Understanding and managing hardware affinities on hierarchical platforms

With Hardware Locality (hwloc)

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Agenda

- Quick example as an Introduction
- Bind your processes
- What's the actual problem?
- Introducing hwloc (Hardware Locality)
- Command-line tools
- C Programming API
- Conclusion
Materials

- All hwloc tutorials are available at

http://www.open-mpi.org/projects/hwloc/tutorials
Quick example as an Introduction
Machines are increasingly complex
Machines are increasingly complex

- Multiple processors
- Multicore processors (package = socket)
- Simultaneous multithreading
- Shared caches
- NUMA nodes
- Multiple GPUs, NICs, ...

- We cannot expect users to understand all this
Example with MPI

- Our latest cluster at Inria Bordeaux
  - 12-core Xeon E5-2600v3 with NVIDIA K40, etc.

- Nice, let's run some benchmarks!
  - Open MPI 1.8.1
  - Intel MPI benchmarks 3.2
Example with MPI – Results

- Between cores 0 and 1
  - 540ns, 3500MiB/s
- Between cores 0 and 2
  - 330ns, 4220MiB/s
- Between cores 0 and 12
  - 430ns, 4290MiB/s
- Between cores 0 and 23
  - 590ns, 3410MiB/s
What is going on?

Machine 1: 4290MiB/s
Machine 2: 4220MiB/s
Machine 3: 3500MiB/s
Machine 4: 3410MiB/s
First take away messages

- Locality matters to communication performance
  - Machines are really far from flat
    - Similar issues with POWER8, AMD Opterons, Fujitsu Sparc XIfx

- Cores numbering is crazy
  - Never expect anything sane
It's actually worse than that
I/O affinity

• If you use GPUs or high performance networks, you must allocate host memory close to them
  • Otherwise DMA to GPUs slows down by 10-20% here
  • InfiniBand latency increases by 10%

• Need a way to know which cores/memory is close to which I/O device
Bind your processes
Where does locality actually matter?

- MPI communication performance varies with distance
  - Inside or outside nodes
- Shared memory too (threads, OpenMP, etc.)
  - Synchronization
    - Barriers use caches and memory too
  - Concurrent access to shared buffers
    - Producer-consumer, etc
- 15 years ago, locality was mostly an issue for large NUMA SMP machines (SGI, etc.)
  - Today it's everywhere
    - Because multicore and NUMA are everywhere
What to do about locality in runtimes?

- Place processes/tasks according to their affinities
  - If two tasks communicate/synchronize/share a lot, keep them physically close
    - Main focus of this talk
- Adapt your algorithms to the locality
  - Adapt communication/synchronization implementations to the topology
    - Hierarchical OpenMP barriers
    - Adapt your buffers to (shared) cache size
Process binding

- Some MPI implementations bind processes by default (Intel MPI, Open MPI 1.8 in some cases)
  - Because it's better for reproducibility
- Some don't
  - Because it may hurt your application
    - Oversubscribing? Dynamic processes?
- Binding doesn't guarantee that your processes are optimally placed
  - It just means your processes won't move
    - No migration, less cache issues, etc.
To bind or not to bind?

Zeus MHD Blast. 64 Processes/Cores. Mvapich2 1.8. + ICC
Ok, I need to bind. But where?

- Default binding strategies?
  - By core first (compact, --map-by core, etc.)
    - One process per core on first node, then one process per core on second node, ...
  - By node first (scatter, --map-by node/socket, etc.)
    - One process on first core of each node, then one process on second core of each node, ...

- Your application likely prefers one to the other
  - The first one?
    - Because your algorithms often communicate more between immediate neighbors
  - Sometimes the other one...
Binding strategy impact
How do I choose?

