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OpenMP Affinity in Many-core Computing

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IXPUG
THE INTEL® XEON PHI™ USERS GROUP

Outline

- Motivation
- Affinity -- what is it
- OpenMP Affinity
- Ways to show process masks
- Hybrid Computing
  - How it works
  - Advancing Standards

Motivation

Where do application processes execute?

- Xeon-Phi (KNL) Node: 72 Cores 288 hardware threads
- Xeon (SKL-X) Node: 2x28=56 Cores 112 hardware threads

- process count < hardware thread count
- L2/L3 cache sharing (tiles/sockets)
- Minimal Memory Distance
- Messaging/IO process near PCI-e

Motivation

Practical Consulting Question:

- Where does my master thread run?
- How are my threads assigned in a hybrid run?
- How can I pin my threads.
- ...

View Affinity

Control Affinity

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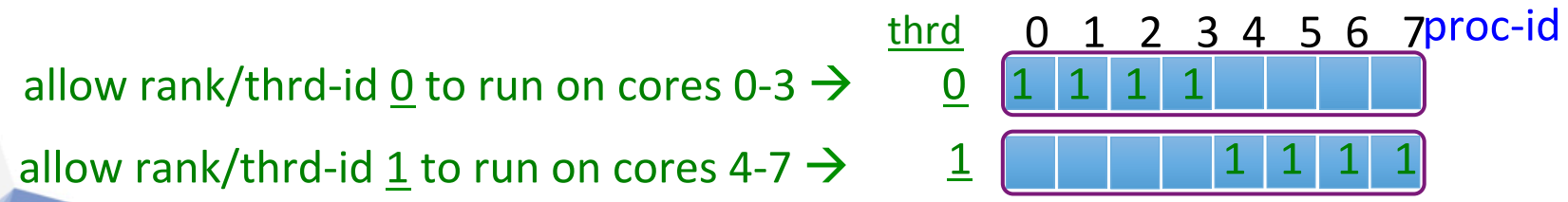
CPU Affinity -- the mask

processes map onto processors

Rank or thread-id proc-id

Each process has a bit mask: a set bit→ process can run on proc-id.

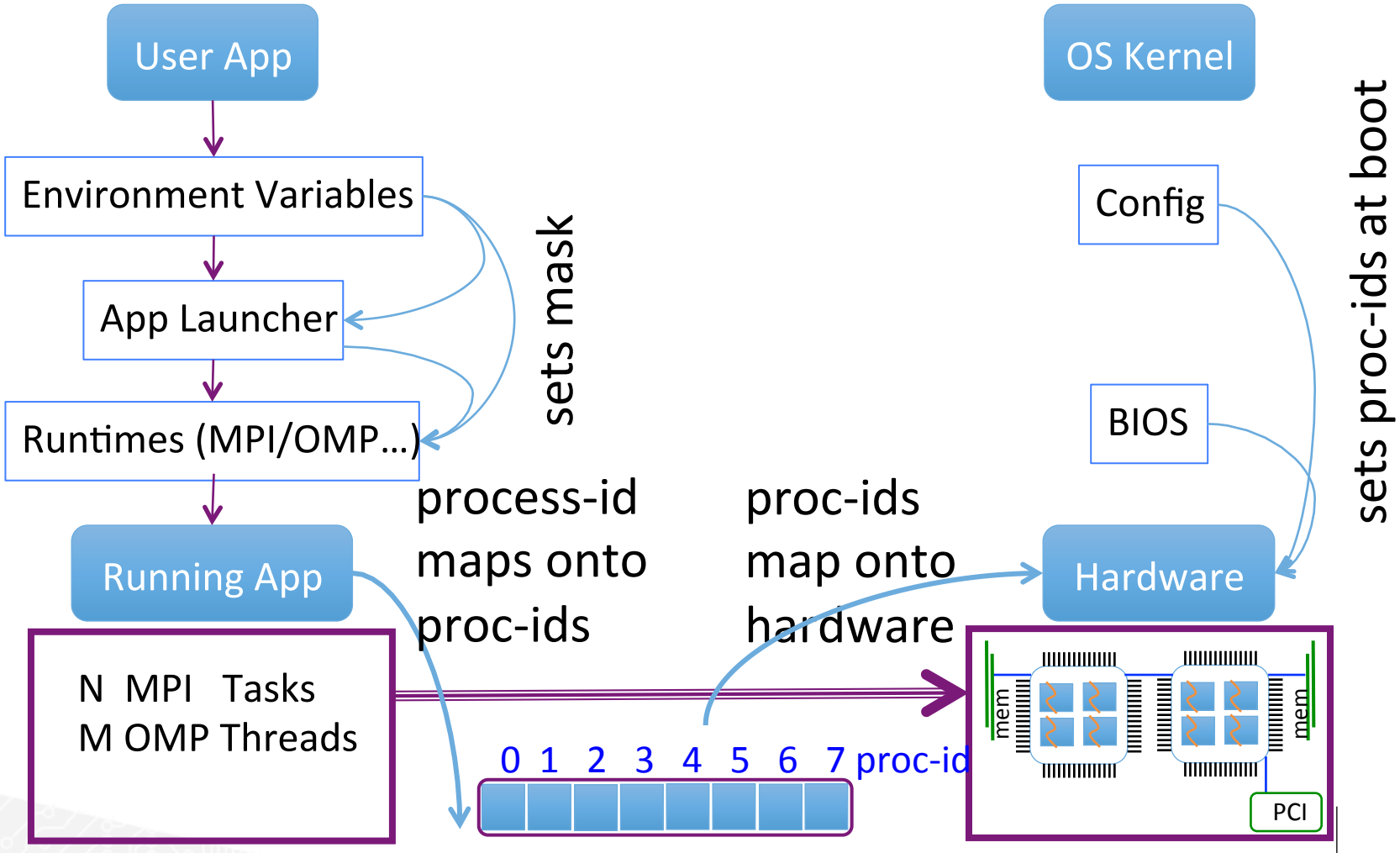


Setting Mask

The mask can be set at various places:

