Obtaining hardware information and monitoring performance

August 2-6, 2021
SDSC Summer Institute
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Introduction

- Most of you are here because you are computational scientists
  - Have a specific scientific problem you're trying to solve
  - Support researchers from a variety of domains
- The actual hardware is probably of secondary interest
  - Hardware is interesting but not *that* interesting
- Nonetheless, it's still helpful to know a bit about hardware
- In this talk we'll learn how to
  - Get information about your system
  - Use some common usage monitoring tools

Outline

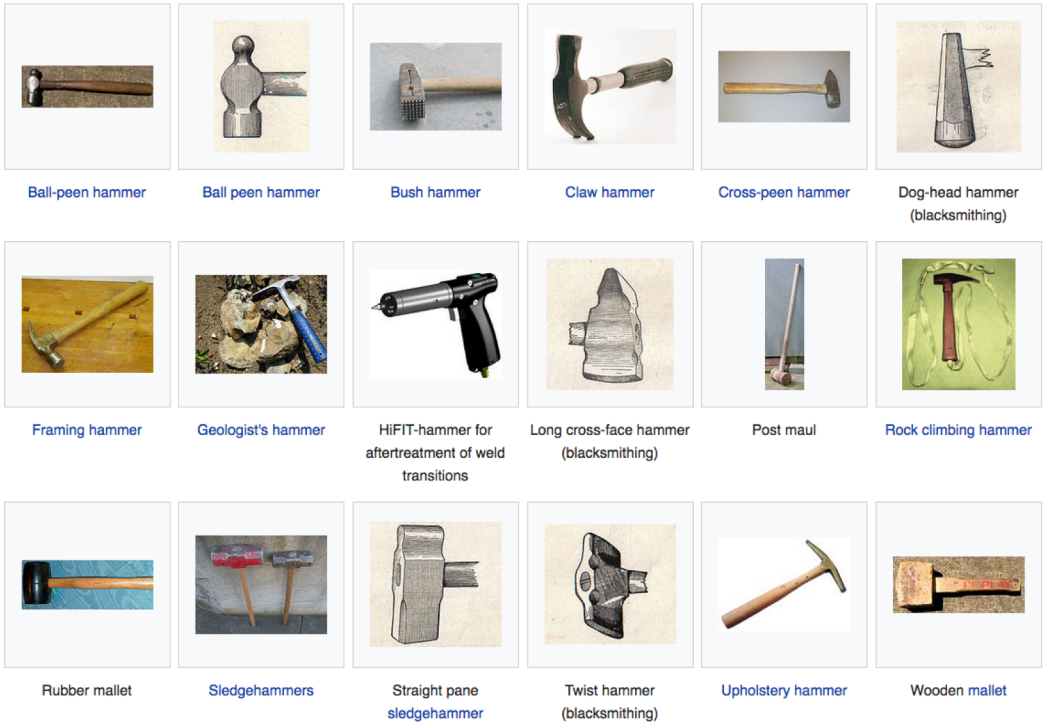
- Introduction
- Hardware information
  - CPU
  - GPU
  - Memory
  - Cache
  - SCSI, df, network, OS
- top and htop tools
- Manually instrumenting code (time permitting)
- gprof (time permitting)

Getting hardware information – why do I care?

- You may be asked to report details of your hardware in a manuscript, presentation, proposal or request for computer time
- You'll know what you're running on and can answer questions like
  - Is the login node the same as the compute nodes?
  - How does one machine compare to another?
- It will give you a way of estimating performance or at least bounds on performance relative to another system. *All else being equal*, jobs will run at least as fast on hardware with
  - Faster CPU clock speeds
  - Larger caches
  - Faster local drives

Computers are like hammers!

Just like hammers, there is a wide variety of computer hardware. You can probably get away with using the wrong one, but your performance may be suboptimal and you might end up using a bigger tool than you need.