● Dilemma
  ● Use cores 0 & 1 to share cache and improve synchronization cost?
  ● Use cores 0 & 2 to maximize memory bandwidth?
● Depends on the application needs
  ● And machine characteristics
Topology-aware MPI process placement with TreeMatch

- Some tasks communicate a lot with each other
  - The physical distance will slow down some messages
  - Try to keep them close!
- Some don't
  - No constraint on placement
Reordering tasks to improve locality

No binding communication pattern – ZeusMP/2
Metric : msg

TreeMatch communication pattern – ZeusMP/2
Metric : msg
Reordering with TreeMatch

- At process launch-time
  - mpiexec options
- Dynamically
  - MPI_Dist_graph_create() to swap MPI ranks' roles between application steps
  - Charm++ load-balancer

- The communication volume is unchanged
  - But big volumes move inside nodes
- Faster execution!
What's the actual problem?
Example of dual Nehalem Xeon machine
Another example of dual Nehalem Xeon machine

<table>
<thead>
<tr>
<th>Machine (24GB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NUMANode P#0 (12GB)</td>
</tr>
<tr>
<td><strong>Socket P#1</strong></td>
</tr>
<tr>
<td>L3 (8192KB)</td>
</tr>
<tr>
<td>L2 (256KB)</td>
</tr>
<tr>
<td>L1d (32KB)</td>
</tr>
<tr>
<td>L1i (32KB)</td>
</tr>
<tr>
<td>Core P#0</td>
</tr>
<tr>
<td>PU P#0</td>
</tr>
</tbody>
</table>

| NUMANode P#1 (12GB) |
| **Socket P#0** |
| L3 (8192KB) |
| L2 (256KB) | L2 (256KB) | L2 (256KB) | L2 (256KB) |
| L1d (32KB) | L1d (32KB) | L1d (32KB) | L1d (32KB) |
| L1i (32KB) | L1i (32KB) | L1i (32KB) | L1i (32KB) |
| Core P#0 | Core P#1 | Core P#2 | Core P#3 |
| PU P#1 | PU P#3 | PU P#5 | PU P#7 |
Processor and core numbers are crazy

- Resource ordering/numbering is unpredictable
  - Can (and does) change with the vendor, BIOS version, etc.

- Some resources may be unavailable
  - Batch schedulers allocates parts of machines
    - Core numbers may be non-consecutive, not start at 0, etc.

- Don't assume anything about these numbers
  - Otherwise your code won't be portable
Vertical ordering of levels (who contains who)
Vertical ordering isn't reliable either

- Modern processors have 2 NUMA nodes each
  - Xeon E5v3, Opteron 6000, Power8, Sparc64 XIIfx
  - But old platforms have multiple processor packages per NUMA nodes
- Levels of caches and sharing may vary

- Don't assume anything about vertical ordering
  - Or (again) your code won't be portable
  - e.g.: Even the Intel OpenMP binding isn't always correct
Gathering topology information is difficult

- Lack of generic, uniform interface
  - Operating system specific
    - /proc and /sys on Linux
    - rset, sysctl, lgrp, kstat on other OS
  - Hardware specific
    - x86 CPUID instruction, device-tree, PCI config space, etc.

- Evolving technology
  - AMD Bulldozer introduced dual-core Compute Units
    - It's not two real cores, neither one hyper-threaded core
    - New kinds of hierarchy/resources?
  - And some BIOS report buggy information
Binding is difficult too

- Lack of generic, uniform interface (again)
  - Process/thread binding
    - `sched_affinity()` system call changed twice in Linux
  - Memory binding
    - 3 different system-calls on Linux
      - `mbind()`, `migrate_pages()`, `move_pages()`
  - Different constraints
    - Bind to single core only? To contiguous set of cores? To random sets of cores?
  - Many different policies
4 Introducing hwloc (Hardware Locality)
What hwloc is

- Detection of hardware resources
  - Processing units (PU) = logical processors, hardware threads, hyperthreads
    - Things that can run a task
  - Core, packages (sockets), … (things that contain PUs)
  - Memory nodes, shared caches
  - I/O devices
    - PCI devices and corresponding software handles
- Described as a tree
  - Logical resources identification and organization
    - Based on locality
What hwloc is (2/2)

- API and tools to consult the topology
  - Which cores are near this NUMA memory node?
  - Give me a single thread in this package
  - Which NUMA memory node is near this GPU?
  - What shared cache size between these cores?
- Without caring about hardware strangeness
  - Non portable and crazy numbers, names, …
- A portable binding API
  - No more Linux sched_setaffinity() API breakage
  - No more tens of different binding API with different types
What hwloc is **NOT**

