Hardware locality (hwloc)

Managing hardware affinities for HPC applications

Runtime project
Samuel Thibault
INRIA Bordeaux - Sud-Ouest

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Machines are getting increasingly complex

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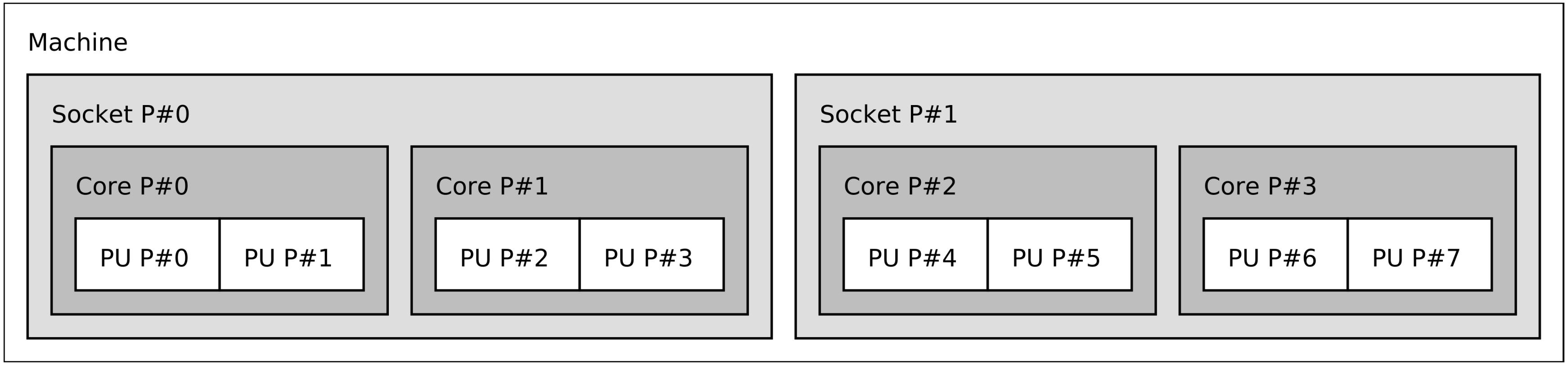
- Multiple processors, manycores, SMT, …



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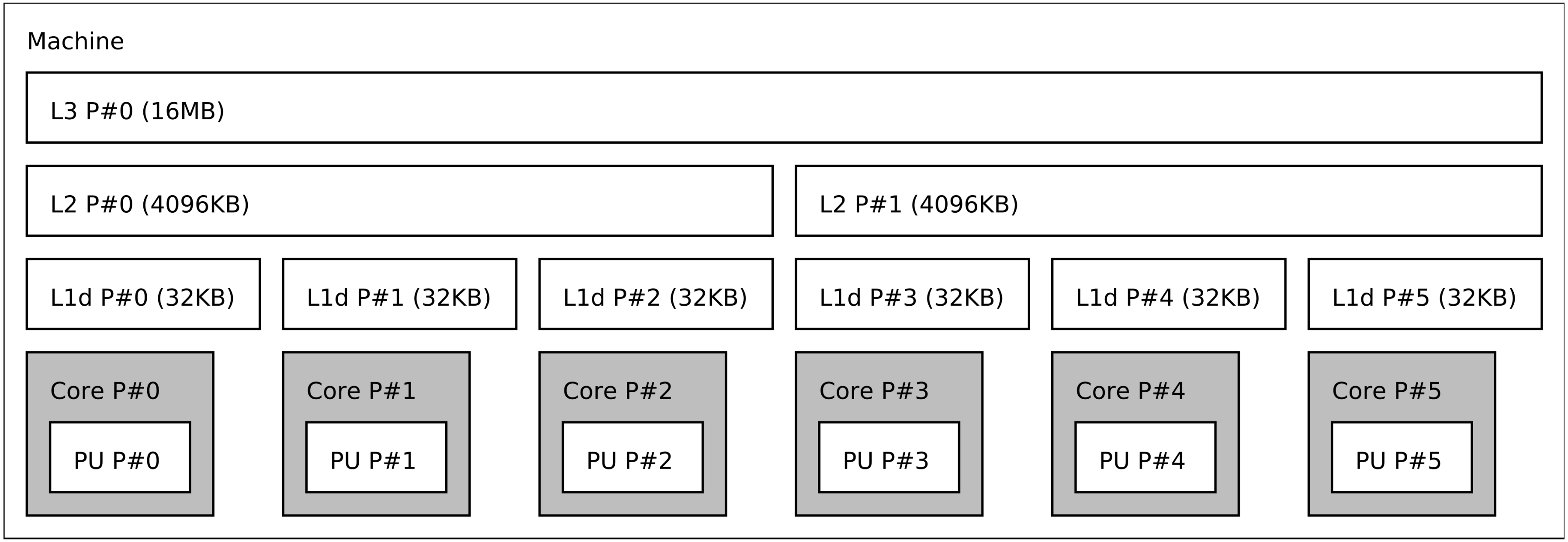
- Shared caches between some cores



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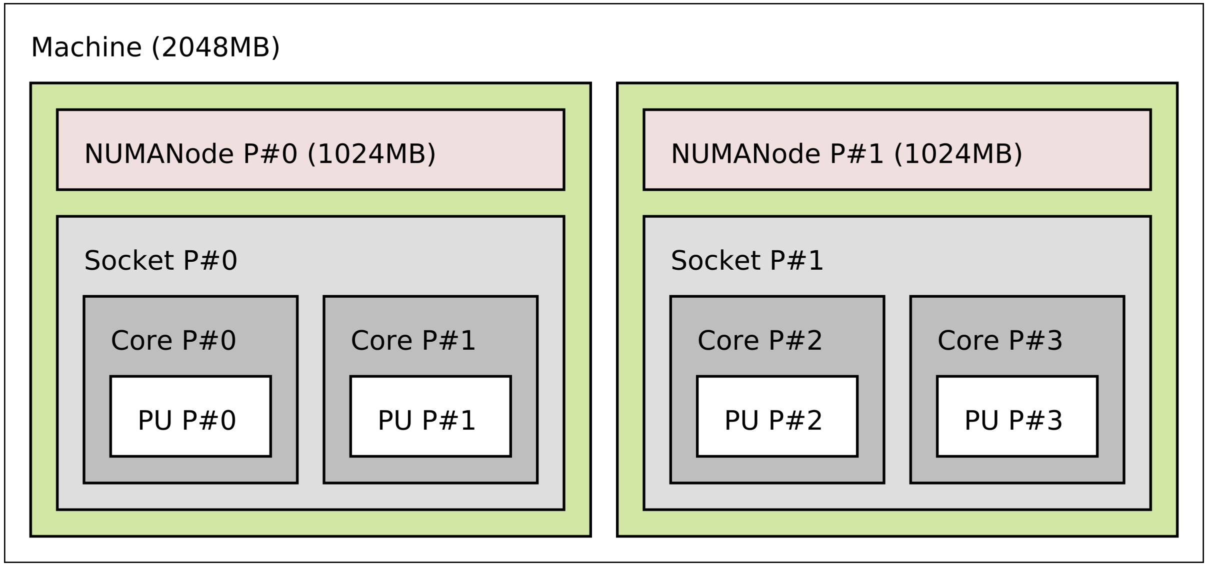
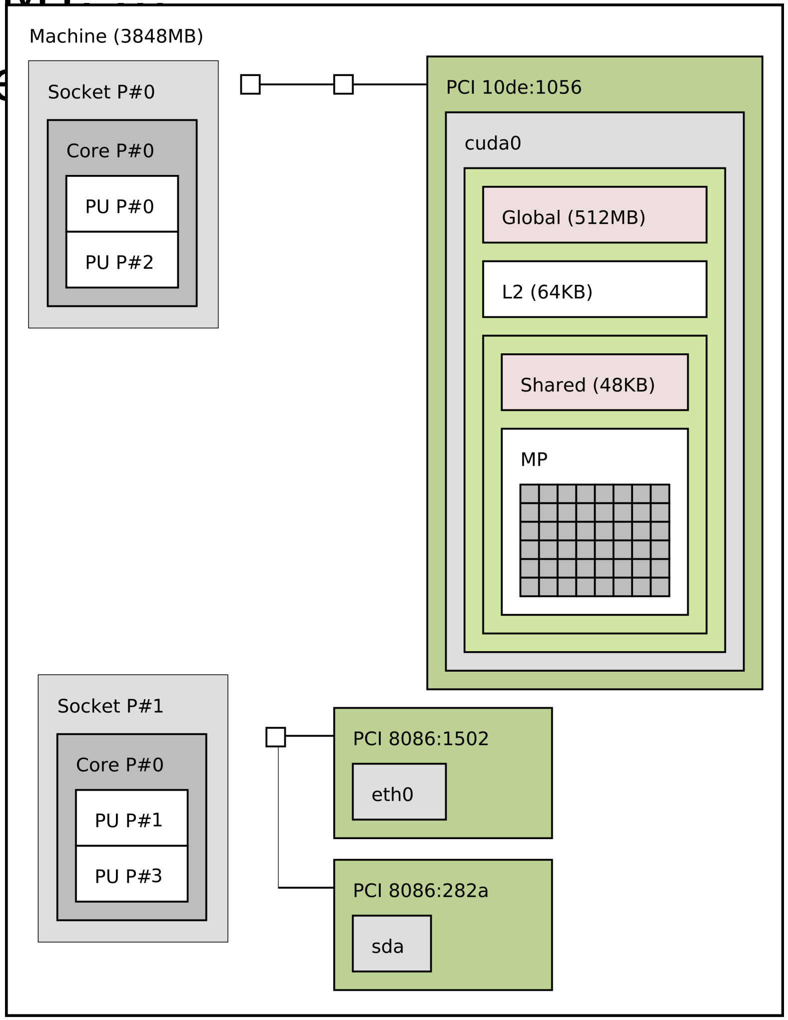
- Multiple memory nodes (NUMA)