OpenMP Affinity
KMP Affinity
Intel/MV2 MPI

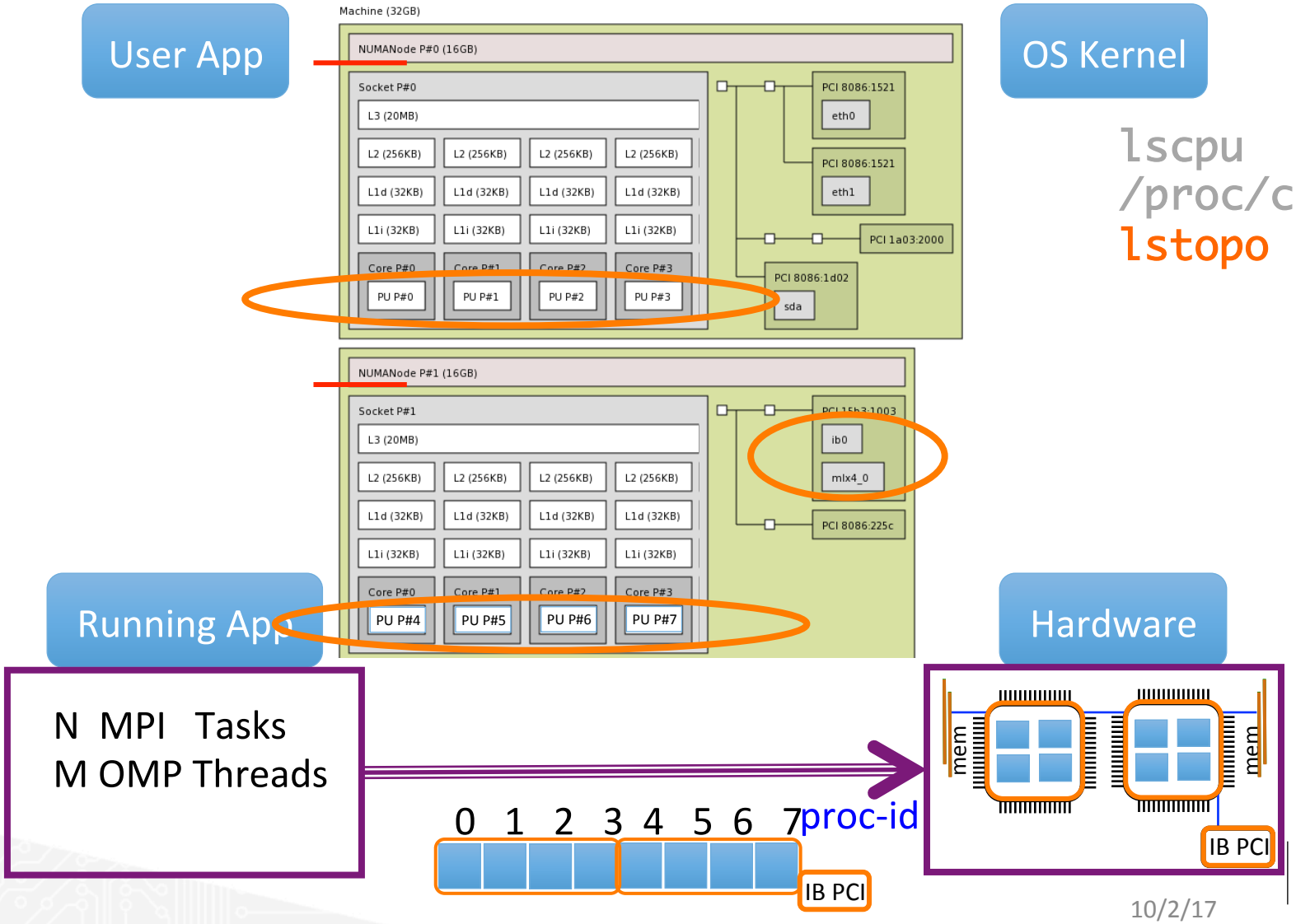
Lib/Compiler/site/
Vendor defaults



Hardware/OS Setup

Placing processes– depends on Hardware

Unix proc-id info

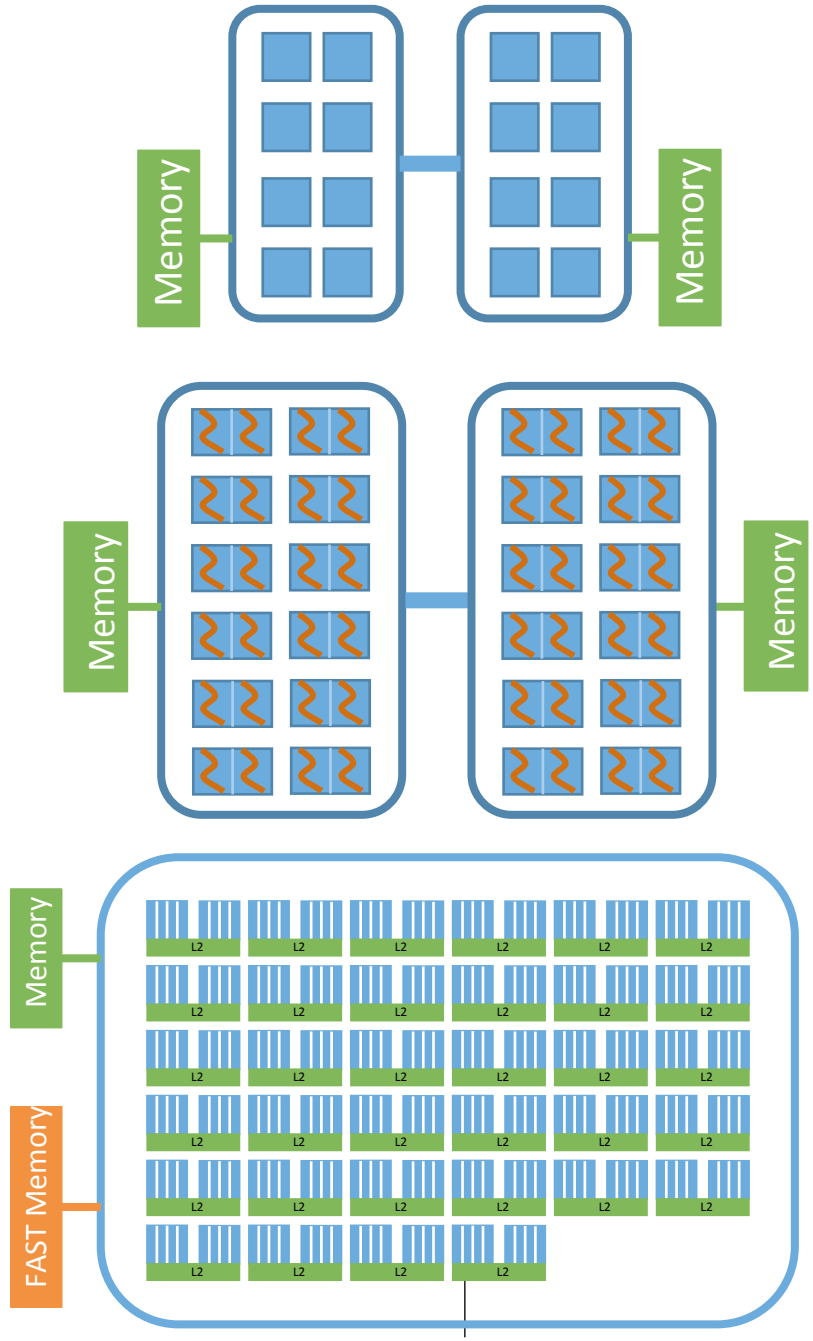


lscpu

```
sp$ lscpu | grep -i 'core\|thread\|Socket'
Thread(s) per core:    1
Core(s) per socket:    8
Socket(s):             2

ls5%  lscpu | grep -i 'core\|thread\|Socket'
Thread(s) per core:    2
Core(s) per socket:    12
Socket(s):             2

knl$ lscpu | grep -i 'core\|thread\|socket'
Thread(s) per core:    4
Core(s) per socket:    68
Socket(s):             1
```



