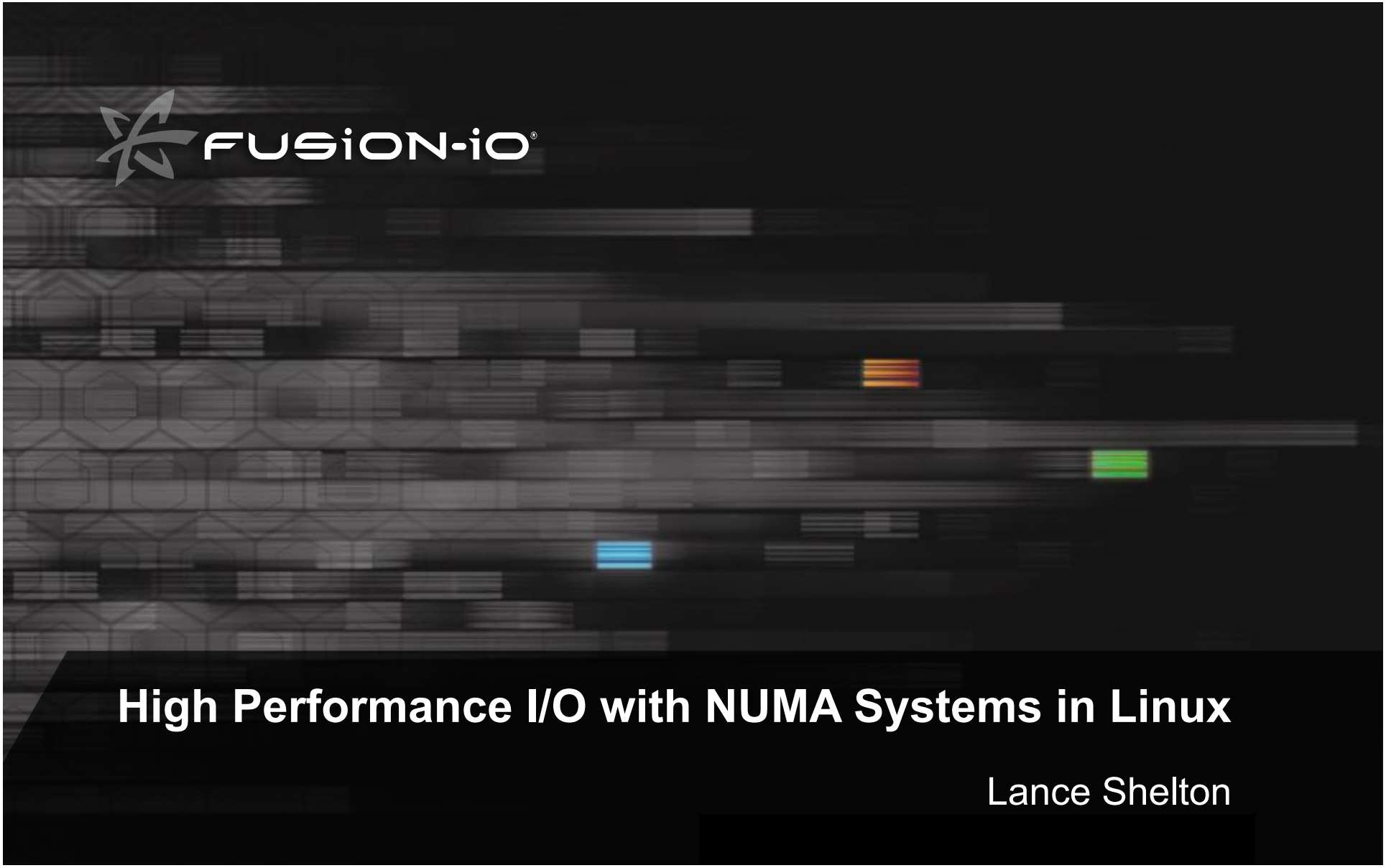


High Performance I/O with NUMA Systems in Linux

Lance Shelton

How prevalent is NUMA?

- All major vendors
  - HP, Dell, IBM, Cisco, SuperMicro, Hitachi, etc.
- As small as 1U
- 2, 4, and 8 socket systems
- 2 to 10 cores per socket
- Number of cores doubles with HyperThreading

  8 x 10 x 2 = 160 CPU cores

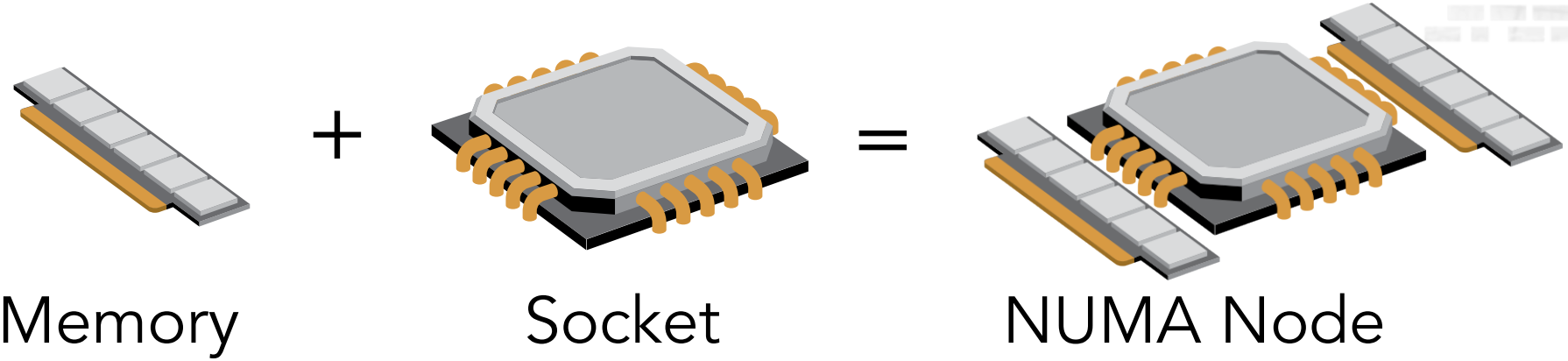
NUMA is mainstream.

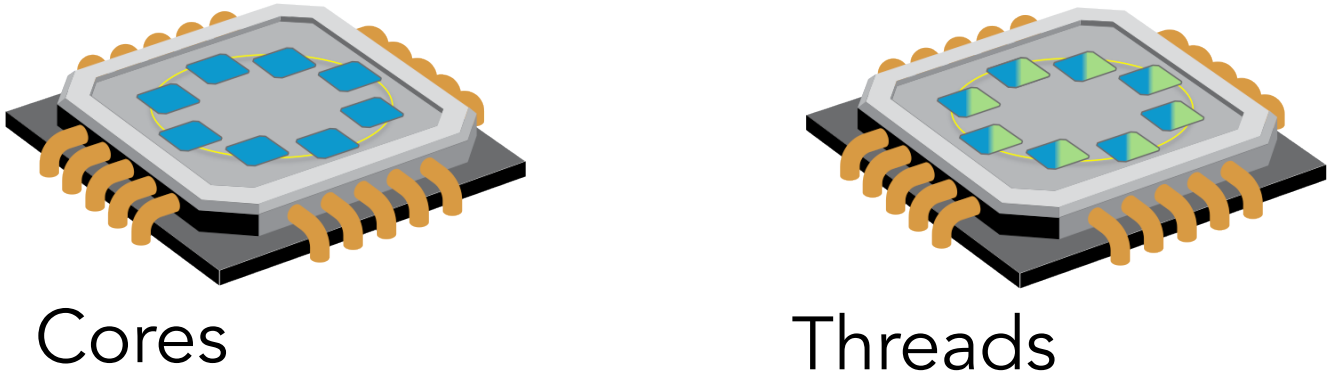
Why use large NUMA servers?