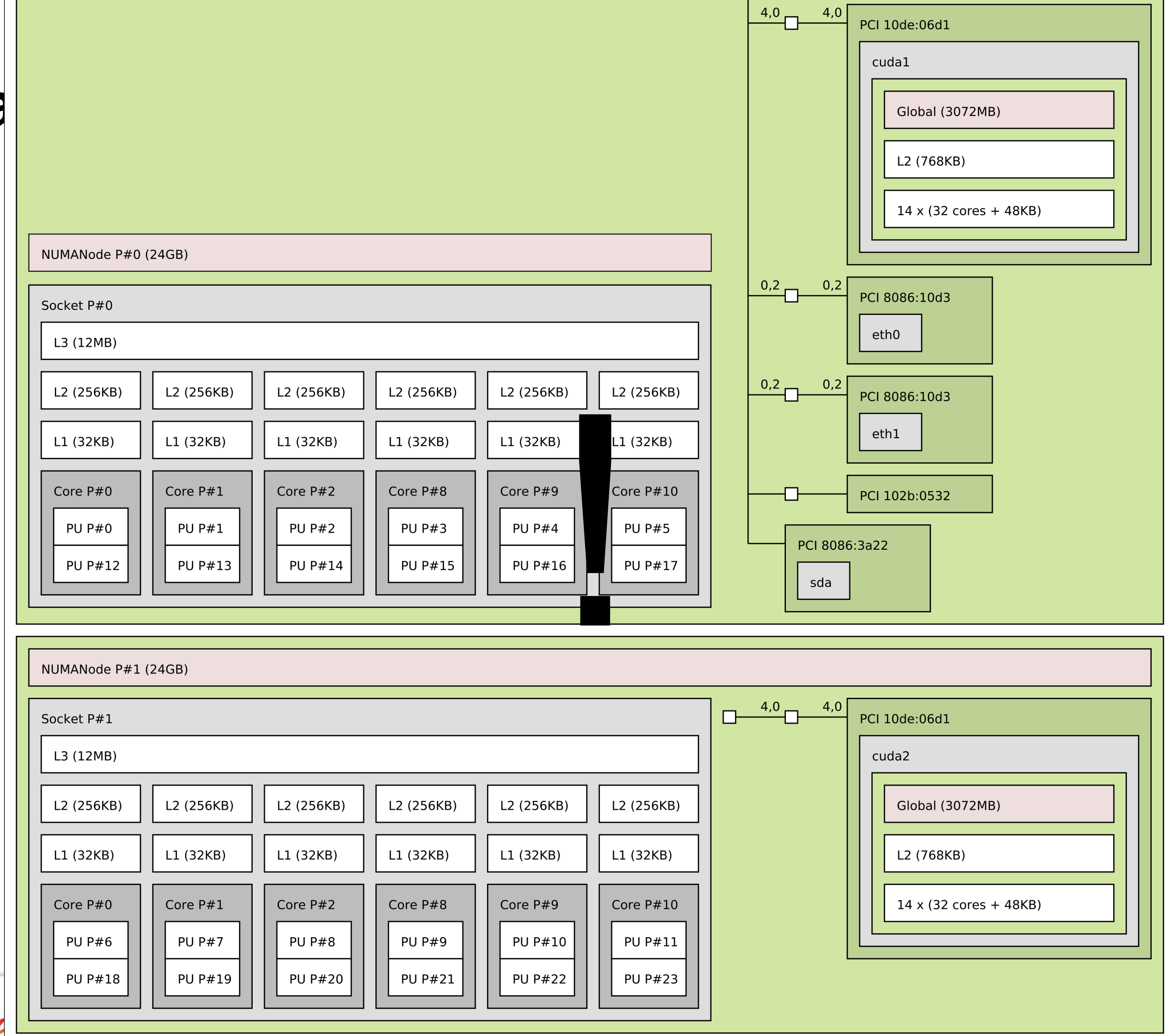


Machines are getting increasingly complex

- Multiple processors, manycores, SMT, …
- Shared caches between some core
- Multiple memory nodes (NUMA)
- NICs, GPUs, …



Ma… …ex



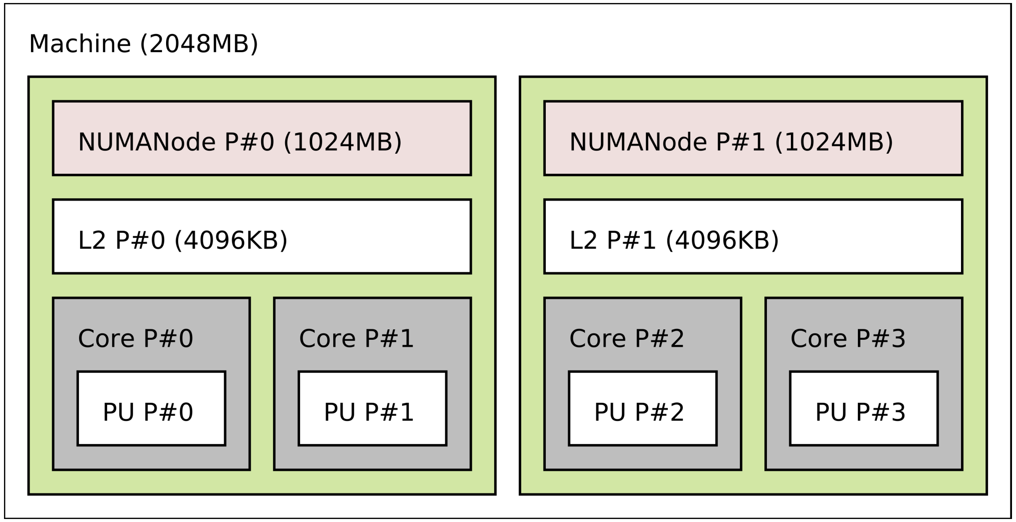
NUMANode P#0 (24GB)
Socket P#0
L3 (12MB)
L2 (256KB)
L2 (256KB)
L2 (256KB)
L2 (256KB)
L2 (256KB)
L2 (256KB)
L1 (32KB)
L1 (32KB)
L1 (32KB)
L1 (32KB)
L1 (32KB)
L1 (32KB)
Core P#0
PU P#0
PU P#12
Core P#1
PU P#1
PU P#13
Core P#2
PU P#2
PU P#14
Core P#8
PU P#3
PU P#15
Core P#9
PU P#4
PU P#16
Core P#10
PU P#5
PU P#17
4,0
4,0
PCI 10de:06d1
cuda1
Global (3072MB)
L2 (768KB)
14 x (32 cores + 48KB)
0,2
0,2
PCI 8086:10d3
eth0
0,2
0,2
PCI 8086:10d3
eth1
PCI 102b:0532
PCI 8086:3a22
sda
NUMANode P#1 (24GB)
Socket P#1
L3 (12MB)
L2 (256KB)
L2 (256KB)
L2 (256KB)
L2 (256KB)
L2 (256KB)
L2 (256KB)
L1 (32KB)
L1 (32KB)
L1 (32KB)
L1 (32KB)
L1 (32KB)
L1 (32KB)
Core P#0
PU P#6
PU P#18
Core P#1
PU P#7
PU P#19
Core P#2
PU P#8
PU P#20
Core P#8
PU P#9
PU P#21
Core P#9
PU P#10
PU P#22
Core P#10
PU P#11
PU P#23
4,0
4,0
PCI 10de:06d1
cuda2
Global (3072MB)
L2 (768KB)
14 x (32 cores + 48KB)