- A placement algorithm
  - hwloc gives hardware information
  - You're the one that knows what your software does/needs
  - You're the one that must match software affinities to hardware localities
    - We give you the hardware information you need

- A performance analysis tool
hwloc’s History

- Ideas from Samuel Thibault’s PhD on hierarchical thread scheduling (2003)
- Standalone library to ease MPI process placement (2009)
- Mainly developed by TADaaM@Inria Bordeaux
  - Within the Open MPI consortium
  - Collaboration with many industrial and academic partners
- BSD-3 license
- Many users
Alternative software
with advanced topology knowledge

• **numactl/libnuma**
  • Only for NUMA + hardware threads
    • No cache, core, package/socket, etc.
• **lscpu, lshw, lsusb, …**
  • Specific to some resources
  • Inventory without locality information
• **Likwid (performance optimization tool)**
  • Now uses hwloc internally
• **Intel Compiler (icc)**
  • x86 specific, no API
hwloc Status

- Current stable release: 1.11.3 (April 2016)
- Support for most operating systems and HPC platforms

- Major release every 6 months
  - Backward compatible
- Next major release will be super-major
  - 2.0 expected in 2016H2
  - Will break the ABI (not fully backward compatible)
    - Fix bad ideas from the first hwloc API
hwloc's view of the hardware

• Tree of objects
  • Machines, NUMA memory nodes, packages, caches, cores, threads
    • Logically ordered
  • Grouping similar objects using distances between them
    • Avoids enormous flat topologies
  • Many attributes
    • Memory node size
    • Cache type, size, line size, associativity
    • Physical ordering
    • Miscellaneous info, customizable
Installing hwloc

- Packages available in Debian, Ubuntu, Redhat, Fedora, CentOS, ArchLinux, NetBSD, etc

- You want the development headers too
  - libhwloc-dev, hwloc-devel, …
Manual installation

- Take a recent tarball at http://www.open-mpi.org/projects/hwloc
- Dependencies
  - On Linux, numactl/libnuma development headers
  - Cairo headers for lstopo graphics
- ./configure --prefix=$PWD/install
  - Very few configure options
- Check the summary at the end of configure
Manual installation

• make
• make install

• Useful environment variables

```
export C_INCLUDE_PATH=$C_INCLUDE_PATH:<prefix>/include
export LD_LIBRARY_PATH=$LD_LIBRARY_PATH:<prefix>/lib
export PKG_CONFIG_PATH=$PKG_CONFIG_PATH:<prefix>/lib/pkgconfig
export PATH=$PATH:<prefix>/bin
export MANPATH=$MANPATH:<prefix>/share/man
```
Using hwloc for this tutorial

- Install hwloc on your preferred cluster
- And install it on your laptop too
  - It will make remote machine consulting easier
Using hwloc

- Many hwloc command-line tools
  - lstopo and hwloc-*
- ... but the actual hwloc power is in the C API
- Perl and Python bindings
5 Command-line Tools
Istopo (displaying topologies)

Machine (3828MB)
- Package L#0 + L3 L#0 (4096KB)
  - L2 L#0 (256KB) + Core L#0
    - PU L#0 (P#0)
    - PU L#1 (P#2)
  - L2 L#1 (256KB) + Core L#1
    - PU L#2 (P#1)
    - PU L#3 (P#3)
- HostBridge L#0
  - PCI 8086:0046
    - GPU L#0 "controlD64"
  - PCI 8086:10ea
    - Net L#2 "eth0"
- PCIBridge
  - PCI 8086:422b
    - Net L#3 "wlan0"
  - PCI 8086:3b2f
    - Block L#4 "sda"
    - Block L#5 "sr0"
Istopo

- Many output formats
  - Text, Cairo (PDF, PNG, SVG, PS), Xfig, ncurses
    - Automatically guessed from the file extension
- XML dump/reload
  - Faster, convenient for remote debugging
- Configuration options for nice figures for papers
  - Horizontal/Vertical placement
  - Legend
  - Ignoring some resources
  - Creating fake topologies
lstopo

$ lstopo
$ lstopo --no-io -
$ lstopo myfile.png
$ ssh host lstopo saved.xml
$ lstopo -i saved.xml
$ ssh myhost lstopo -.xml | lstopo --if xml -i -
$ lstopo -i “numa:4 package:2 core:2 pu:2”
hwloc-bind
(binding processes, threads and memory)

- Bind a process to a given set of CPUs
  
  $ hwloc-bind package:1 -- mycommand myargs...
  