- NUMA is key to the current evolution of performance
  - Storage rates are drastically increasing
  - Processor speeds are stagnant
  - Multi-core cannot scale infinitely without NUMA

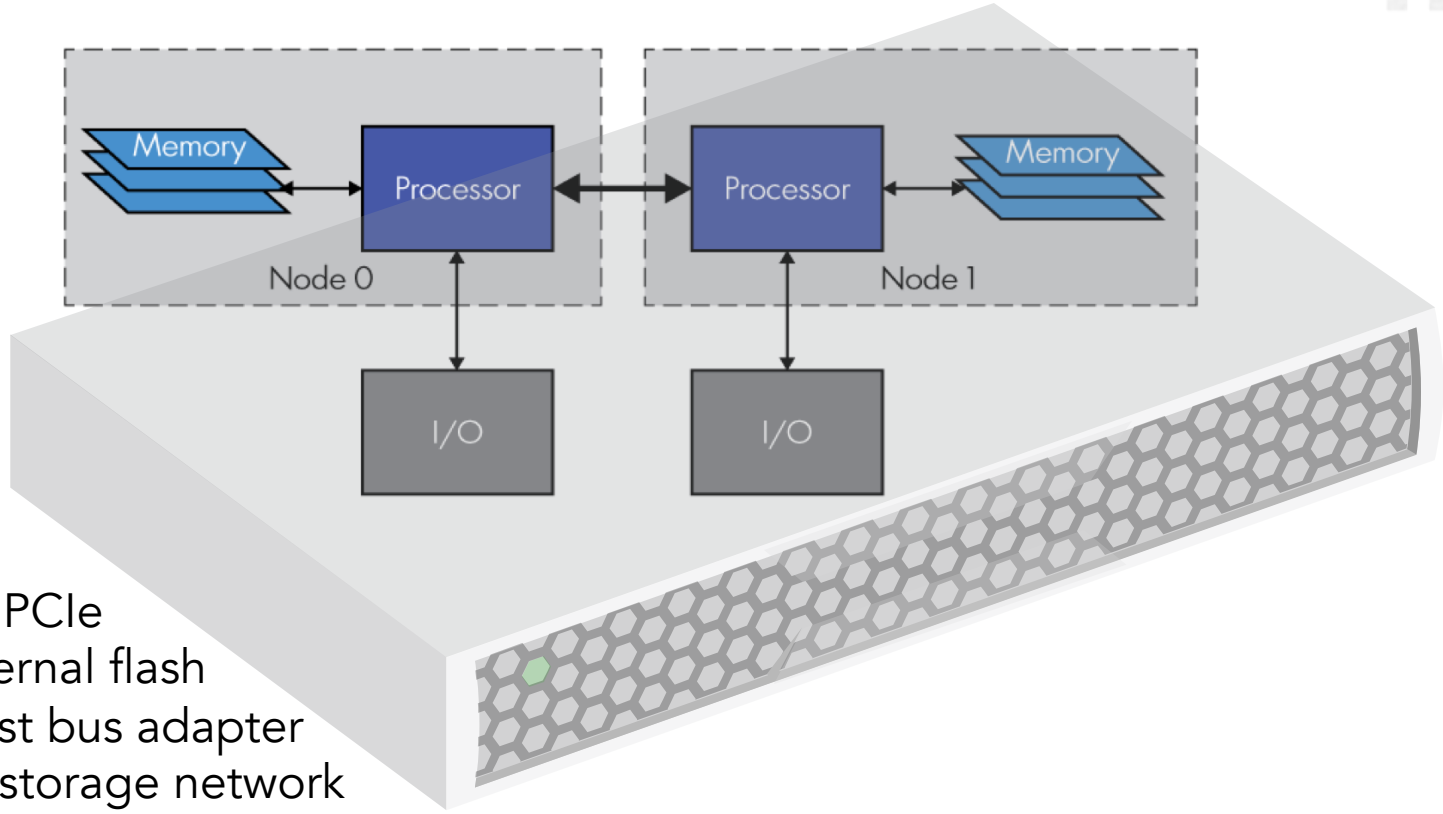
- NUMA meets the needs of the application
  - No partitioning is required
  - Faster than clustering multiple servers
  - Works well in combination with scale out

