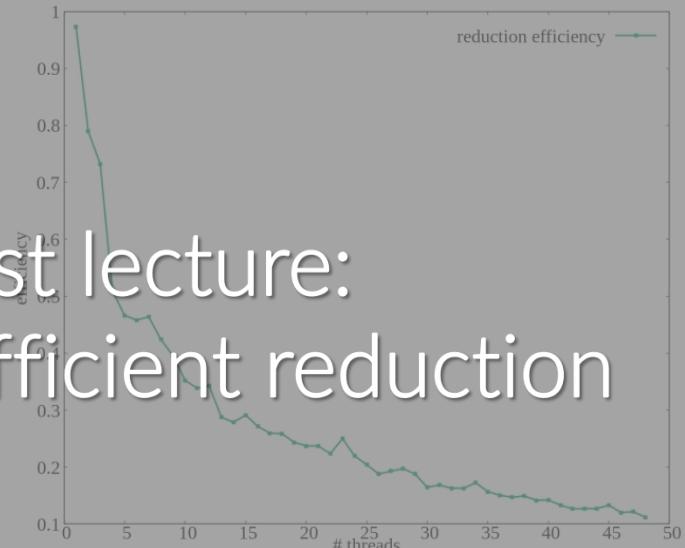
| “touch-by-all” policy



If each thread “touches” as first the data it will operate on subsequently, those data – by the “touch-first” policy – are allocated in the physical memory that is the closest.
Hence, each thread will have its data placed in the most convenient memory and the remote accesses will be minimized



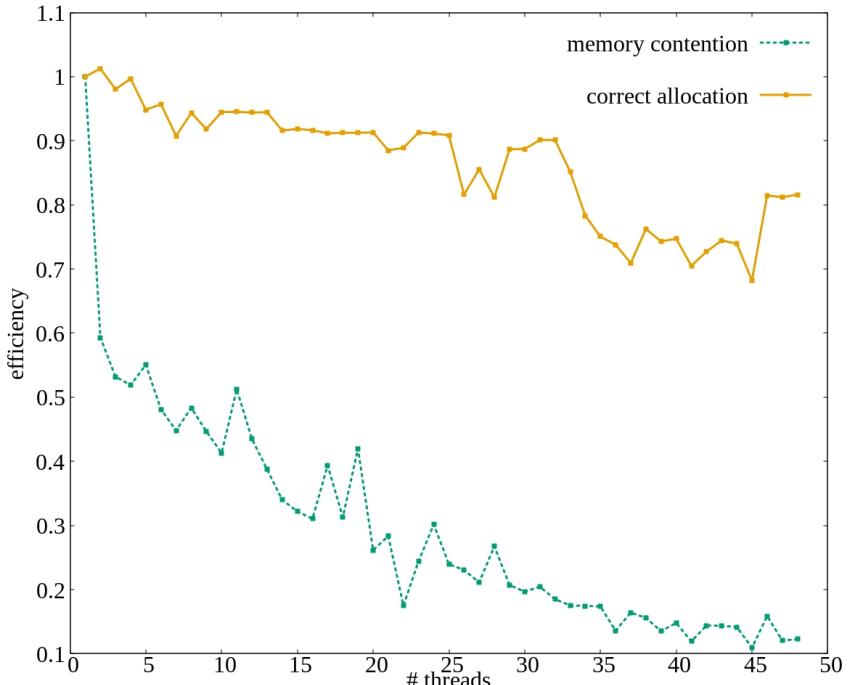
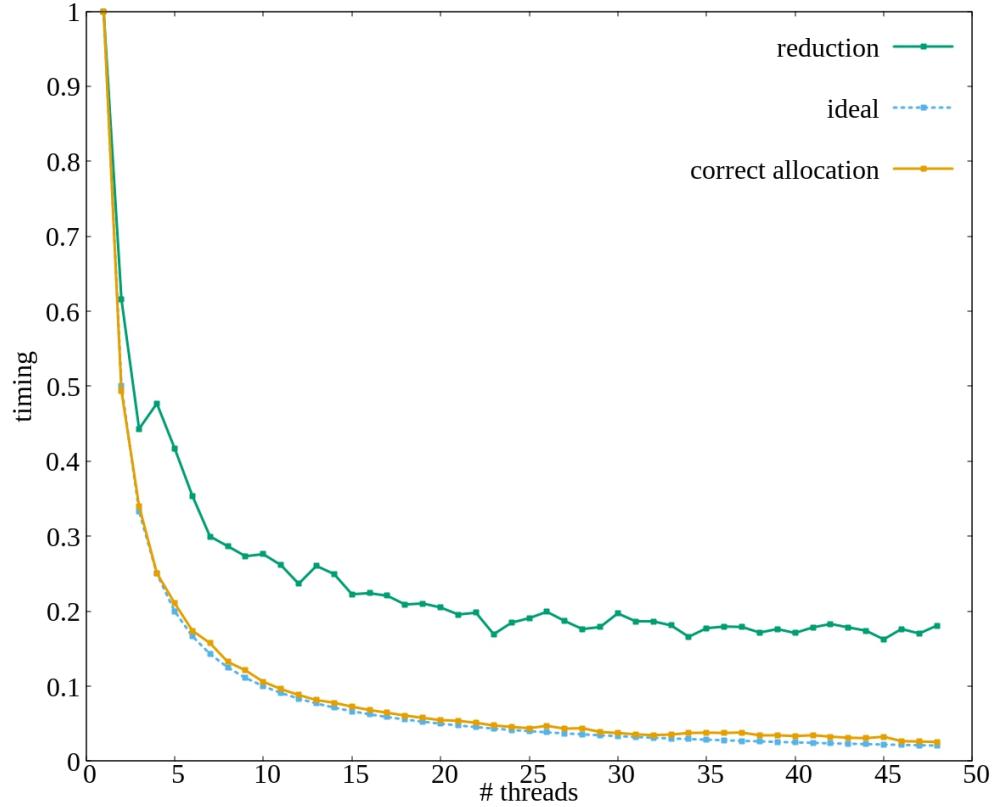
We saw this in the last lecture:
We were unable to get an efficient reduction