proc-id #'s in /cpu/info

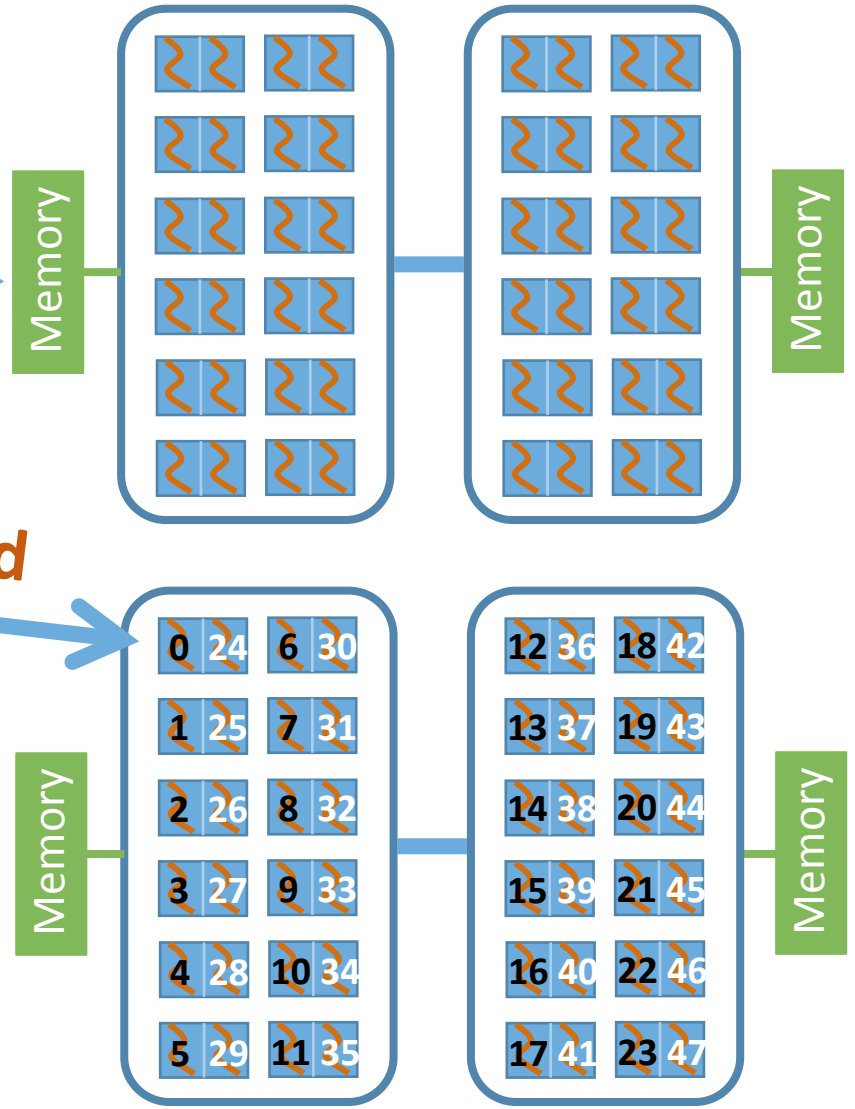
```
ls5%  lscpu | grep -i 'core\|thread\|socket'
Thread(s) per core:    2
Core(s) per socket:    12
Socket(s):             2
```

Hierarchy summary

ls5% cat /proc/cpuinfo ...awk* ...

```
   physical id : 0    core id  : 0    processor : 0
   physical id : 0    core id  : 0    processor : 24
   physical id : 0    core id  : 1    processor : 1
   physical id : 0    core id  : 1    processor : 25
   ...
   physical id : 1    core id  : 0    processor : 12
   physical id : 1    core id  : 0    processor : 36
   physical id : 1    core id  : 1    processor : 13
   ...
```

proc-id #s




```
ls5% * awk '/processor|core id|physical id/ {arr[j++]=$0};
       END{for(i=0;i<j;i+=3) {printf "%-20s %-20s %-20s\n",
       arr[i+1],arr[i+2],arr[i]} }' /proc/cpuinfo | \
       sed -e 's/[ \t]/ /g' | sort -n -k4,4 -k8,8 -k11,11
```

Unix Process View

User App

OS Kernel

```
top -load average: 0.77, 0.33, 0.29
Tasks: 584 total,3 running, 579 sleeping,...

Cpu0  : 99.7%us,  0.3%sy,...   0.0%id, ...
Cpu1  :  0.0%us,  0.0%sy,... 100.0%id, ...
Cpu2  :  0.0%us,  0.0%sy,... 100.0%id, ...
Cpu3  :  0.3%us,  0.3%sy,...  99.3%id, ...
Cpu4  :100.0%us,  0.0%sy,...   0.0%id, ...
Cpu5  :  0.0%us,  0.0%sy,... 100.0%id, ...
Cpu6  :  0.0%us,  0.0%sy,... 100.0%id, ...
Cpu7  :  0.0%us,  0.0%sy,... 100.0%id, ...

Mem:    ... total,   ... used, ... free, ...
Swap:   ... total,   ... used, ... free, ...

  PID USER      ...   COMMAND
60673 milfeld   ...   mpi_affinity
60672 milfeld   ...   mpi_affinity
58787 milfeld   ...   top
```

mpirun –np 2 …
top -- *hit 1 key*

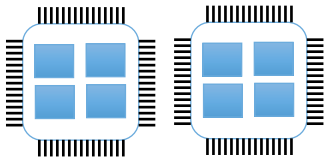
Running App

N MPI Tasks
M OMP Threads

rank0 1 ? ? ? ? ? ? ?

rank1 ? ? ? ? 1 ? ? ?

Hardware



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OpenMP Affinity

Portable: works with GNU, Intel, IBM, Oracle, …

There are two components to setting affinity:

(after setting the number of threads)

Distribution Policy:	PROC_BIND	policy
Locations:	PLACES	abstract name or list

OpenMP Affinity (distribution policy)

- PROC_BIND Policy:
  - #pragma omp parallel proc_bind(close | spread | master) *
  - export OMP_PROC_BIND=close | spread | master **

Default

* Clause: Policy applies only to the parallel region with clause.
**Env. Var: Applies to all parallel regions, except where proc_bind clause is used.

OpenMP Affinity (set of places)

- OMP_PLACES
  - export OMP_PLACES=<abstract_name>

    abstract name: sockets, cores, threads

} Defines a set of places

The precise definitions of the abstract names are implementation defined. An implementation may also add abstract names as appropriate for the target platform.

OpenMP Affinity (List)

- OMP_PLACES, as a list

(place = “smallest unit of execution”= proc-id # in Linux systems)

- export OMP_PLACES=<place_list>

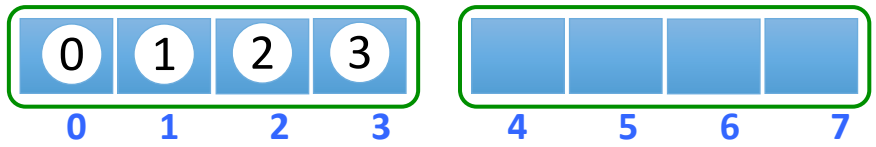
A place:	{0}	
Place List:	{0},{1},{2},{3}	
Interval notation:	<place>:<len>:<stride>	e.g. {0}:4:1

Default Place list: with HyperThreading =list of HW-threads #’s
without HyperThreading = list of cores.