Nodes, Sockets, Cores, Threads





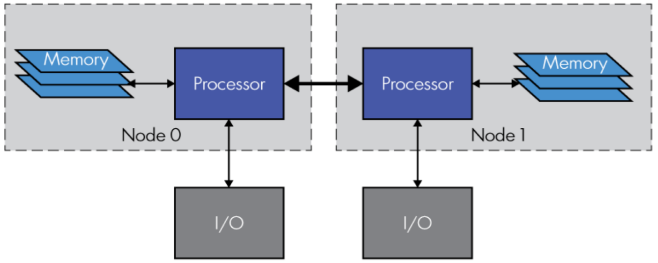
Non-Uniform I/O Access

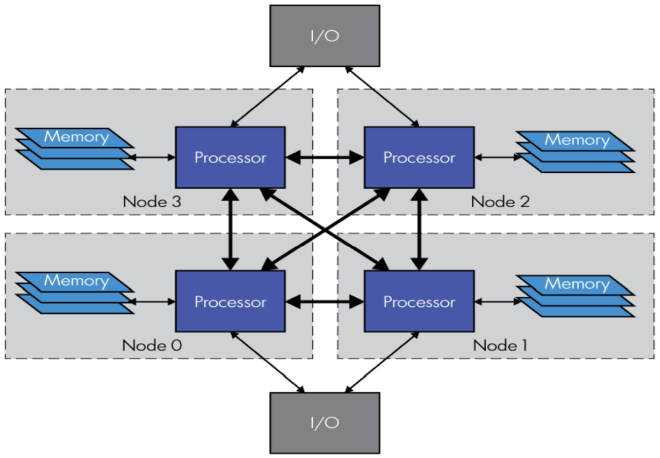


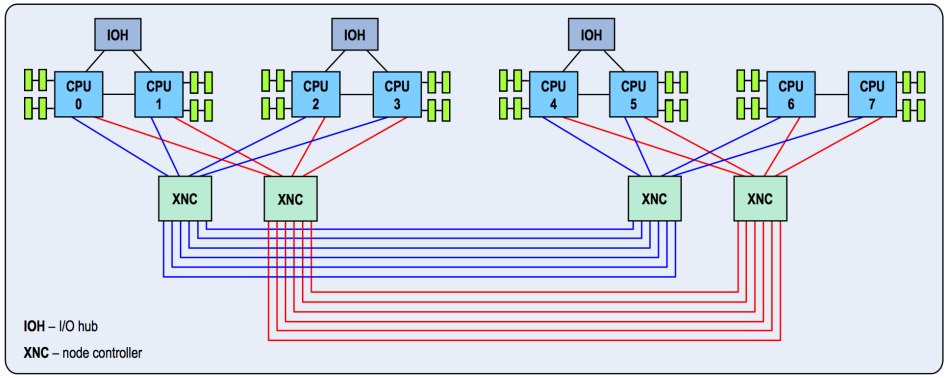
I/O = PCIe

- Internal flash
- Host bus adapter to storage network

2, 4, and 8 Socket Servers

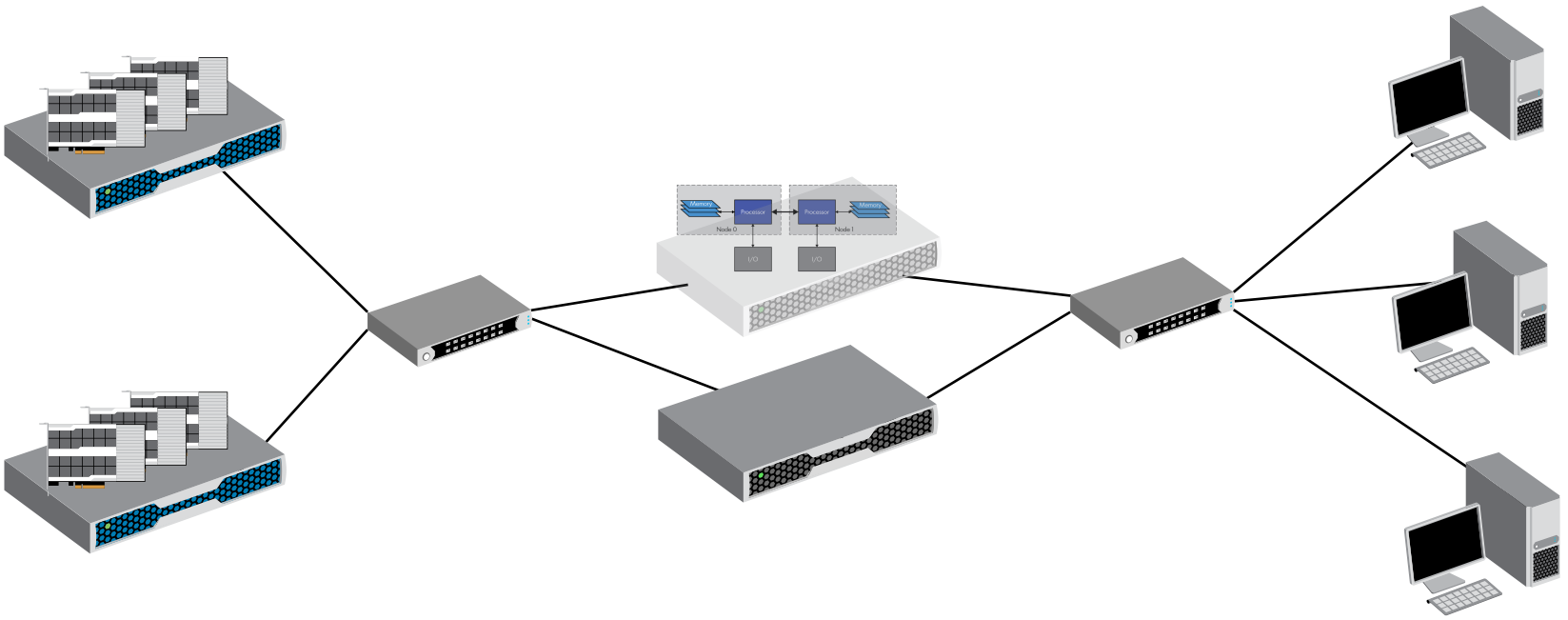




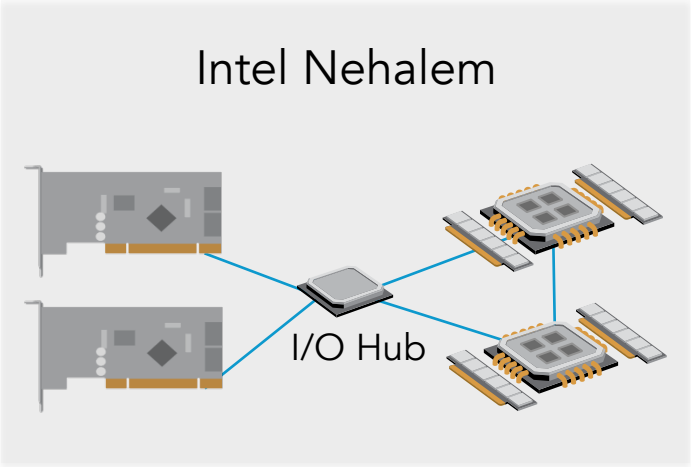


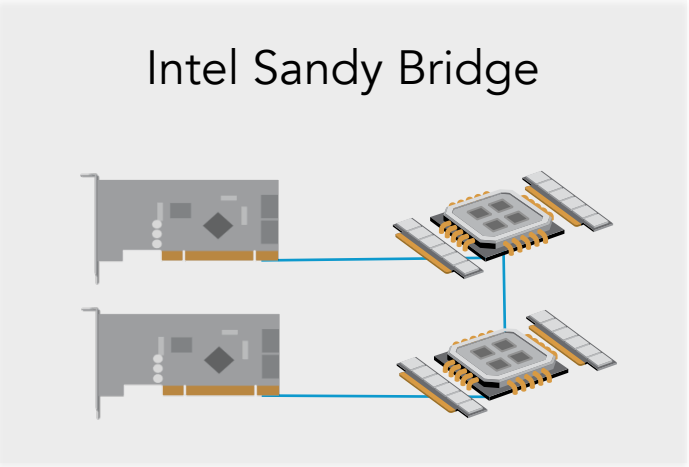

```
# numactl --hardware
node   0   1   2   3   4   5   6   7
  0:  10  12  17  17  19  19  19  19
  1:  12  10  17  17  19  19  19  19
  2:  17  17  10  12  19  19  19  19
  3:  17  17  12  10  19  19  19  19
  4:  19  19  19  19  10  12  17  17
  5:  19  19  19  19  12  10  17  17
  6:  19  19  19  19  17  17  10  12
  7:  19  19  19  19  17  17  12  10
```