  $ hwloc-bind os=mlx4_0 -- mympiprogram ...

- Bind an existing process
  
  $ hwloc-bind --pid 1234 numa:0

- Bind memory
  
  $ hwloc-bind --membind numa:1 --cpubind numa:0 ...

- Find out if a process is already bound
  
  $ hwloc-bind --get --pid 1234
  
  $ hwloc-ps
hwloc-calc
(calculating with objects)

- Convert between ways to designate sets of CPUs, objects... and combine them
  $ hwloc-calc package:1.core:1 ~pu:even 0x00000008
  $ hwloc-calc --number-of core numa:0 2
  $ hwloc-calc --intersect pu package:1 2,3
- The result may be passed to other tools
- Multiple invocations may be combined
- I/O devices also supported
  $ hwloc-calc os=eth0
Other tools

• Get some object information
  • hwloc-info

• Generate bitmaps for distributing multiple processes on a topology
  • hwloc-distrib

• Save a Linux node topology info for debugging
  • hwloc-gather-topology

• Manipulating multiple topologies, etc.
Hands-on Istopo

- Gather the topology of one server
- Display it on another machine
- Hide caches
- Remove the legend
- Restrict the display to a single package
- Export to PDF
Hands-on hwloc-bind and hwloc-calc

- Bind a process to a core and verify its binding
- Find out how many cores are in the second NUMA node
- Find out the physical numbers of all non-first hyperthreads
- Find out which cores are close to InfiniBand
- Compare the DMA bandwidth from GPU#0 to both NUMA nodes using cudabw
6 C Programming API
API basics

- A hwloc program looks like this

```c
#include <hwloc.h>

hwloc_topology_t topo;

hwloc_topology_init(&topo);
/* ... configure what topology to build ... */
hwloc_topology_load(topo);

/* ... play with the topology ... */

hwloc_topology_destroy(topo);
```
Major hwloc types

- The topology context : `hwloc_topology_t`
  - You always need one
- The main hwloc object : `hwloc_obj_t`
  - That's where the actual info is
  - The structure isn't opaque
    - It contains many pointers to ease traversal
- Object type : `hwloc_obj_type_t`
  - `HWLOC_OBJ_PU, _PACKAGE, _CORE, _NUMANODE, ...`
Object information

- Type
- Optional name string
- Indexes (see later)
- cpusets and nodesets (see later)
- Tree pointers (*cousin, *sibling, arity, *child*, parent)
- Type-specific attribute union
  - obj->attr->cache.size
  - obj->attr->pcidev.linkspeed
- String info pairs
Browsing as a tree

- The root is `hwloc_get_root_obj(topo)`
- Objects have children
  - `obj->arity` is the number of children
  - The array of children is `obj->children[]`
  - They are also in a list
    - `obj->first_child`, `obj->last_child`
    - `child->prev_sibling`, `child->next_sibling`
    - NULL-terminated
- The parent is `obj->parent` (or NULL)
Browsing as levels

- The topology is also organized as levels of identical objects
  - Cores, L2d Caches, ...
  - All PUs at the bottom
- Number of levels \texttt{hwloc\_topology\_get\_depth(topo)}
- Number of objects on a level
  \texttt{hwloc\_get\_nbobjs\_by\_type(topo, type)}
  \texttt{hwloc\_get\_nbobjs\_by\_depth(topo, depth)}
- Convert between depth and type using
  \texttt{hwloc\_get\_type\_depth()} or \texttt{hwloc\_get\_depth\_type()}