OpenMP Affinity
PROC_BIND Distribution

```
export OMP_NUM_THREADS=4
export OMP_PROC_BIND=close

!$omp parallel private(tid);
   tid=omp_get_thread_num();
```

```
export OMP_NUM_THREADS=4
export OMP_PROC_BIND=spread

!$omp parallel private(tid);
   tid=omp_get_thread_num();
```



COMPACT PACKING

SCATTER PACKING

←thread id

←proc-id

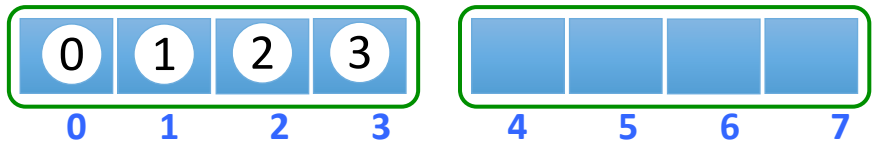
core

2 sockets x 4 cores

OpenMP Affinity Places

```
export OMP_NUM_THREADS=4
export OMP_PLACES='{0},{1},{2},{3}'

!$omp parallel private(tid);
   tid=omp_get_thread_num();
```

```
export OMP_NUM_THREADS=4
export OMP_PLACES='{0},{2},{4},{6}'

!$omp parallel private(tid);
   tid=omp_get_thread_num();
```



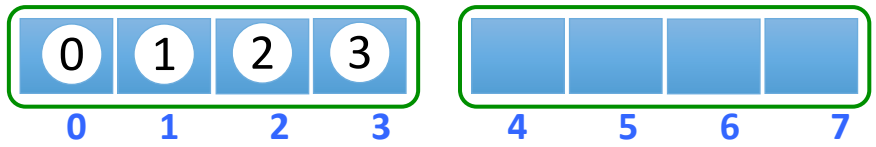
COMPACT PACKING

SCATTER PACKING

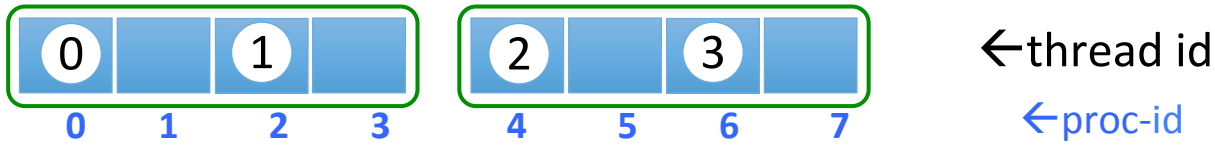
OpenMP Affinity
Places → Interval Expression

```
export OMP_NUM_THREADS=4
export OMP_PLACES='{0}:4'

!$omp parallel private(tid);
   tid=omp_get_thread_num();
```

```
export OMP_NUM_THREADS=4
export OMP_PLACES='{0}:4:2'

!$omp parallel private(tid);
   tid=omp_get_thread_num();
```



COMPACT PACKING



SCATTER PACKING

OpenMP Affinity
Places abstract name

Hyper-Threading Enabled

```
export OMP_NUM_THREADS=8
export OMP_PLACES=threads

!$omp parallel private(tid);
   tid=omp_get_thread_num();
```

Binding to Single HW-thread

```
export OMP_NUM_THREADS=8
export OMP_PLACES=cores

!$omp parallel private(tid);
   tid=omp_get_thread_num();
```

Binding to Core

←thread id

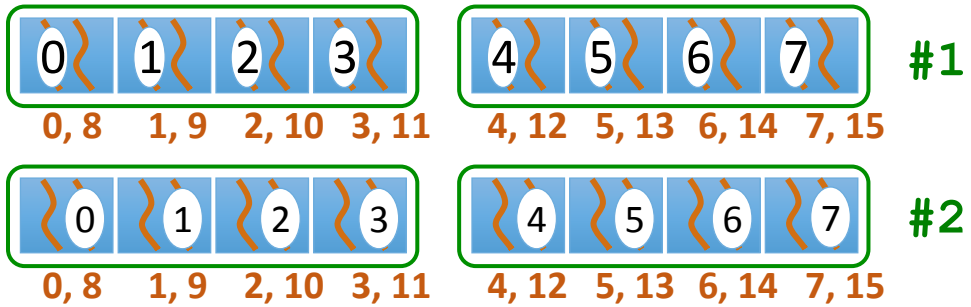
←proc-id

HW-thread

OpenMP Affinity
Places expression

Hyper-Threading Enabled

```
export OMP_NUM_THREADS=8
export OMP_PLACES='{0}:8'   #1
export OMP_PLACES='{8}:8'   #2

!$omp parallel private(tid);
   tid=omp_get_thread_num();
```



Binding to Single HW-thread

```
export OMP_NUM_THREADS=8
export OMP_PLACES='{0,8}:8'

!$omp parallel private(tid);
   tid=omp_get_thread_num();
```

Binding to Core

OpenMP Affinity
Places abstract name

Hyper-Threading Enabled

```
export OMP_NUM_THREADS=4
export OMP_PLACES=threads
export OMP_PROC_BIND=close


!$omp parallel private(tid);
   tid=omp_get_thread_num();
```

Binding to Single HW-thread

```
export OMP_NUM_THREADS=4
export OMP_PLACES=cores
export OMP_PROC_BIND=spread


!$omp parallel private(tid);
   tid=omp_get_thread_num();
```

Binding to Core

←thread id

←proc-id

HW-thread

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Viewing Affinity: Intel I_MPI_DEBUG=4

```
KNL IMPI    $ export I_MPI_DEBUG=4
            $ mpirun –np 16 my_favorite_app

           Rank    Node name                                  Pin cpu
           0       c401-001   {0,1,2,3,4,68,69,70,71,136,137,138,139,204,205,206,207}
           1       c401-001   {5,6,7,8,72,73,74,75,76,140,141,142,143,208,209,210,211}
           2       c401-001   {9,10,11,12,77,78,79,80,144,145,146,147,148,212,213,214,215}
           3       c401-001   {13,14,15,16,81,82,83,84,149,150,151,152,216,217,218,219,220}
           4       c401-001   {17,18,19,20,21,85,86,87,88,153,154,155,156,221,222,223,224}
           5       c401-001   {22,23,24,25,89,90,91,92,93,157,158,159,160,225,226,227,228}
           6       c401-001   {26,27,28,29,94,95,96,97,161,162,163,164,165,229,230,231,232}
           7       c401-001   {30,31,32,33,98,99,100,101,166,167,168,169,233,234,235,236,237}
           8       c401-001   {34,35,36,37,38,102,103,104,105,170,171,172,173,238,239,240,241}
           9       c401-001   {39,40,41,42,106,107,108,109,110,174,175,176,177,242,243,244,245}
           10      c401-001   {43,44,45,46,111,112,113,114,178,179,180,181,182,246,247,248,249}
           11      c401-001   {47,48,49,50,115,116,117,118,183,184,185,186,250,251,252,253,254}
           12      c401-001   {51,52,53,54,55,119,120,121,122,187,188,189,190,255,256,257,258}
           13      c401-001   {56,57,58,59,123,124,125,126,127,191,192,193,194,259,260,261,262}
           14      c401-001   {60,61,62,63,128,129,130,131,195,196,197,198,199,263,264,265,266}
           15      c401-001   {64,65,66,67,132,133,134,135,200,201,202,203,267,268,269,270,271}
```