Affinities are one of the key performance criteria

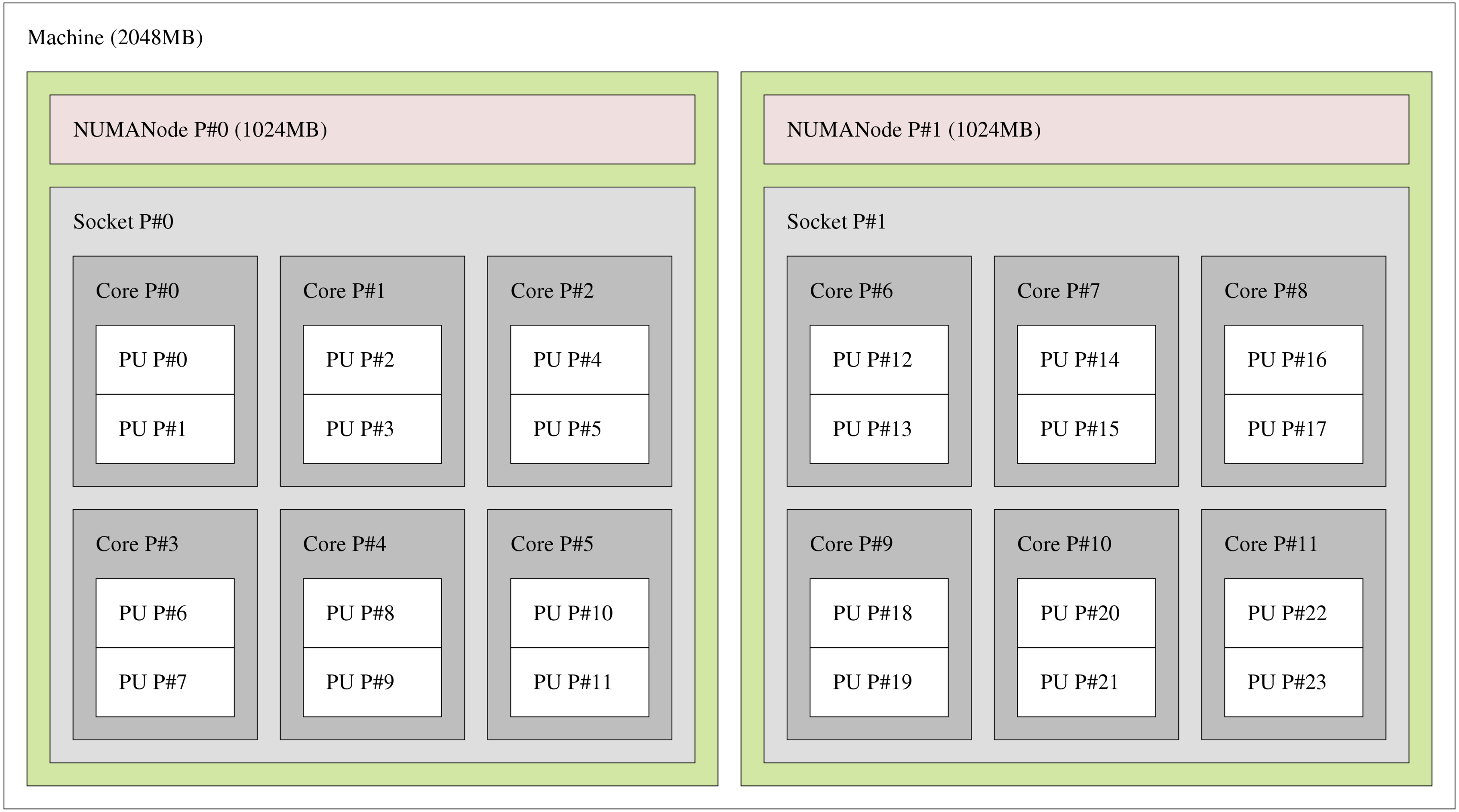
Dilemma

- Use cores 0 & 1 to share cache and improve synchronization cost?
- Use cores 0 & 2 to maximize memory bandwidth?
- How to choose portably?

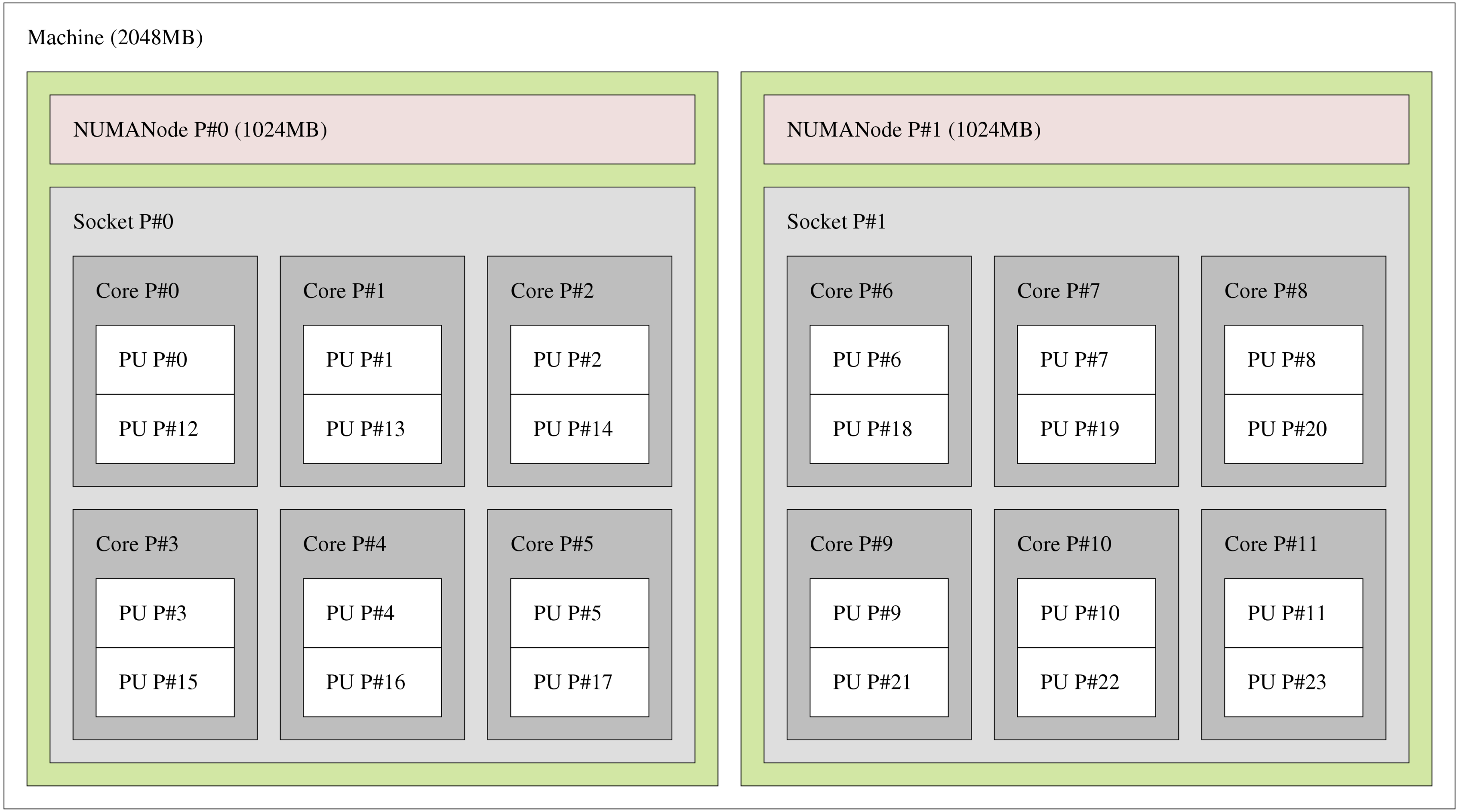
Depends both on the application structure and the machine structure