Enterprise Storage

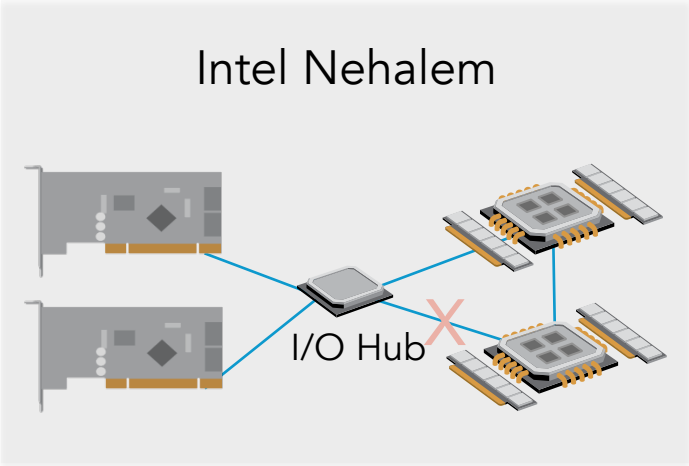


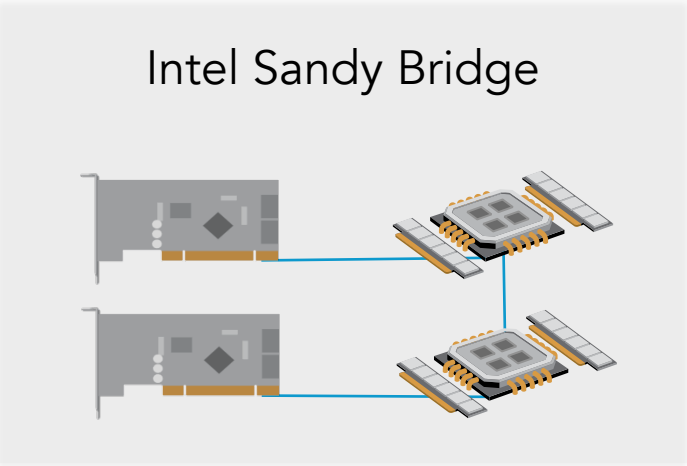
PCIe Local Nodes





PCIe Local Nodes

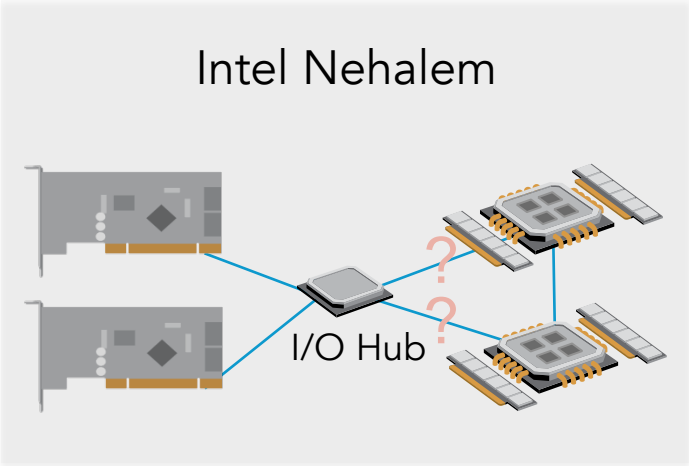


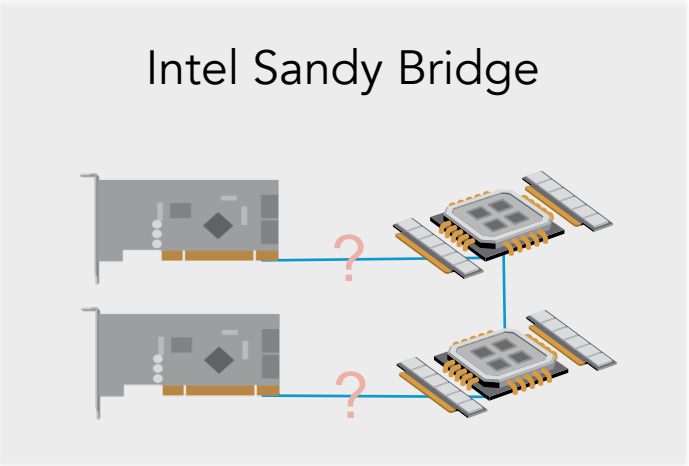



```
# cat /sys/devices/pci0000:50/0000:50:09.0/numa_node
0
```

Only one local node is presented to the OS

PCIe Local Node?

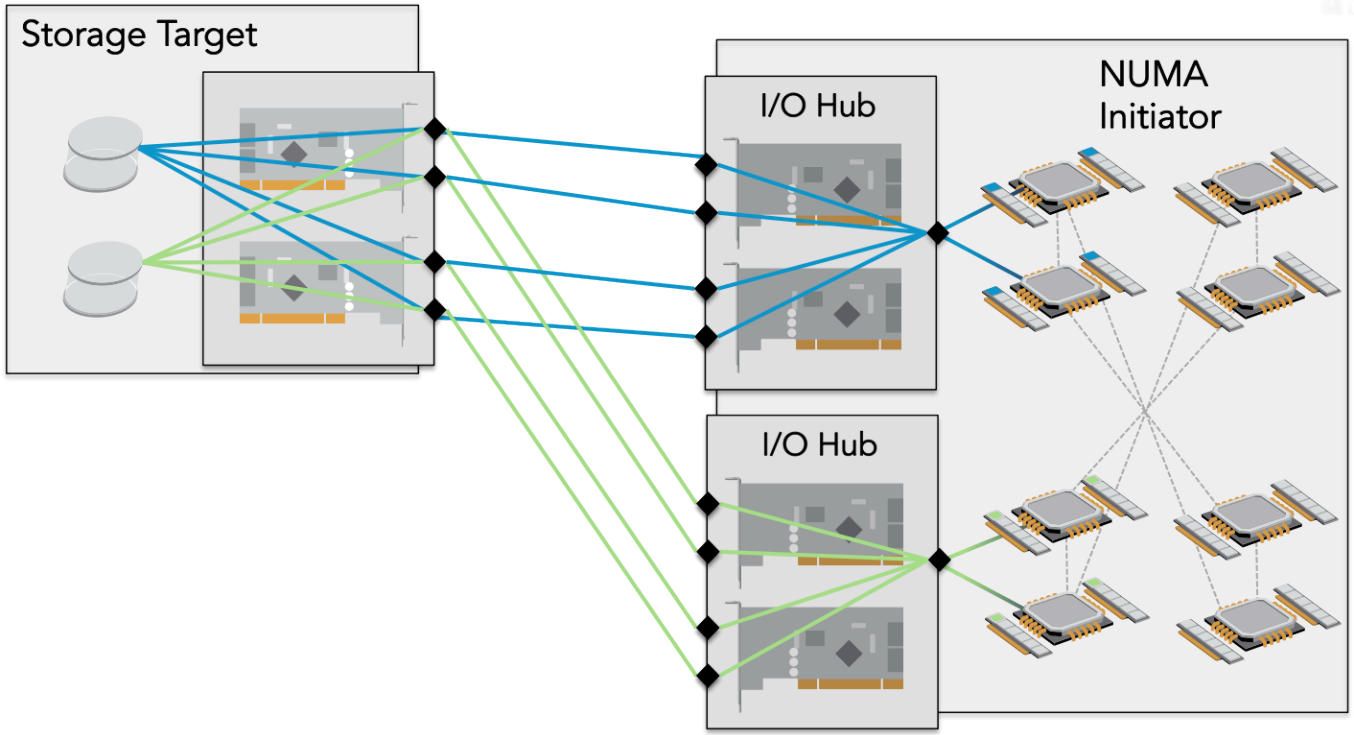





```
# cat /sys/devices/pci0000:50/0000:50:09.0/numa_node
-1
```