Viewing Affinity mask with amask

Old Stampede: 16-core

export OMP_NUM_THREADS=8 OMP_PROC_BIND=spread

amask_omp

```
        0   proc-id    15
thrd    v              v
 | 0   1000000000000000
 v 1   0010000000000000
   2   0000100000000000
   3   0000001000000000
   4   0000000010000000
   5   0000000000100000
   6   0000000000001000
   7   0000000000000010
```

Bit Mask

```
                proc-id
thrd   |  0       |    10   |
   0   1...............
   1   ..1.............
   2   ....1...........
   3   ......1.........
   4   ........1.......
   5   ..........1.....
   6   ............1...
   7   ..............1.
       |  0       |    10   |
```

More Readable

```
                proc-id
thrd   |  0       |    10   |
   0   0...............
   1   ..2.............
   2   ....4...........
   3   ......6.........
   4   ........8.......
   5   ..........0.....
   6   ............2...
   7   ..............4.
       |  0       |    10   |
```

Even More Readable

What about … hyper-threading?

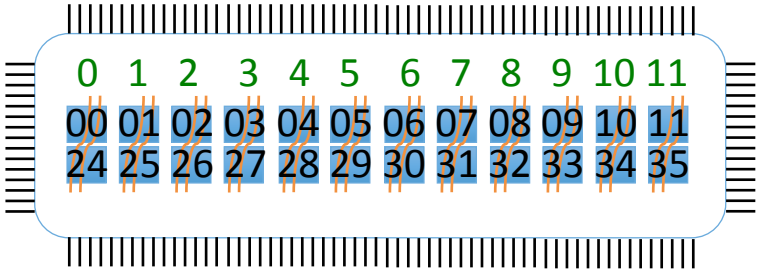
- There are many reasons to assign processes to proc-ids which have specific hardware capabilities.

  NUMA nodes
  Sockets
  Tiles
  PCI Interfaces
  …
  Hyperthreads

Masks for hyper-threaded platform

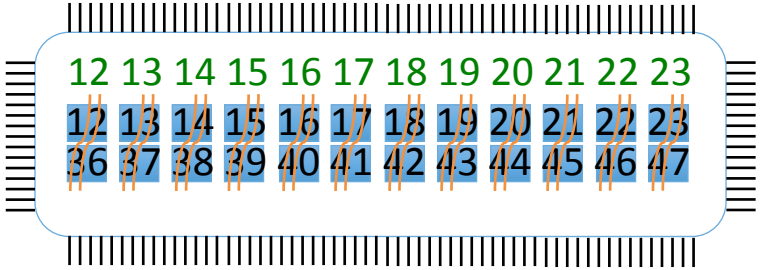
Hyper-Threaded systems 2 sockets x 12 cores → 48 hardware threads (lonestar)

Socket 0



core-id
proc-id – 1st SMT
proc-id – 2nd SMT

Socket 1

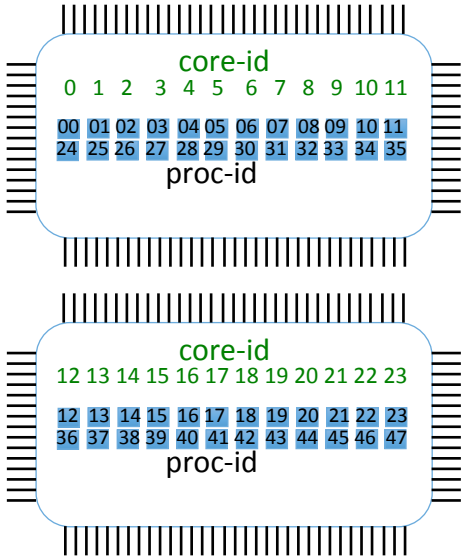


core-id
proc-id – 1st SMT
proc-id – 2nd SMT

What about hyper-threading…

Hyper-Threaded systems 2 x 12 cores → 48 hardware threads

Kernel-Centric MAP



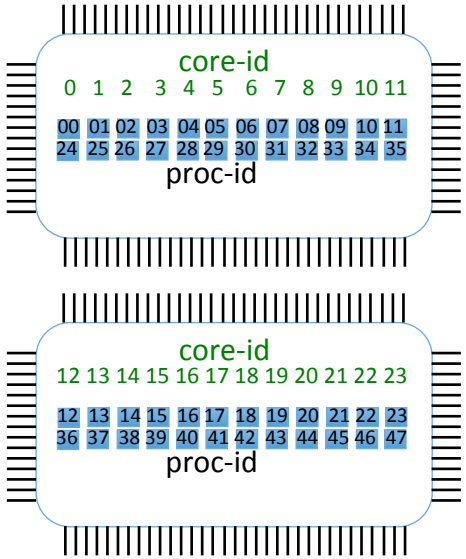

```
$ export OMP_NUM_THREADS=4 OMP_PLACES=cores;  amask_omp  -vk

      Each row of matrix is an Affinity mask.
      A set mask bit = matrix digit + column group # in |...|

thrd |    0    |   10    |   20    |   30    |   40
|
0000 0-----------------------4-----------------------
0001 ------6-----------------------0----------------
0002 ------------2-----------------------6-----------
0003 ------------------8-----------------------2-----
SMT 0 ═══════════════════════════════════════════════ SMT 1
      socket 0   socket 1   socket 0   socket 1
```

What about hyper-threading…

Hyper-Threaded systems 2 x 12 cores → 48 hardware threads

Core-Centric MAP

```
$ export OMP_NUM_THREADS=4 OMP_PLACES=cores;  amask_omp
```



Each row of matrix is a CORE mask for a SMT.
core id = matrix digit + column group # in |...|
proc-id = core id + add 24 to each additional row

```
thrd |    0    |   10    |   20    | ← core-id
0000 0=======================          SMT-thread 0 of cores
     0-----------------------          SMT-thread 1 of cores
0001 ======6=================
     ------6-----------------
0002 ============2===========
     ------------2-----------
0003 ==================8=====
     ------------------8-----
```

What about hyper-threading… on KNL

KNL: 68 cores
4 SMT

```
$ export OMP_NUM_THREADS=17 OMP_PLACES=cores; amask_omp
```

```
thrd |    0    |   10    |   20    |   30    |   40    |   50    |   60    |
0000 0=========================================================
     0---------------------------------------------------------
     0---------------------------------------------------------
     0---------------------------------------------------------
0001 ====4=====================================================
     ----4-----------------------------------------------------
     ----4-----------------------------------------------------
     ----4-----------------------------------------------------
0002 ========8=================================================
     --------8-------------------------------------------------
     --------8-------------------------------------------------
     --------8-------------------------------------------------
...
0016 ===============================================================4===
     -------------------------------------------------------------4---
     -------------------------------------------------------------4---
     -------------------------------------------------------------4---
```

git amask

Origin: maskeraid → Now: amask

```
$ git clone https://github.com/tacc/amask
  Cloning into 'amask'…
```

```
$ cd amask
$ vi Makefile
$ make
…

$ ls
bin  doc  lib  License  Makefile  README  README.md  src  TODO

$ ls bin lib
bin:
amask_hybrid  amask_mpi  amask_omp

lib:
amask.a
```