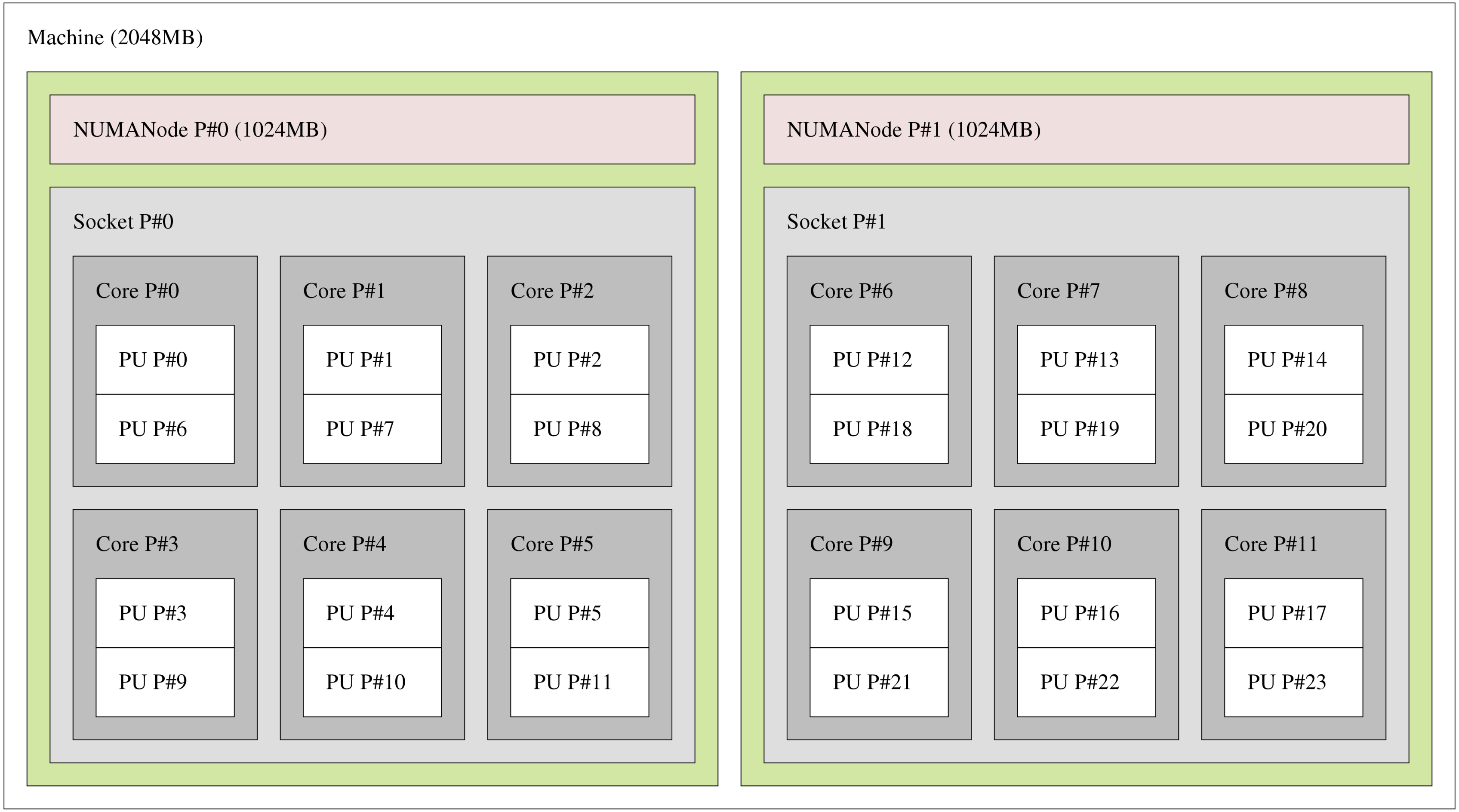
What's in my machine?



Or maybe it's a bit different



Wait!? After rebooting, it's different again…



Hardware organization is unpredictable

You may know what you bought…

… but you can't assume how processors, cores, threads, … will be *physically* numbered

- Depends on vendor
- May change after BIOS or OS upgrade

Gathering topology information and binding threads/memory is difficult

Lack of generic, uniform interface

- OS specific
  - /proc, /sys, rset, sysctl, lgrp, kstat, CPUID, …
  - setaffinity, rset, ldom_bind, radset, affinity_set, …
  - mbind, rset, mmap, nmadvise, affinity_set, ...
- Distribution specific
- Low-level APIs

Evolving technology

- E.g. : AMD Bulldozer “half-cores”, Intel SCC “tiles”

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Evolving technology

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➔ Need generic tools & abstract API

- Logical resource identification

Hwloc
Portable Hardware Locality

- **Portable topology information**
- **Portable binding toolset**

Hwloc

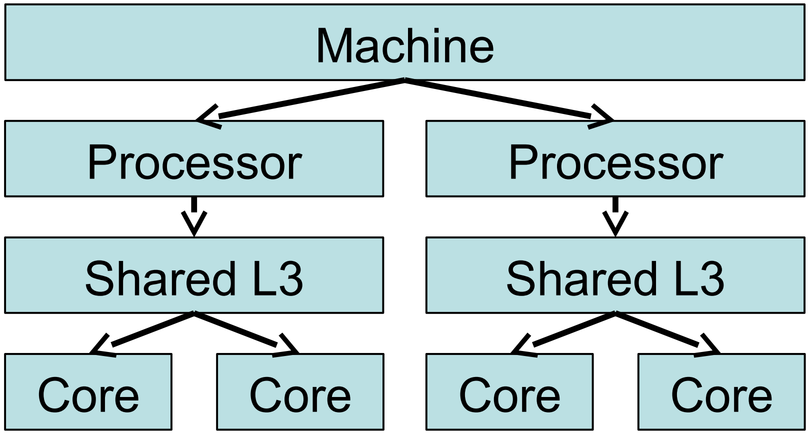
- Joint development
  - Runtime group + Open-MPI/Cisco
  - Libtopology (initially part of the Marcel scheduler)
  - PLPA
- Two parts
  - Set of command line tools (lstopo, hwloc-bind, calc, etc.)
  - C API + library, Perl and Python bindings
- Portable: Linux, Solaris, AIX, HP-UX, FreeBSD, Darwin, Windows
- BSD-3 license
- Used by a lot of projects: most MPI, runtimes, batch scheds, ...

http://www.open-mpi.org/projects/hwloc/

Hwloc's view of the hardware

Tree of objects

- Machines, memory nodes, sockets, caches, cores, threads, …
  - Logically ordered
- Grouping of similar objects based on distances between them
- Many attributes
  - ✓ Memory node size
  - ✓ Cache type, size and line size
  - ✓ Machine model
  - ✓ Physical ordering



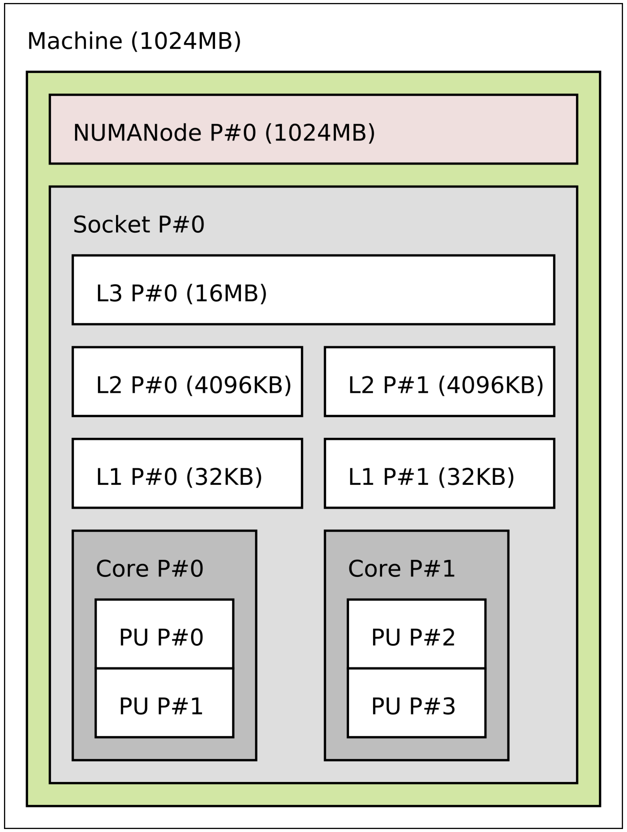
Tools
- Nice output
- shell-prone utilities

lstopo – Displaying topology information

Textual rendering: lstopo -

```
Machine (total=1024MB)
 NUMANode #0 (phys=0 local=1024MB)
  Socket #0 (phys=0)
   L3Cache #0 (16MB)
    L2Cache #0 (4096KB)
     L1Cache #0 (32KB)
      Core #0 (phys=0)
       PU #0 (phys=0)
       PU #1 (phys=2)
    L2Cache #1 (4096KB)
     L1Cache #1 (32KB)
      Core #1 (phys=2)
       PU #2 (phys=1)
       PU #3 (phys=3)
```