It seems that, after all, our reduction efficiency is very poor. Although one could conclude that OpenMP is somehow a bad affair, hidden in these plots there is a very important issue in multi-threading that we inquire in the next lectures.



“touch-by-all” policy





Discover your topology



Lots of tools are usually available on HPC platforms.

We'll see the details in the last lectures devoted to special topics

numactl numactl --hardware a summary of the topology
 this may change your general policy for membinding

lscpu

lstopo lstopo -s a summary of the topology
 lstopo -v more verbose details
 lstopo --only [core, socket, cache, pu, ..]
 check the man page.. :)

hwloc hwloc-info, hwloc-distances, hwloc-ps, hwloc-ls, ...

likwid likwid-topology [-g]
 likwid-pin <- this lets you pin your threads

/proc/cpuinfo

/sys/devices/system/



At least two handy tools:

taskset	<code>-a pid</code>	set/retrieve the CPU affinity for all the threads of a given PID
	<code>-c <mask></code>	(hexadecimal) mask for cores (both physical and logical) 0x00000001 is cpu #0 49 is cpu #0, #4 and #5
	<code>--cpu-list <list></code>	List of cores, may contain ranges 0-4,15-19 is cpu #0 to #4 and #15 to #19 0-12:2 is cpu #0, #2, #4, .. the :2 is the stride
numactl	<code>--cpunodebind n</code>	binds the execution to the NUMA nodes <i>n</i> (multiple nodes may be specified, see the man page)
	<code>--membind n</code>	binds the memory allocation to DRAM associated to NUMA nodes <i>n</i> (multiple nodes may be specified, see the man page)

that's all, have fun

"So long
and thanks
forall the fish"