Wikipedia

Processor specifications: lscpu

On Linux systems, the **lscpu** command lists key processor information

- Number of processors (sockets)
- Processor type or model
- Nominal clock speed
- Number of cores per processor
- Cache sizes
- Instruction set architecture
- NUMA nodes

Processor specifications: Expanse compute node

```
Architecture:          x86_64
CPU op-mode(s):        32-bit, 64-bit
Byte Order:            Little Endian
CPU(s):                128
On-line CPU(s) list:   0-127
Thread(s) per core:    1
Core(s) per socket:    64
Socket(s):             2
NUMA node(s):          8
Vendor ID:             AuthenticAMD
CPU family:            23
Model:                 49
Model name:            AMD EPYC 7742 64-Core Processor
Stepping:              0
CPU MHz:               3257.493
BogoMIPS:              4491.71
Virtualization:        AMD-V
L1d cache:             32K
L1i cache:             32K
L2 cache:              512K
L3 cache:              16384K
```

```
NUMA node0 CPU(s):     0-15
NUMA node1 CPU(s):     16-31
NUMA node2 CPU(s):     32-47
NUMA node3 CPU(s):     48-63
NUMA node4 CPU(s):     64-79
NUMA node5 CPU(s):     80-95
NUMA node6 CPU(s):     96-111
NUMA node7 CPU(s):     112-127
Flags:                 fpu vme de pse tsc msr pae mce
cx8 apic sep mtrr pge mca cmov pat pse36 clflush mmx
fxsr sse sse2 ht syscall nx mmxext fxsr_opt pdpe1gb
rdtscp lm constant_tsc rep_good nopl xtopology
nonstop_tsc cpuid extd_apicid aperfmperf pni
pclmulqdq monitor ssse3 fma cx16 sse4_1 sse4_2
x2apic movbe popcnt aes xsave avx f16c rdrand
lahf_lm cmp_legacy svm extapic cr8_legacy abm sse4a
misalignsse 3dnowprefetch osvw ibs skinit wdt tce
topoext perfctr_core perfctr_nb bpext perfctr_llc
mwaitx cpb cat_l3 cdp_l3 hw_pstate sme ssbd mba sev
ibrs ibpb stibp vmmcall fsgsbase bmi1 avx2 smep bmi2
cqm rdt_a rdseed adx smap clflushopt clwb sha_ni
xsaveopt xsavec xgetbv1 xsaves cqm_llc cqm_occup_llc
cqm_mbm_total cqm_mbm_local clzero irperf xsaveerptr
wbnoinvd arat npt lbrv svm_lock nrip_save tsc_scale
vmcb_clean flushbyasid decodeas
```