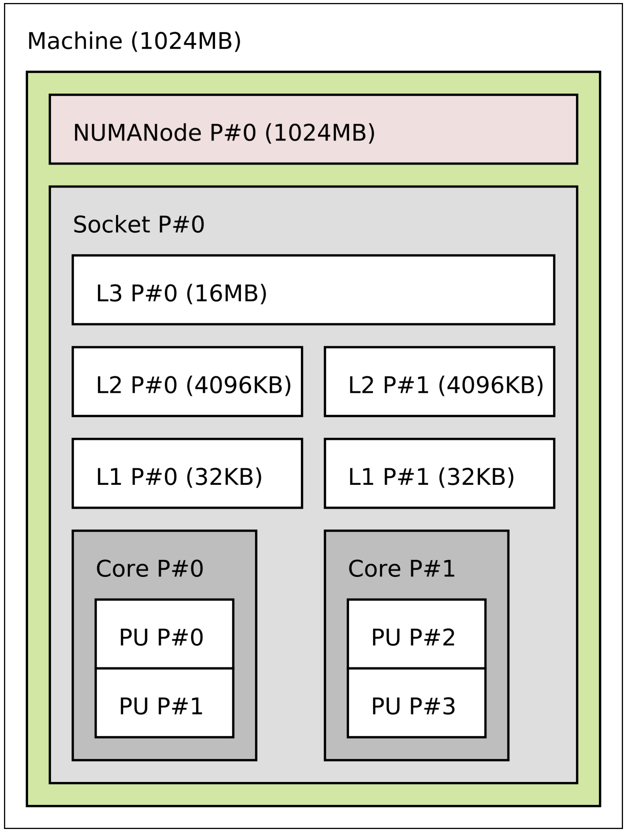
Graphical rendering



lstopo – Displaying topology information

- Lstopo supports various output formats
  - .fig, .pdf, .ps, .png, .svg

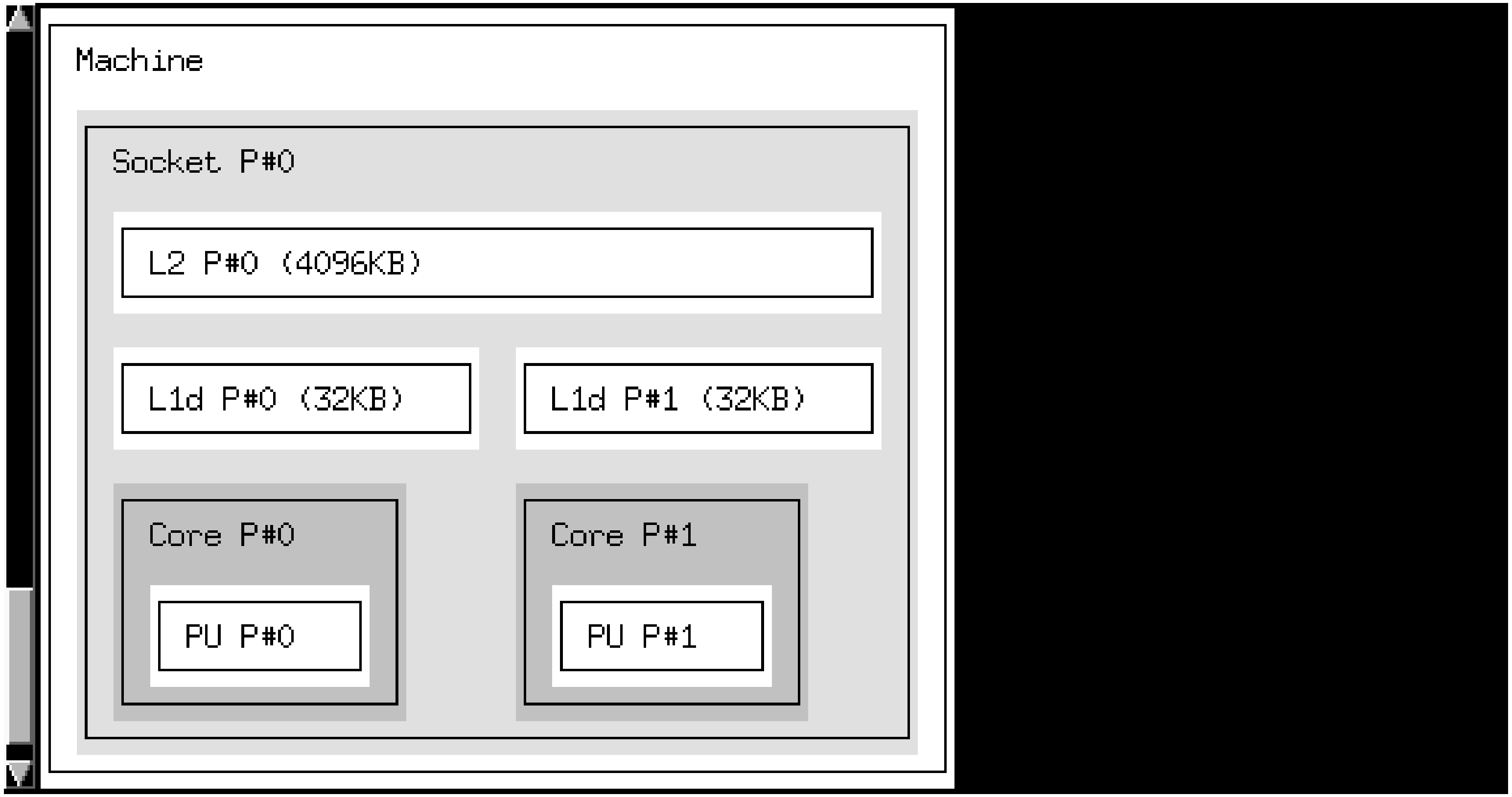
$ lstopo output.png



- It also supports XML format
  - Permits to save and quickly restore instead of re-performing detection
  - Permits to store other machine's topology for reference

lstopo – Displaying topology information

Even text-mode pseudo-graphical display!   lstopo -.txt



lstopo – Displaying topology information

Various output options, useful for slides :)

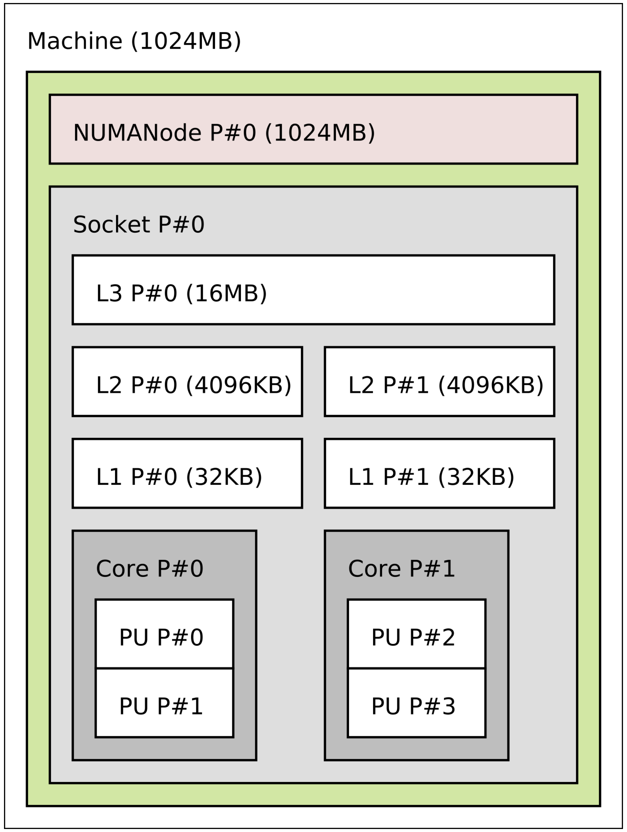
- --horiz: force horizontal layout
- --ignore cache: drop caches from the output
- --restrict <cpuset>: restrict output to a mask of processors
- ...

lstopo – Displaying topology information

Synthetic topology, useful for slides too :)

$ lstopo --input “node:1 socket:1 cache:1 cache:2 cache:1 core:1 pu:2”