How to get masks with amask executables

Pure OpenMP

```
$    export OMP_NUM_THREADS=68
$    amask_omp                          # amask executable
$    my_omp_app
```

Pure MPI

```
$    mpirun -np 4   amask_mpi       # amask executable
$    mpirun -np 4   my_mpi_app
```

Hybrid

```
$    export OMP_NUM_THREADS=16
$    mpirun –np 17 amask_hybrid    # amask executable
$    mpirun –np 17 my_mpiomp_app
```

How to get masks with the API

Pure OpenMP

```
$    export OMP_NUM_THREADS=68
$    my_omp_app
```

```
...
#pragma omp parallel
amask_omp();
```

Pure MPI

```
$    mpirun -np 4   my_mpi_app
```

```
MPI_Init(NULL,NULL);
   amask_mpi();
      ...
MPI_Finalize();
```

Hybrid

```
$    export OMP_NUM_THREADS=16
$    mpirun –np 17 my_mpiomp_app
```

```
MPI_Init(NULL,NULL);
...
   #pragma omp parallel
   amask_hybrid();
...
MPI_Finalize();
```

Callable from C/C++ and Fortran

amask options

- View kernel (proc-id)/core (core-id): -vk -vc
- Print speed slow/fast: -ps -pf
- Wait (sec) at end of listing: -w#
- Help: -h

```
export OMP_NUM_THREADS=2
./amask_omp -vk -pf -w10
```

Kernel view (thrd vs proc-id)
No hesitation between prints
Wait up to 10 sec. at end

```
thrd |    0    |   10    |   20    |   30    |   40    |   50    |   60    |   70    | ...
0000 0---------------------------------------------------------------------------------- ...
0001 ----------------------------------------------------------------8----------- ...
```

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Hybrid Affinity– MPI + OpenMP

- An OpenMP team inherits the MPI process mask
- A thread's mask can only contain the set, or subset of the MPI process mask.
- Easiest Approach:
  Use Distribution of OMP_PROC_BIND (close, spread)
  Use granularity of OMP_PLACES (threads, cores, <vendor_defined>)
- Complicated (Advanced) Approach:
  Launch script for each MPI process that uses proc-id list in OMP_PLACES tailored for each process (depending upon rank).

```
#SLURM -N 2 --tasks-per-node 17

export OMP_NUM_THREADS=2 \
       OMP_PROC_BIND=spread \
       OMP_PLACES=cores

ibrun ./a.out   # 1 thread per tile
```

```
#SLURM -N 2 --tasks-per-node 17

export OMP_NUM_THREADS=2


ibrun ./mpi_script   # later
```

MPI mask

```
$ ibrun -np 2 amask_mpi
```

```
 Each row of matrix is a mask for a SMT-id -- 0, 1, 2, or 3.
     CORE ID  = matrix digit + column group # in |...|
     A set mask bit (proc-id) = core id + add 68 to each additional row.

rank |    0    |   10    |   20    |   30    |   40    |   50    |   60    |
0000 01234567890123456789012345678901234567890123456789012345678901234567
     01234567890123456789012345678901234567890123456789012345678901234567
     01234567890123456789012345678901234567890123456789012345678901234567
     01234567890123456789012345678901234567890123456789012345678901234567
0001 ================================================================
     ----------------------------------------------------------------
     ----------------------------------------------------------------
     ----------------------------------------------------------------
```

MPI process Rank 0 allowed anyplace on 1st 34 cores. →

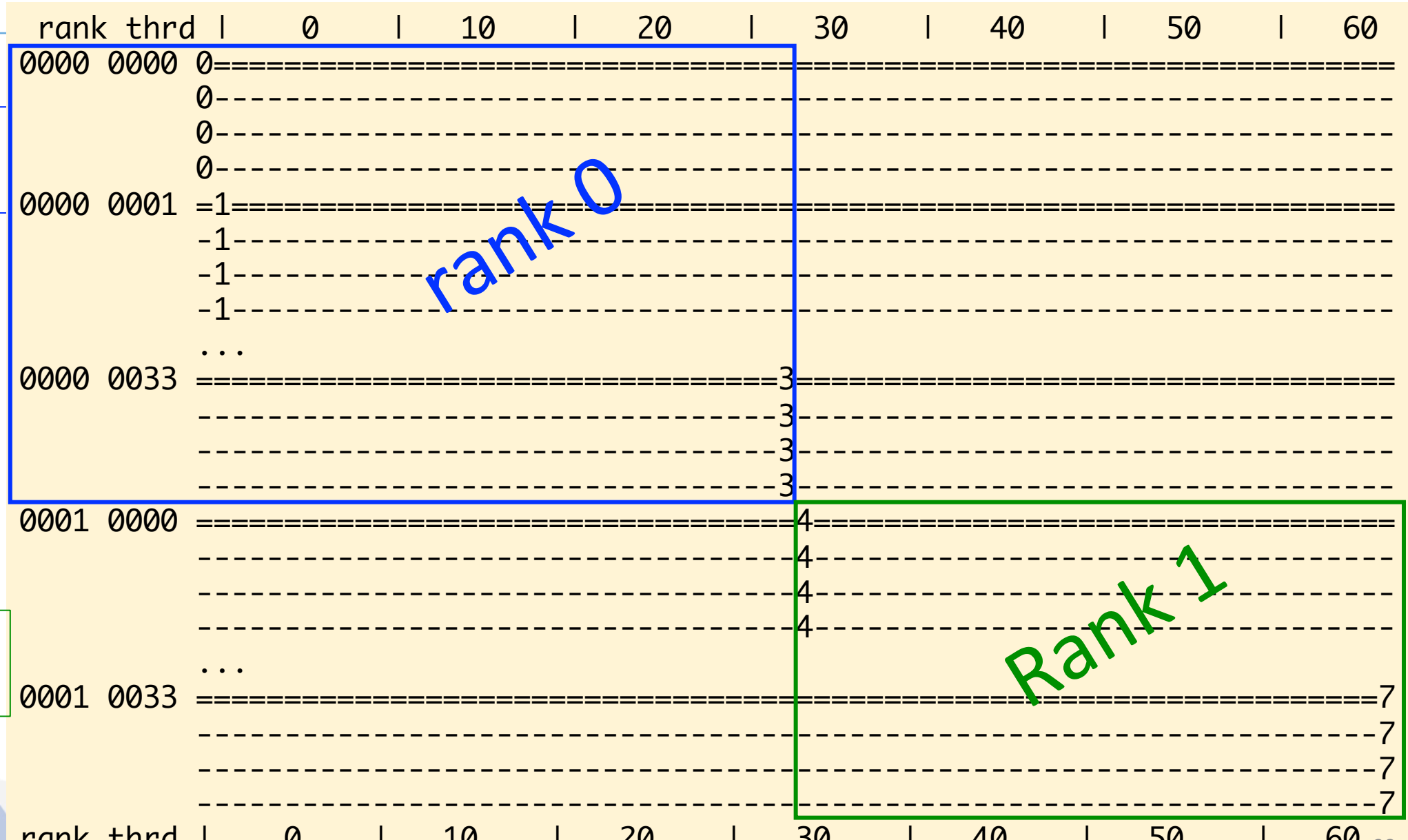
MPI process Rank 1 allowed anyplace on 2nd set of 34 cores. →