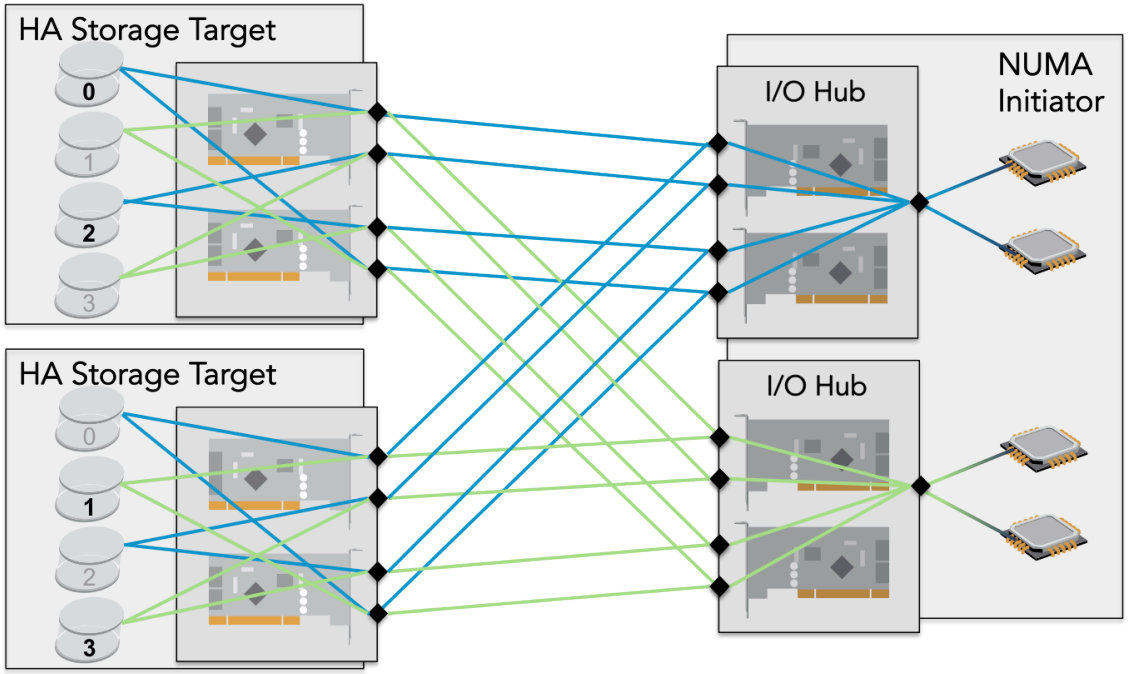
Not detected? Update the BIOS.

Localizing I/O from Storage



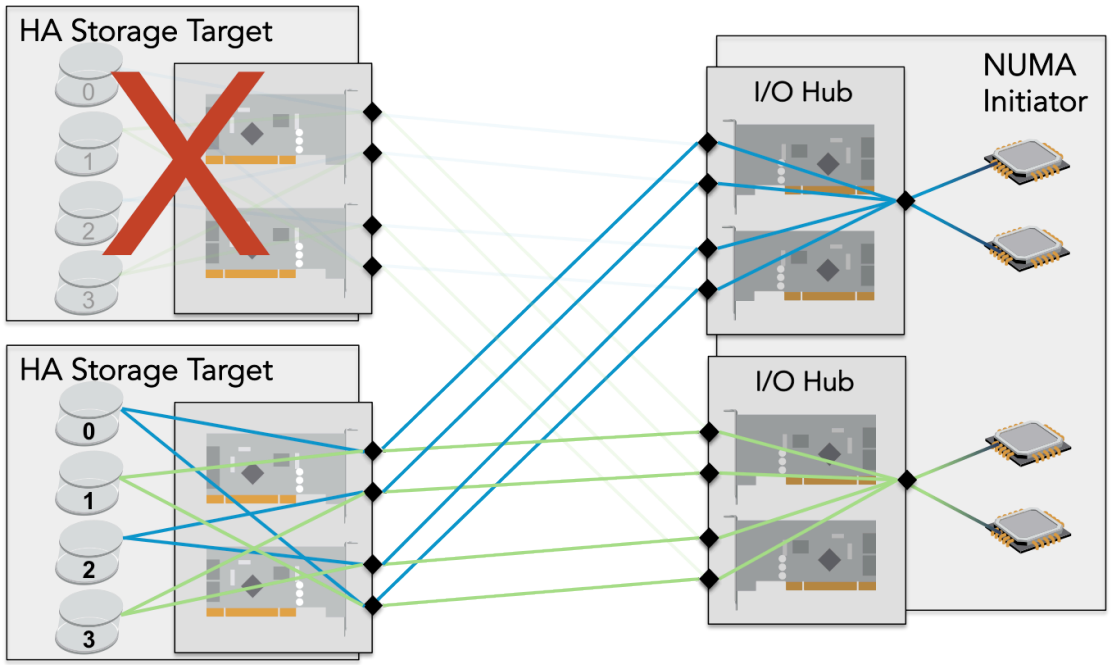
- 50-100% performance improvement vs. non-NUMA aware volume placement

Localizing I/O – High Availability



- Node locality of volumes must still be maintained

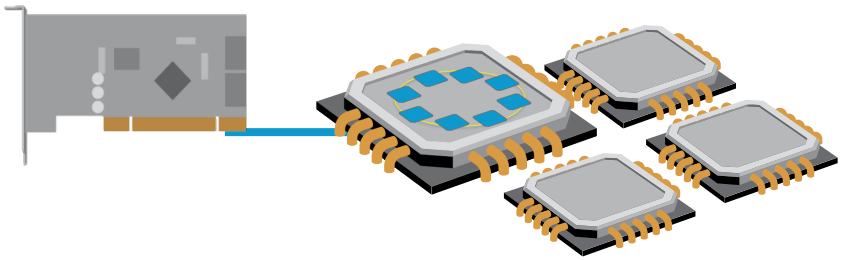
Localizing I/O – HA Failover



- Node locality maintained
- All available ports are still used

Localizing I/O – Components

- HBA placement
- Interrupt affinity
- Kernel thread affinity
- Application affinity



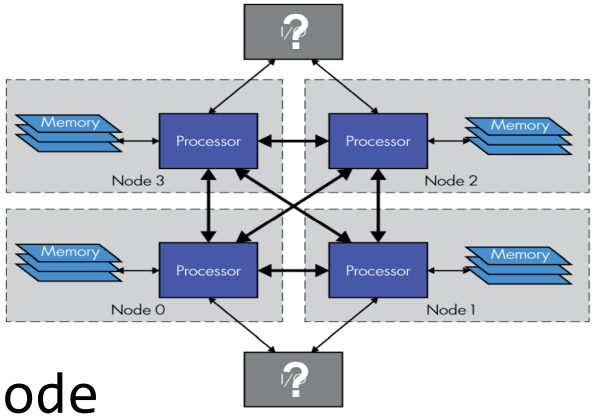
Analyze everything in the data path.