… and a lot more, see lstopo --help



hwloc-distances – show object distances

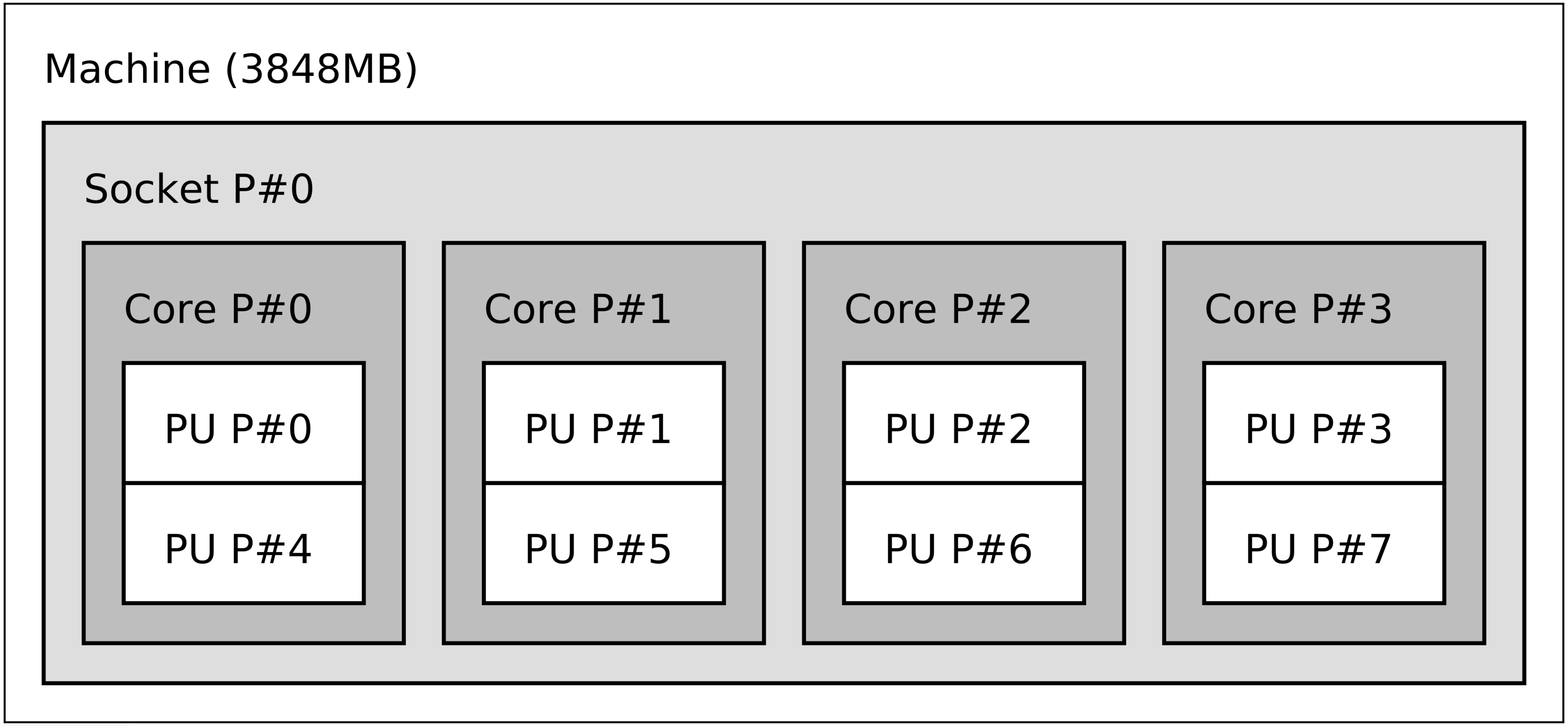
Notably NUMA distances:

```
$ ./utils/hwloc-distances
  index     0     1     2     3     4     5     6     7
      0 1.000 1.600 1.600 2.200 1.600 2.200 1.600 2.200
      1 1.600 1.000 2.200 1.600 2.200 1.600 1.600 2.200
      2 1.600 2.200 1.000 1.600 1.600 2.200 1.600 2.200
      3 2.200 1.600 1.600 1.000 1.600 2.200 2.200 1.600
      4 1.600 2.200 1.600 1.600 1.000 1.600 1.600 1.600
      5 2.200 1.600 2.200 2.200 1.600 1.000 1.600 1.600
      6 1.600 1.600 1.600 2.200 1.600 1.600 1.000 1.600
      7 2.200 2.200 2.200 1.600 1.600 1.600 1.600 1.000
```

Physical indexes

As returned by the OS, default lstopo output

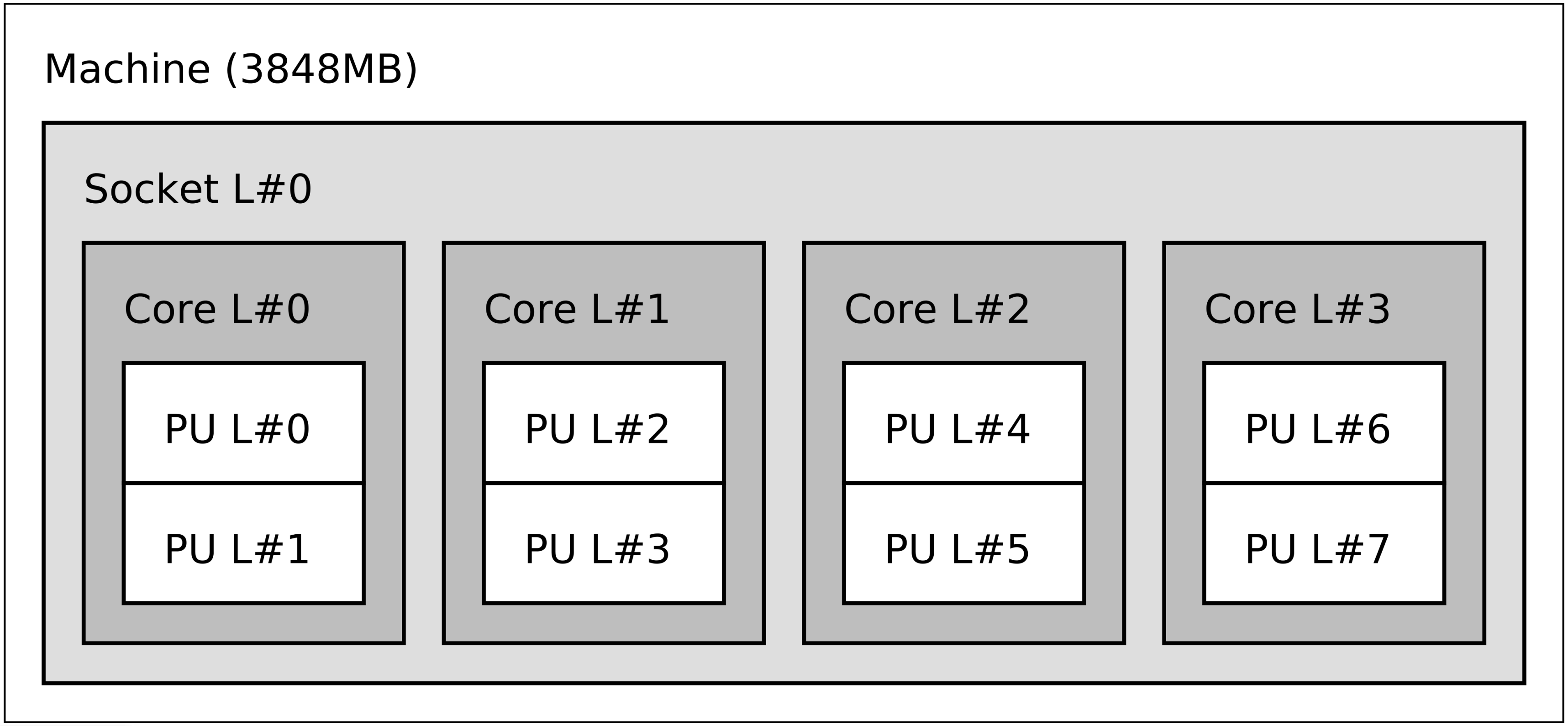
As mentioned earlier: often rather odd, depends on motherboard, BIOS, moon, ...



Logical indexes

As computed by hwloc, lstopo -l

Always represents proximity (depth-first walk)



Sets of CPUs

Hwloc tools have several ways to designate a set of cpus

- A set of objects:

  socket:0   core:4-7

- Can be more specific: two first cores of second socket:

  socket:1.core:0-1

- A bitmask:

  0x44

- CPUs close to a given PCI device

  pci=01:00.0

- Or to an OS device

  os=eth0

hwloc-calc - compute CPU sets

Permits to convert between ways to designate CPU sets, and make combinations:

```
$ hwloc-calc socket:1
0x000000f0
$ hwloc-calc os=eth0
0x00005555
$ hwloc-calc socket:2 ~PU:even
0x00000c00
$ hwloc-calc --number-of core socket:1
4
$ hwloc-calc --intersect PU socket:1
4,5,6,7
```

hwloc-bind – bind process

Bind a new process to a given set of CPUs:

$ hwloc-bind socket:1 -- mycommand

Bind an existing process:

$ hwloc-bind --pid 1234 socket:1

Bind memory:

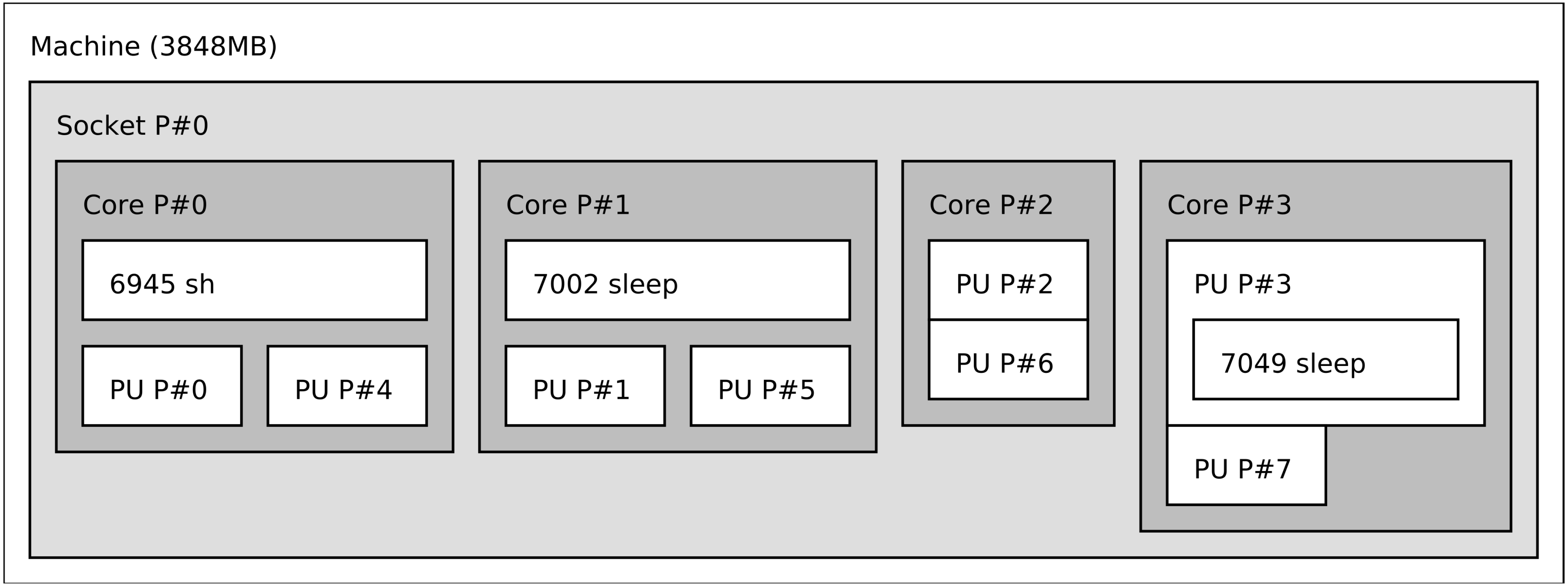
$ hwloc-bind --membind node:1 --cpubind node:1.socket:0 -- mycommand

Distribute memory:

$ hwloc-bind --membind --mempolicy interleave all -- mycommand

lstopo – show bound processes

$ lstopo –ps



Also hwloc-ps:

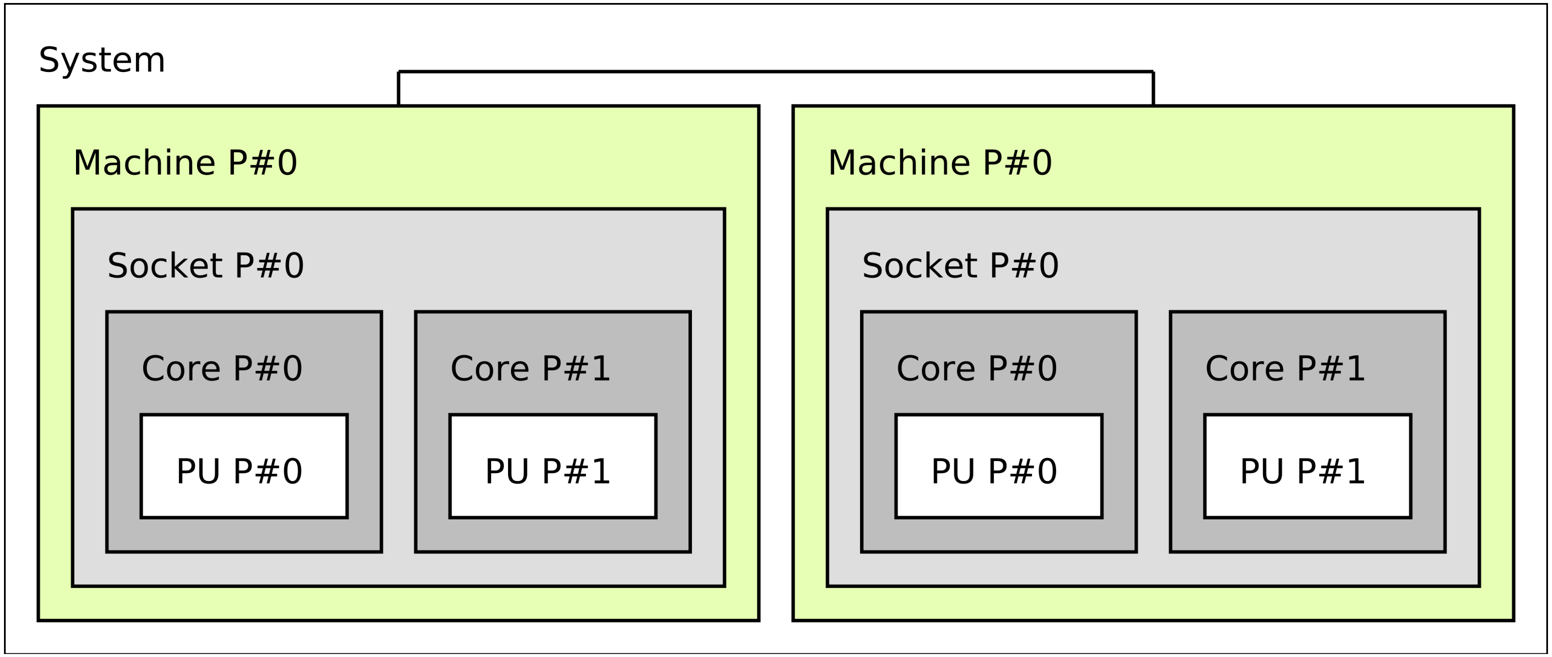
6945 core:0   sh

hwloc-assembler – combine trees

Permits to create network topologies

$ hwloc-assembler combined.xml machine1.xml machine2.xml

$ lstopo --input combined.xml



Hands-on: 1st part
http://runtime.bordeaux.inria.fr/hwloc/hwloc_tutorial.html

Programming Interface
- browsing objects
- CPU/node set operations
- CPU/memory binding

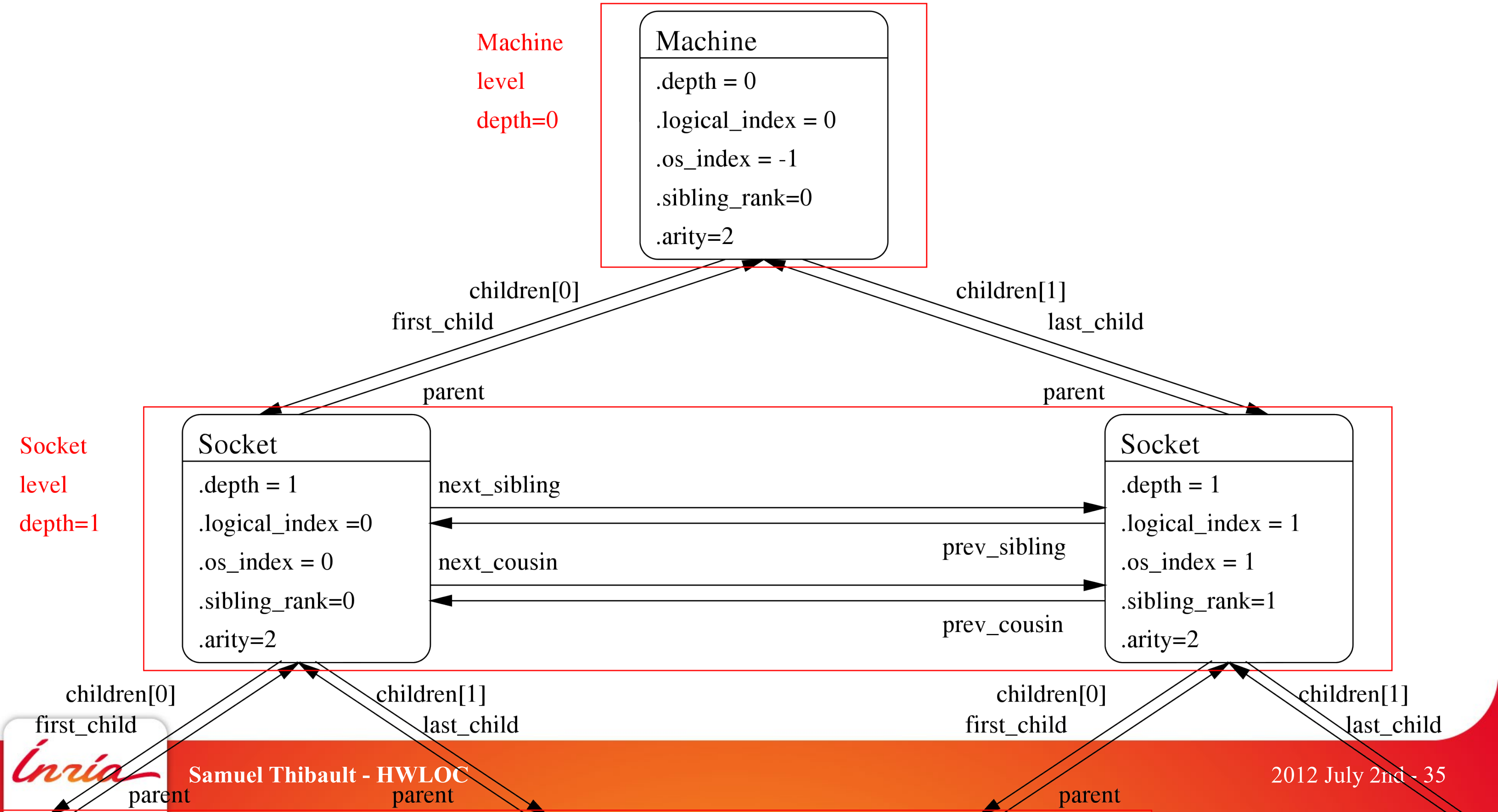
Initialization / termination

Should be trivial enough :)