MPI mask

```
$ export OMP_NUM_THREADS=34 OMP_PLACES=cores
$ ibrun -np 2 amask_hybrid
```

Thread Team inherits mask of MPI process Rank 0-- and adjusts for each thread

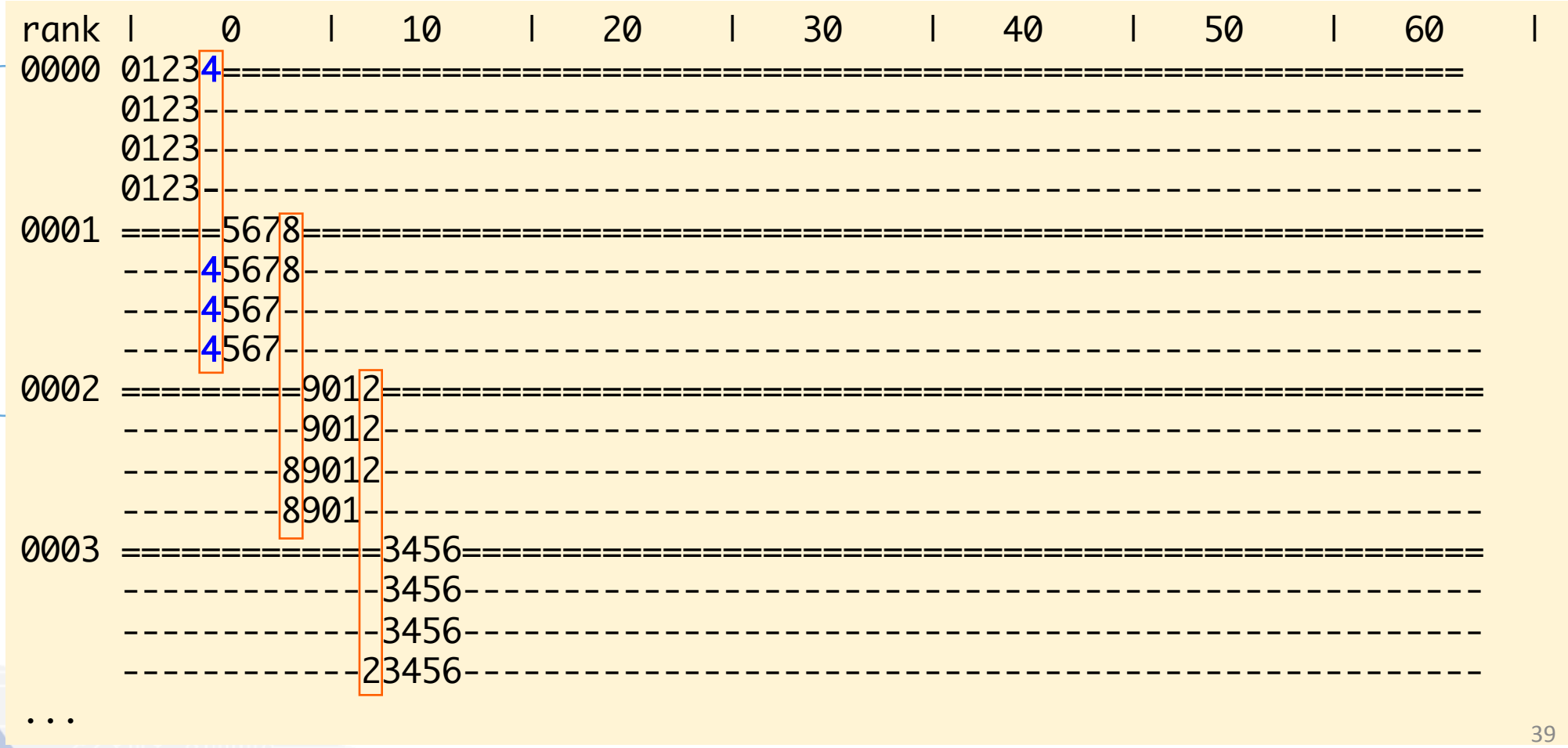
Thread Team inherits mask of MPI process Rank 1-- and adjusts for each thread



An Interesting Case

```
$ mpirun -np 16 amask_mpi     # for hybrid, export OMP_NUM_THREADS=17
```

Core sharing by two MPI processes →



Potato (16x17) or Potahto (17x16)

```
$ mpirun -np 17 amask_mpi  # for hybrid, export OMP_NUM_THREADS=16
```

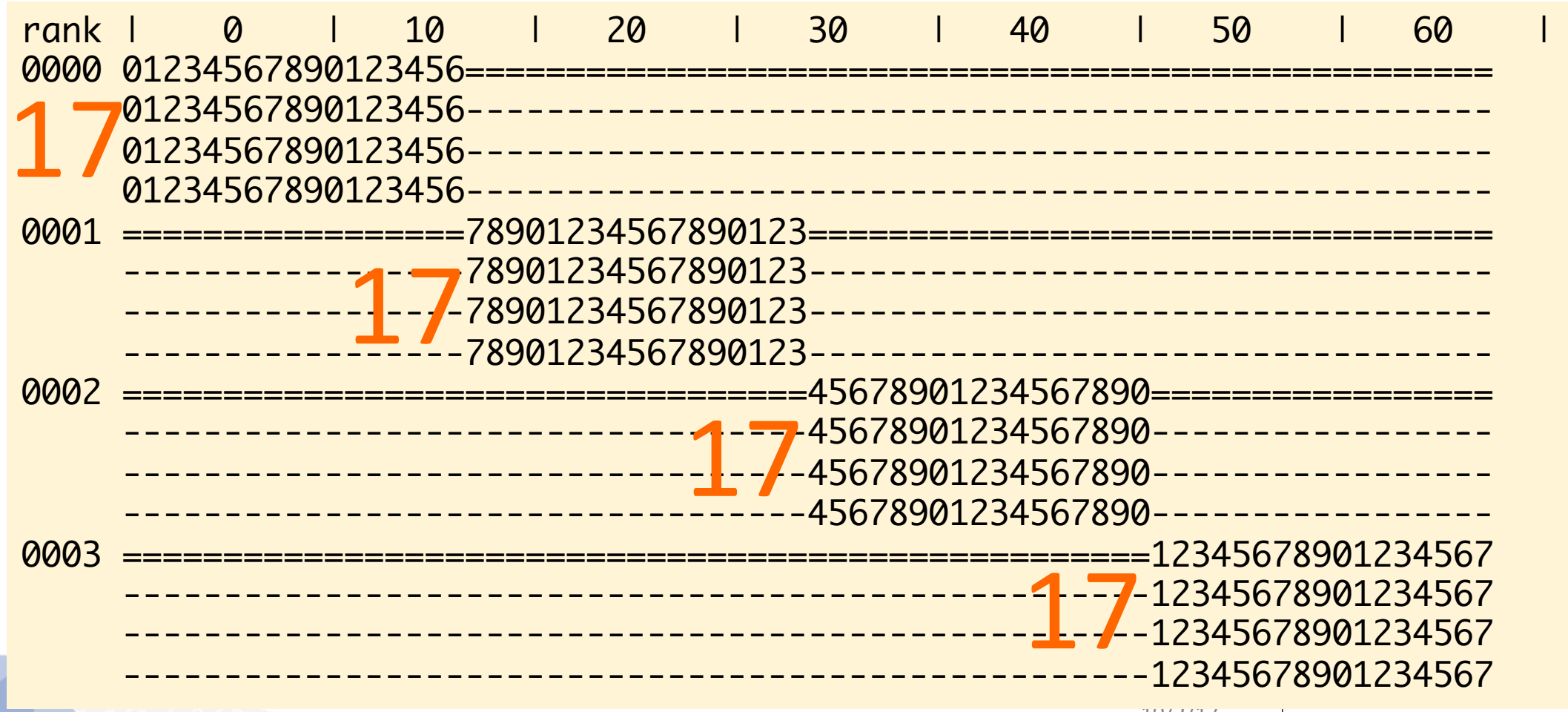
NO Core sharing by any MPI processes

```
rank |    0    |   10    |   20    |   30    |   40    |   50    |   60    |
0000 0123=======================================================
     0123-------------------------------------------------------
     0123-------------------------------------------------------
     0123-------------------------------------------------------
0001 ====4567===================================================
     ----4567-------------------------------------------------------
     ----4567-------------------------------------------------------
     ----4567-------------------------------------------------------
0002 ========8901===============================================
     --------8901-------------------------------------------------
     --------8901-------------------------------------------------
     --------8901-------------------------------------------------
...
0016 ===============================================================4567
     -------------------------------------------------------------4567
     -------------------------------------------------------------4567
     -------------------------------------------------------------4567
```