Browsing as levels

- Find objects by level and index
  - `hwloc_get_obj_by_type(topo, type, index)`
  - There are variants taking a depth instead of a type
    - Note: the depth of my child is not always my depth + 1
      - Think of asymmetric topologies
- Iterate over objects of a level
  - Objects at the same levels are also interconnect by prev/next_cousin pointers
    - Don't mix up siblings (children list) and cousins (level)
  - `hwloc_get_next_obj_by_type/depth()`
Hands-on browsing the topology

Starting from basic.c

- Print the number of cores
- Print the type of the common ancestor of cores 0 and 2
- Print the memory size near core 0
- Iterate over all PUs and print their physical numbers
Physical or OS indexes

- `obj->os_index`
  - The ID given by the OS/hardware
- P#3
  - Default in `lstopo` graphic mode
  - `lstopo -p`
- NON PORTABLE
  - Depend on motherboards, BIOS, version, ...
- DON'T USE THEM
Logical indexes

- `obj->logical_index`
  - The index among an entire level
- L#2
  - Default in lstopo except in graphic mode
  - lstopo -l
- Always represent proximity (depth-first walk)
- PORTABLE
  - Does not depend on OS/BIOS/weather
- That's what you want to use
But I still need OS indexes when binding?! 

- NO!
- Just use hwloc for binding, you won't need physical/OS indexes ever again

- If you want to bind the execution to a core
  - `hwloc_set_cpubind(core->cpuset)`
    - Other API functions for binding entire processes, single thread, memory, for allocating bound memory, etc.
Bitmap, CPU sets, Node sets

- Generic mask of bits: `hwloc_bitmap_t`
  - Possibly infinite
  - Opaque, used to describe object contents
    - Which PU are inside this object (`obj->cpuset`)
    - Which NUMA nodes are close to this object (`obj->nodeset`)
  - Can be combined to bind to multiple cores, etc.
    - and, or, xor, not, ...
Hands-on bitmaps and binding

- Bind a process to 1st core
- Rebind the same process to cores 2 and 4
- Print its binding
- Print where it's actually running
  - Repeat
- Rebind to avoid migrating between cores
  - hwloc_bitmap_singlify()
I/O devices

• Binding tasks near the devices they use improves their data transfer time
  • GPUs, high-performance NICs, InfiniBand, …

• You cannot bind tasks or memory on these devices
  • But these devices may have interesting attributes
    • Device type, GPU capabilities, embedded memory, link speed, …
I/O objects

- Some I/O trees are attached to the object they are close to
- PCI device objects
  - Optional I/O bridge objects
- How to match your software handle with a PCI device?
  - OS/Software devices (when known)
    - sda, eth0, ib0, mlx4_0
  - Disabled by default
    - Except in lstopo
Hands-on I/O

- Load cuda modules, etc.

Starting from cuda.c
- Find the NUMA node near each CUDA device

Starting from ib.c
- Find the NUMA node near each IB device
Extended attributes

- obj->userdata pointer
  - Your application may store whatever it needs there
  - hwloc won't look at it, it doesn't know what's it contains

- (name,value) info attributes
  - Basic string annotations, hwloc adds some
    - Hostname, Kernel release, CPU model, PCI vendor, ...
    - See lstopo -v for (many) examples
  - You may add your own
Configuring the topology

- Between `hwloc_topology_init()` and `load()`
  - `hwloc_topology_set_xml()`, `set.synthetic()`
  - `hwloc_topology_set_flags()`, `set.pid()`
  - `hwloc_topology_ignore_type()`

- After `hwloc_topology_load()`
  - `hwloc_topology_restrict()`
  - `hwloc_topology_insert_misc_object...`
Helpers

- hwloc/helper.h contains a lot of helper functions
  - Iterators on levels, children, restricted levels
  - Finding caches
  - Converting between cpusets and nodesets
  - Finding I/O objects
  - And much more
- Use them to avoid rewriting basic functions
- Use them to understand how things work and write what you need
8 Conclusion
More information

- The documentation
- Related pages
- FAQ
- README and HACKING in the source
- hwloc-users@open-mpi.org for questions
- hwloc-devel@open-mpi.org for contributing
- hwloc-announce@open-mpi.org for new releases
- https://github.com/open-mpi/hwloc/issues for reporting bugs
Thanks!

Questions?

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

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