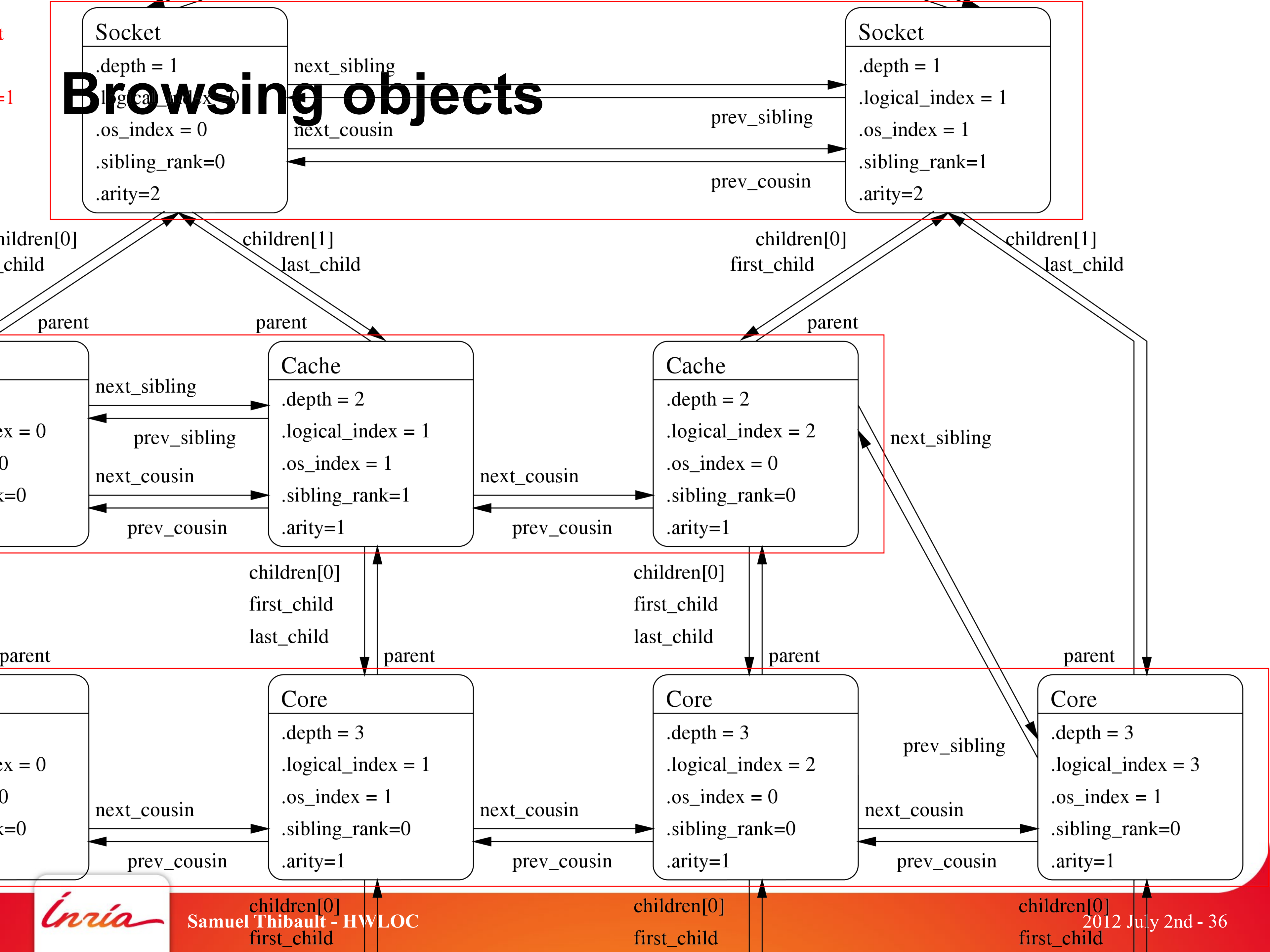
```
hwloc_topology_t t;

hwloc_topology_init(&t);  // initialization
Optional detection configuration...
hwloc_topology_load(t);   // actual detection

Play with it...
nbcores = hwloc_get_nbobjs_by_type(t, HWLOC_OBJ_CORE);

hwloc_topology_destroy(t);
```

Browsing objects

Always remember that hwloc's basic representation of the machine is a tree, but it also has levels.



Browsing objects



Browsing objects

Thus several ways to traverse objects

- Tree way

```
void traverse(hwloc_obj_t obj) {
  work_on(obj);
  for (i=0; i<obj->arity; i++)
    traverse(obj->children[i]);
}
traverse(hwloc_get_root_obj(t));
```

- Array way

```
for (depth=0; depth<hwloc_topology_get_depth(t); depth++)
  for (i=0; i<hwloc_get_nbobjs_by_depth(t,depth); i++)
    work_on(hwloc_get_obj_by_depth(t, depth, i));
```

Or various combinations of both, see <hwloc/helper.h> examples

Browsing objects

A **lot** of browsing helpers and examples in <hwloc/helper.h>

- hwloc_get_common_ancestor_obj
- hwloc_obj_is_in_subtree
- hwloc_get_largest_objs_inside_cpuset
- hwloc_get_obj_covering_cpuset
- hwloc_get_cache_covering_cpuset
- hwloc_get_shared_cache_covering_obj
- ...

Browsing objects

Accessing devices

- They are on separate levels
  - HWLOC_TYPE_DEPTH_PCI_DEVICE
  - HWLOC_TYPE_DEPTH_OS_DEVICE
- Helpers are provided to access them directly
  - hwloc_get_pcidev_by_busid(topology, domain, bus, dev, fun);
  - hwloc_cuda_get_device_pcidev(topology, cudevice);
  - hwloc_ibv_get_device_osdev_by_name(topology, name);

Look at their source code, they are examples of browsing the tree.

Object information

- obj->type
- obj->cpuset
- obj->father, children, next_cousin, ...

Depending on the type of object

- obj->cache.size
- obj->cache.linesize
- obj->pcidev.linkspeed
- ...

CPU/node set manipulations

Bitmap data structure, with all usual operations

hwloc_bitmap_alloc/free/dup/copy

hwloc_bitmap_set/set_range/clr/clr_range

hwloc_bitmap_isset/iszero/isfull

hwloc_bitmap_first/next/last/weight

hwloc_bitmap_foreach_begin/end

hwloc_bitmap_or/and/andnot/xor/not

hwloc_bitmap_intersects/isincluded/isequal/compare

...

CPU binding API

OS support varies
- Process-wide binding, thread binding, strict, …
- ENOSYS returned when not supported

Should be supported mostly everywhere: single-threaded process binding itself
- hwloc_set_cpubind(t, cpuset, 0);

Or the thread itself only
- hwloc_set_cpubind(t, cpuset, HWLOC_CPUBIND_THREAD);

Another process
- hwloc_set_proc_cpubind(t, pid, cpuset, 0);

...

Memory binding API

OS support varies even more

- Binding existing range, migrating allocated memory, allocating bound memory, strict, ...
- ENOSYS returned when not supported

Should be supported mostly everywhere: allocating bound memory, possibly through process policy change

- hwloc_alloc_membind_policy(t, size, cpuset, DEFAULT, 0);

Changing the binding policy for future mallocs and friends

- hwloc_set_membind(t, cpuset, DEFAULT, 0);

Migrating existing range

- hwloc_set_area_membind(t, addr, len, cpuset, DEFAULT, 0);

Whether already-allocated pages are migrated depends on the OS

Hands-on: part 2
http://runtime.bordeaux.inria.fr/hwloc/hwloc_tutorial.html

Conclusion

- Hwloc provides a generic way to represent the machine, and bind processes/threads/memory
- Both command-line tools and API
- Already used by a lot of HPC project, available in most distributions
- Large documentation

What next?

- Plug-in support
  - Automatic network topology discovery
  - Measurement-based discovery
  - X server OS object

http://www.open-mpi.org/projects/hwloc/

Thanks!

INVENTEURS DU MONDE NUMÉRIQUE

www.open-mpi.org/projects/hwloc/