SNC-4 mode (4 memory numa nodes)

```
$ mpirun -np 4 amask_mpi  # MPI mask
```

NOTE THE DISTRIBUTION
Should be:
18 x 18 x 16 x 16
Cores according to lscpu



Hybrid Affinity-script

```
#SLURM -N 2 --tasks-per-node 4
# uses numa "aware" script
mpirun -np 8 ./numa.sh
```

numa.sh

```
#!/bin/bash

[[ $PMI_RANK == 0 ]] && export OMP_NUM_THREADS=18
[[ $PMI_RANK == 1 ]] && export OMP_NUM_THREADS=18
[[ $PMI_RANK == 2 ]] && export OMP_NUM_THREADS=16
[[ $PMI_RANK == 3 ]] && export OMP_NUM_THREADS=16

./a.out
```

Hybrid Affinity-script -- how ugly is this?

Can go over this at break with anyone.

```
#!/bin/bash

    R=$PMI_RANK
  TPN=$SLURM_NTASKS_PER_NODE                  #test with R=3 TPN=2 OMP_NUM_THREADS=2

MPI_OFFSET=$((68/TPN))                        #Divide up cores among ranks (MUST BE EVEN)
OMP_stride=$((MPI_OFFSET/OMP_NUM_THREADS)) #Stride between OMP threads

                  # Assume ranks are numbered sequentially across all nodes
                  # Rank :                              node1      node2    node3   ...
                  # rank number on each node:     {0 1 2 3} {4 5 6 7} {8 9 10 11}...
                  # rank modulo TPN (tasks/node)  {0 1 2 3} {0 1 2 3} {0 1  2  3}...

Rm=$((R%TPN))                                 # rank modulo tasks-per-node

off0=$((      Rm*MPI_OFFSET))                 # proc-id offset for SMT thread 0
off1=$(( 68 + Rm*MPI_OFFSET))                 #
off2=$((136 + Rm*MPI_OFFSET))                 #
off3=$((204 + Rm*MPI_OFFSET))                 # proc-id offset for SMT thread 3

export OMP_PLACES="{$off0,$off1,$off2,$off3}:$OMP_NUM_THREADS:$OMP_stride"

                        #    {Core HW-threads}          :       no. of PLACES  :  Stride

amask_hybrid      #test echo `hostname` $R $OMP_PLACES
```

Perspective:

- OpenMP PLACES syntax is simple and handles granularity
- MPI needs to standardize MPI Affinity
- Needed:
  - Common Affinity Language/Syntax for MPI and OpenMP
  - Interface for OpenMP to acquire basic MPI information

Thanks for your attention!
Questions?

An Example

TACC KNL: 4 SMTs x 68 cores = 272 hardware threads

```
$ mpirun –np 16 amask_mpi -vk  # for hybrid, export OMP_NUM_THREADS=17
```

Each row of matrix is an Affinity mask. A set mask bit = matrix digit + column # in |...|

```
rank |     | 10  | 20  | 30  | 40  | 50  | 60  | 70  | 80  | 90  | 100 | 110 | 120 | 130 | 140 | 150 | 160 | 170 | 180 | 190 | 200 | 210 | 220 | 230 | 240 | 250 | 260 | 270 |
0000 01234-----------------------------------------------------8901-----------------------------------------------------6789-----------------------------------------------------4567-----
0001 -----5678-----------------------------------------------------23456----------------------------------------------------0123-----------------------------------------------------8901-----
0002 ---------9012-----------------------------------------------------7890-----------------------------------------------------45678----------------------------------------------------2345-----
0003 ------------3456-----------------------------------------------------1234-----------------------------------------------------9012-----------------------------------------------------67890----
0004 ----------------78901-----------------------------------------------------5678-----------------------------------------------------3456-----------------------------------------------------1234----
0005 --------------------2345-----------------------------------------------------90123----------------------------------------------------7890-----------------------------------------------------5678----
0006 ----------------------6789-----------------------------------------------------4567-----------------------------------------------------12345----------------------------------------------------9012----
0007 ------------------------0123-----------------------------------------------------8901-----------------------------------------------------6789-----------------------------------------------------34567----
0008 --------------------------45678----------------------------------------------------2345-----------------------------------------------------0123-----------------------------------------------------8901----
0009 ----------------------------9012-----------------------------------------------------67890----------------------------------------------------4567-----------------------------------------------------2345----
0010 ------------------------------3456-----------------------------------------------------1234-----------------------------------------------------89012----------------------------------------------------6789----
0011 --------------------------------7890-----------------------------------------------------5678-----------------------------------------------------3456-----------------------------------------------------01234---
0012 ----------------------------------12345----------------------------------------------------9012-----------------------------------------------------7890-----------------------------------------------------5678---
0013 ------------------------------------6789-----------------------------------------------------34567----------------------------------------------------1234-----------------------------------------------------9012---
0014 --------------------------------------0123-----------------------------------------------------8901-----------------------------------------------------56789----------------------------------------------------3456----
0015 ----------------------------------------4567-----------------------------------------------------2345-----------------------------------------------------0123-----------------------------------------------------78901
```

Not a monospace font.

17 masked bits in each row → makes sense, since 16 tasks x 17 threads = 272 → “great” for hybrid.

A closer look:

```
rank |    0    |   10    |   20    |   30    |   40    |   50    |   60    |   70 ...|  270
0000 01234-------------------------------------------------------------8901------  ...
0001 -----5678-------------------------------------------------------------23456-  ...
0002 ----------9012-------------------------------------------------------------7  ...
...
                                  .
                                      .
                                          .


0016 ---------------------------------------------------------4567----------  ...
```

Maybe a core listing would be insightful?