Localize all components to the HBA local nodes.

Reduces latency and improves caching

Discovering Device Locality

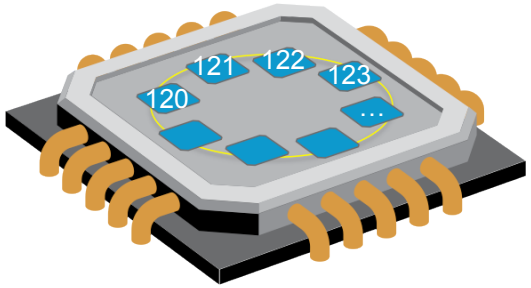
- Devices associated with each volume
  - `multipath -ll`
  - `ls -d /sys/bus/pci/devices/*/host*`
- Device location
  - `dmidecode -t slot`
  - `lspci -tv`
- NUMA node of devices
  - `/sys/devices/pci*/*/numa_node`



Pinning Interrupts

- Pin IRQs to the local node
- Distribute IRQs between cores in the local node

```
# grep [driver] /proc/interrupts
[num]: ...
# cat /proc/irq/[num]/node
[node]
# echo [CPU mask] > /proc/irq/[num]/smp_affinity
```



~100% improvement

Reduces latency & CPU contention, improves caching

Persistently Pinning Interrupts

- irqbalance: run-time load balancing
  - Mixed results
  - Better with RHEL 6.4 + kernel update + Sandy Bridge
- Customized init service to set affinity on boot
  - Best results for a known application

Driver Kernel Thread Affinity

- Sometimes handled by Linux drivers
- Verify and adjust

```
# taskset -p -c [cpumask] [pid]
pid [pid]'s current affinity list: 0-159
pid [pid]'s new affinity list: 20-29
```

Block Device Tuning

```
# echo noop > /sys/block/[device]/queue/scheduler
```

- 10% improvement

```
# echo 0 > /sys/block/[device]/queue/add_random
```

- 10% improvement

```
# echo 2 > /sys/block/[device]/queue/rq_affinity
```

- 5% improvement

```
# echo [0 or 1] > /sys/block/[device]/queue/rotational
```

- Mixed results

Reduces latency and CPU utilization

Persistent Block Device Tuning

- udev rules (/etc/udev/rules.d/)
  - I/O devices

```
ACTION=="add|change", SUBSYSTEM=="block", ATTR{device/vendor}=="FUSIONIO", ATTR{queue/scheduler}
="noop", ATTR{queue/rq_affinity}="2", ATTR{queue/add_random}="0”
```

  - devices with I/O slave devices (DM multipath)

```
ACTION=="add|change", KERNEL=="dm-*", PROGRAM="/bin/bash -c 'cat /sys/block/$name/slaves/*/device/
vendor | grep FUSIONIO'", ATTR{queue/scheduler}="noop", ATTR{queue/rq_affinity}="2", ATTR{queue/
add_random}="0"
```

Note: udev rules may only rely on sysfs parameters that are available at the time the device is created.

Power/Performance Tuning

- Disable c-states in the BIOS
- Disable c-states in the boot loader (grub)
  - intel_idle.max_cstate=0
  - processor.max_cstate=0
- 10% improvement

Keeping processors in active states reduces latency

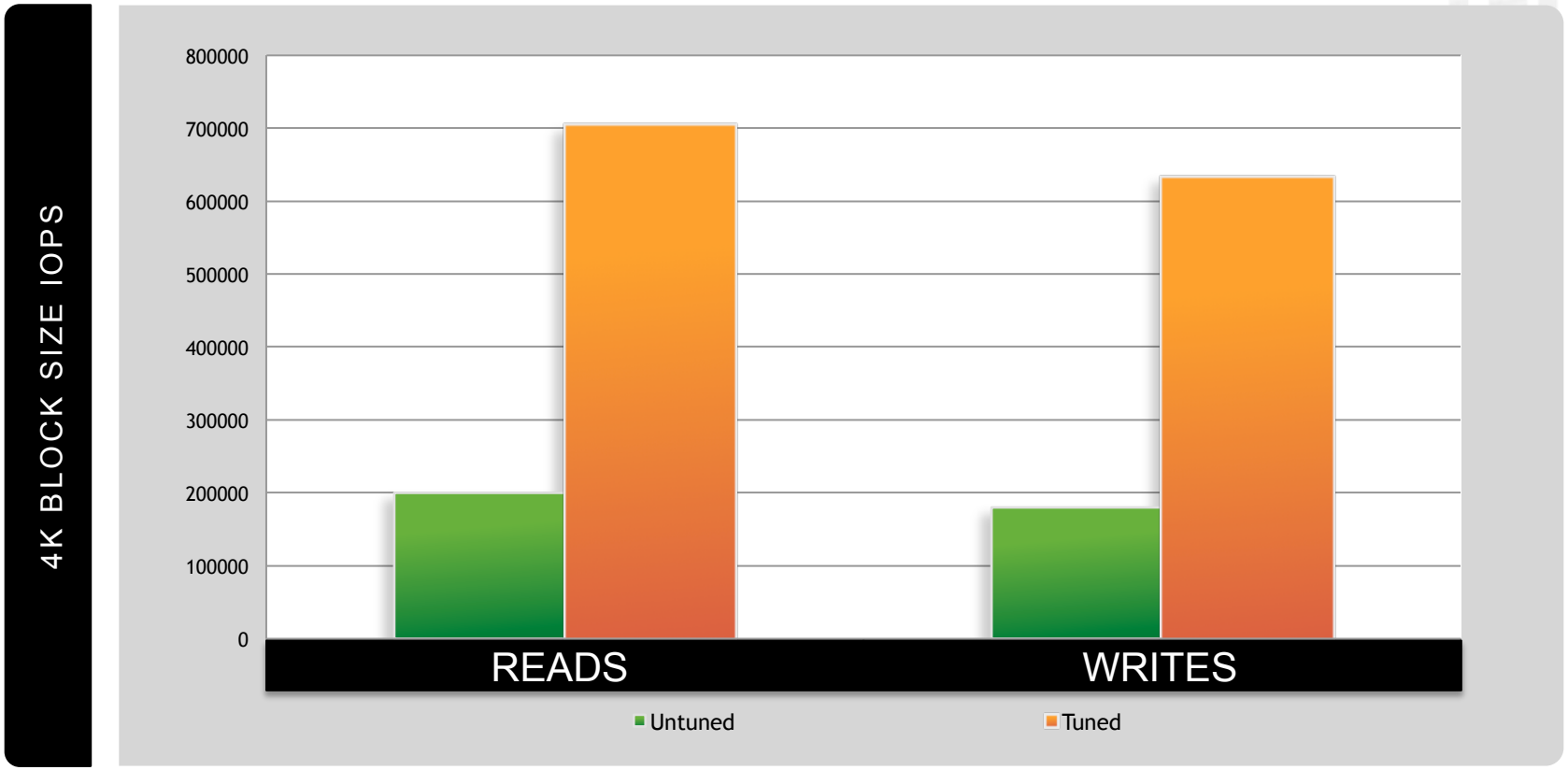
Application Tuning

- OS-provided tools
  - taskset
  - cgroups
  - numad
- Application-specific settings
  - Oracle
    - _enable_NUMA_support

Benchmarking Performance

- Test thread affinity
  - FIO
    - cpus_allowed
    - numa_cpu_nodes
    - numa_mem_policy
  - Oracle Orion and others
    - taskset -c [cpulist] [test command]
- Measuring performance
  - iostat
  - Application-specific

8 Socket Total Performance Gains



Tools for NUMA Tuning

- numactl
- taskset
- dmidecode
- irqbalance
- top
- htop
- irqstat
- cgroups
- lstopo
- sysfs
- numad
- numatop
- tuna
- tuned

top: terminal is not big enough

root@RHEL980:~ root@RHEL980:~ ssh ...

```
top - 13:31:23 up 1 day,  5:17,  2 users,  load average: 3.66, 0.96, 0.42
Tasks: 3897 total,   1 running, 3896 sleeping,   0 stopped,   0 zombie
Cpu(s):  0.2%us,  1.4%sy,  0.0%ni, 95.7%id,  0.5%wa,  0.0%hi,  2.2%si,  0.0%st
Mem:  264521876k total, 118689448k used, 145832428k free,   243928k buffers
Swap: 20971504k total,        0k used, 20971504k free,  2139856k cached
 Sorry, terminal is not big enough
  PID USER      PR  NI  VIRT  RES  SHR S %CPU %MEM    TIME+  COMMAND
124807 root      20   0  824m  59m  48m S 583.5  0.0   1:47.06 fio
    89 root      20   0     0    0    0 S  5.1  0.0   0:46.11 ksoftirqd/21
    85 root      20   0     0    0    0 S  4.5  0.0   0:36.00 ksoftirqd/20
   405 root      20   0     0    0    0 S  4.5  0.0   0:37.30 ksoftirqd/100
   421 root      20   0     0    0    0 S  4.2  0.0   0:12.97 ksoftirqd/104
124743 root      20   0 17964 4232  956 R  3.9  0.0   0:02.39 top
   121 root      20   0     0    0    0 S  2.6  0.0   0:10.04 ksoftirqd/29
   441 root      20   0     0    0    0 S  2.6  0.0   0:10.26 ksoftirqd/109
   101 root      20   0     0    0    0 S  2.2  0.0   0:13.09 ksoftirqd/24
   113 root      20   0     0    0    0 S  1.3  0.0   0:16.79 ksoftirqd/27
 10953 oracle    20   0 1388m 135m 114m S  1.3  0.1  24:00.31 oracle
   409 root      20   0     0    0    0 S  1.0  0.0   0:12.80 ksoftirqd/101
   413 root      20   0     0    0    0 S  1.0  0.0   0:24.10 ksoftirqd/102
   425 root      20   0     0    0    0 S  1.0  0.0   0:05.92 ksoftirqd/105
   437 root      20   0     0    0    0 S  1.0  0.0   0:08.67 ksoftirqd/108
 10945 oracle    -2   0 1365m  14m  12m S  1.0  0.0   6:36.87 oracle
    97 root      20   0     0    0    0 S  0.6  0.0   0:31.75 ksoftirqd/23
   117 root      20   0     0    0    0 S  0.6  0.0   0:08.93 ksoftirqd/28
```

(top in RHEL 6.4)

mpstat with 160 cores

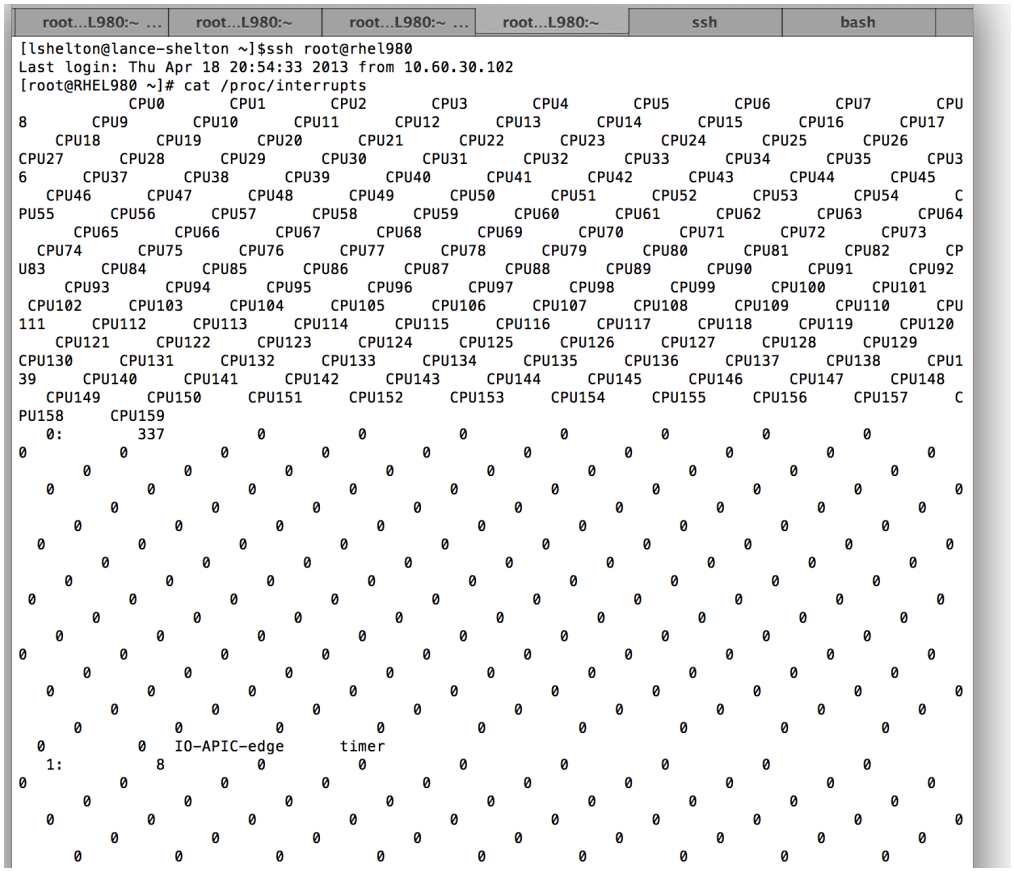
root@RHEL980:~ root@RHEL980:~ ssh ...

```
[root@RHEL980 ~]# mpstat -I ALL
Linux 2.6.32-358.el6.x86_64 (RHEL980.int.fusionio.com)  04/13/2013      _x86_64_        (16

01:57:00 PM  CPU    intr/s
01:57:00 PM  all  14284.04

01:57:00 PM  CPU        0/s        1/s        3/s        4/s        8/s        9/s       12
      103/s      104/s      105/s      106/s      107/s      108/s      109/s      110/s
 120/s      121/s      122/s      123/s      124/s      125/s      126/s      127/s      12
s      138/s      139/s      140/s      141/s      NMI/s      LOC/s      SPU/s      PMI/s
  MIS/s
01:57:00 PM    0       0.01       0.00       0.00       0.00       0.00       0.00       0.
       0.01       0.08       0.00       0.00       0.01       0.00       0.01       0.00
  0.00       0.00       0.00       0.00       0.00       0.00       0.92       0.22       0
0       0.00       0.00       0.00       0.00       0.01      19.33       0.00       0.01
   0.00
01:57:00 PM    1       0.00       0.00       0.00       0.00       0.00       0.00       0.
       0.00       0.00       0.00       0.00     131.68       0.00       0.00       0.00
  0.00       0.00       0.00       0.00       0.00       0.00       0.00       0.00       0
0       0.00       0.00       0.00       0.00       0.02      15.82       0.00       0.02
   0.00
01:57:00 PM    2       0.00       0.00       0.00       0.00       0.00       0.00       0.
       0.00       0.00       0.00       0.00       0.00       0.00       0.00       0.00
  0.00       0.00       0.00       0.00       0.00       0.00       0.00       0.00       0
0       0.00       0.00       0.00       0.00       0.01       4.17       0.00       0.01
```

/proc/interrupts with 160 cores



top: added NUMA support

```
root@RHEL980:~                    root@RHEL980:~        ssh ...
lt-top - 13:32:31 up 1 day,  5:18,  2 users,  load average: 10.55, 3.58, 1.36
Tasks: 3898 total,   1 running, 3897 sleeping,   0 stopped,   0 zombie
%Cpu(s):  0.2 us,  1.3 sy,  0.0 ni, 95.7 id,  0.6 wa,  0.0 hi,  2.2 si,  0.0 st
%Node0 :  0.6 us,  4.4 sy,  0.0 ni, 82.7 id,  3.6 wa,  0.0 hi,  8.7 si,  0.0 st
%Node1 :  0.1 us,  0.1 sy,  0.0 ni, 99.8 id,  0.0 wa,  0.0 hi,  0.0 si,  0.0 st
%Node2 :  0.8 us,  5.9 sy,  0.0 ni, 82.2 id,  1.2 wa,  0.0 hi, 10.0 si,  0.0 st
%Node3 :  0.0 us,  0.0 sy,  0.0 ni,100.0 id,  0.0 wa,  0.0 hi,  0.0 si,  0.0 st
%Node4 :  0.0 us,  0.0 sy,  0.0 ni,100.0 id,  0.0 wa,  0.0 hi,  0.0 si,  0.0 st
%Node5 :  0.0 us,  0.0 sy,  0.0 ni,100.0 id,  0.0 wa,  0.0 hi,  0.0 si,  0.0 st
%Node6 :  0.0 us,  0.0 sy,  0.0 ni,100.0 id,  0.0 wa,  0.0 hi,  0.0 si,  0.0 st
%Node7 :  0.0 us,  0.0 sy,  0.0 ni,100.0 id,  0.0 wa,  0.0 hi,  0.0 si,  0.0 st
KiB Mem:  26452187+total, 11869251+used, 14582937+free,   243976 buffers
KiB Swap: 20971504 total,        0 used, 20971504 free,  2140132 cached

  PID USER      PR  NI    VIRT    RES    SHR S  %CPU  %MEM     TIME+ COMMAND
124807 root      20   0  843984  60460  50076 S 578.6 0.023   8:37.67 fio
    89 root      20   0       0      0      0 S 6.097 0.000   0:48.85 ksoftirqd/21
    93 root      20   0       0      0      0 S 5.776 0.000   0:25.55 ksoftirqd/22
   413 root      20   0       0      0      0 S 4.172 0.000   0:25.72 ksoftirqd/102
    97 root      20   0       0      0      0 S 3.851 0.000   0:33.76 ksoftirqd/23
124881 root      20   0  117652   4820   1136 R 3.851 0.002   0:01.37 lt-top
   105 root      20   0       0      0      0 S 2.888 0.000   0:18.82 ksoftirqd/25
   405 root      20   0       0      0      0 S 2.567 0.000   0:39.12 ksoftirqd/100
   425 root      20   0       0      0      0 S 2.567 0.000   0:06.28 ksoftirqd/105
    85 root      20   0       0      0      0 S 2.246 0.000   0:37.75 ksoftirqd/20
```

https://gitorious.org/procps/procps

irqstat: IRQ viewer for NUMA

root@RHEL980:~/numatools | root@RHEL980:~ ssh ...

```
IRQs / 5 second(s)
IRQ#  TOTAL  NODE0  NODE1  NODE2  NODE3  NODE4  NODE5  NODE6  NODE7  NAME
 125 361145      0      0 361145      0      0      0      0      0  PCI-MSI-edge qla2xxx
 123 356357      0      0 356357      0      0      0      0      0  PCI-MSI-edge qla2xxx
 109  46118  46118      0      0      0      0      0      0      0  PCI-MSI-edge lpfc:fp
 111  46085  46085      0      0      0      0      0      0      0  PCI-MSI-edge lpfc:fp
 115  44369      0      0  44369      0      0      0      0      0  PCI-MSI-edge lpfc:fp
 117  43951      0      0  43951      0      0      0      0      0  PCI-MSI-edge lpfc:fp
 107  37149  37149      0      0      0      0      0      0      0  PCI-MSI-edge lpfc:fp
 113  36305  36305      0      0      0      0      0      0      0  PCI-MSI-edge lpfc:fp
 126     11     11      0      0      0      0      0      0      0  PCI-MSI-edge eth0[0]
 129      5      5      0      0      0      0      0      0      0  PCI-MSI-edge eth0[3]
```

https://github.com/lanceshelton/irqstat

Must end users be NUMA-aware?

- Unfortunately, yes.
  - Users must be aware of PCIe device slot placement
  - Optimal NUMA tuning is not yet performed by the OS
  - Persistent tuning is a non-trivial task
  - Performance challenges are changing faster than tools

How can this be improved?

- NUMA architectures must be detected properly and tuned by default
  - Phase out Nehalem or add SLIT support for multiple local nodes
- Linux distributions need to provide optimal tuning across applications and devices at the OS level
- Improve existing tools

What's next?

- More cores per socket
  - 15 core CPUs by the end of next year?
- Removal of existing bottlenecks
  - Multi-queue block layer
- Improved tools
  - numatop: https://01.org/numatop
  - top: https://gitorious.org/procps/procps
  - irqstat: https://github.com/lanceshelton/irqstat

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THANK YOU
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