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NUMA node7 CPU(s):     112-127
Flags:                 fpu vme de pse tsc msr pae mce
cx8 apic sep mtrr pge mca cmov pat pse36 clflush mmx
fxsr sse sse2 ht syscall nx mmxext fxsr_opt pdpe1gb
rdtscp lm constant_tsc rep_good nopl xtopology
nonstop_tsc cpuid extd_apicid aperfmperf pni
pclmulqdq monitor ssse3 fma cx16 sse4_1 sse4_2
x2apic movbe popcnt aes xsave avx f16c rdrand
lahf_lm cmp_legacy svm extapic cr8_legacy abm sse4a
misalignsse 3dnowprefetch osvw ibs skinit wdt tce
topoext perfctr_core perfctr_nb bpext perfctr_llc
mwaitx cpb cat_l3 cdp_l3 hw_pstate sme ssbd mba sev
ibrs ibpb stibp vmmcall fsgsbase bmi1 avx2 smep bmi2
cqm rdt_a rdseed adx smap clflushopt clwb sha_ni
xsaveopt xsavec xgetbv1 xsaves cqm_llc cqm_occup_llc
cqm_mbm_total cqm_mbm_local clzero irperf xsaveerptr
wbnoinvd arat npt lbrv svm_lock nrip_save tsc_scale
vmcb_clean flushbyasid decodeas
```

Processor specifications: /proc/cpuinfo

On Linux systems, the **/proc/cpuinfo** pseudo-file contains pretty much the same information that you get from lscpu, but with a few differences

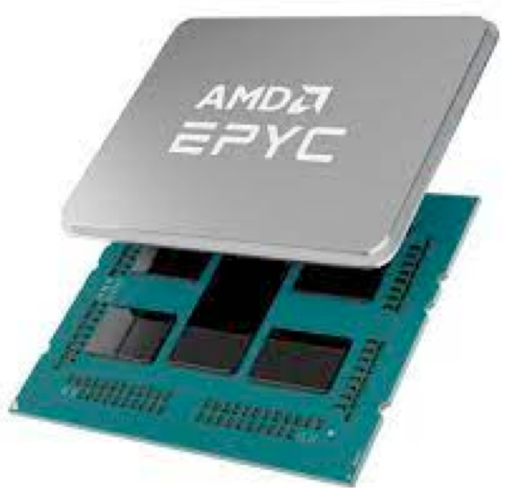
- Information is listed per core
- Access to instantaneous clock speeds
- Bugs detected / addressed
  see discussion: https://unix.stackexchange.com/questions/456425/what-does-the-bugs-section-of-proc-cpuinfo-actually-show
- Microcode, TLB size , power management, cache line flush sizes and other low-level details that you probably don't need to know about

Processor specifications: /proc/cpuinfo

```
$ grep 'cpu MHz' /proc/cpuinfo  | head -5
cpu MHz         : 3325.325
cpu MHz         : 2239.263
cpu MHz         : 3374.887
cpu MHz         : 2360.551
cpu MHz         : 2393.493
```

```
--- selected output ---
microcode       : 0x8301038
bugs            : sysret_ss_attrs spectre_v1 spectre_v2 spec_store_bypass
TLB size        : 3072 4K pages
clflush size    : 64
cache_alignment : 64
address sizes   : 43 bits physical, 48 bits virtual
power management : ts ttp tm hwpstate cpb eff_freq_ro [13] [14]
```

A brief aside on nomenclature



We normally think of the multicore unit that plugs into the motherboard as the “processor”

/proc/cpuinfo uses processor in a different way to mean compute core, counted across all the cores available in a node. lscpu uses more intuitive terminology.

```
processor       : 0
physical id     : 0
cpu cores       : 64
```

Quick aside on simultaneous multithreading

Simultaneous multithreading, abbreviated as SMT, is the process of a CPU splitting each of its physical cores into virtual cores, which are known as threads. This is done in order to increase performance and allow each core to run two instruction streams at once.

Intel branded this process as hyper-threading, but hyper-threading is the same thing as simultaneous multithreading. For example, AMD CPUs with four cores use simultaneous multithreading to provide eight threads, and most Intel CPUs with two cores use hyper-threading to provide four threads.

https://www.tomshardware.com/reviews/simultaneous-multithreading-definition,5762.html

SDSC does not enable hyperthreading on its systems. When hyperthreading is enabled, core count will appear to be doubled.

A brief aside on pseudo-files

Up to this point, we've been using the term pseudo-file without defining what it is. Recall that in the UNIX/Linux world, everything is treated as a file (files, directories, devices, etc.)

/proc and /sys are just interfaces to the Linux kernel data structures in a convenient and familiar file system format

```
$ ls -ld /proc
dr-xr-xr-x 2258 root root 0 Jul 28 09:27 /proc
[sinkovit@login01 ~]$ ls -ld /proc/cpuinfo
-r--r--r-- 1 root root 0 Jul 28 16:56 /proc/cpuinfo

$ head /proc/cpuinfo
processor  : 0
vendor_id  : AuthenticAMD
cpu family : 23
Model.     : 49
model name : AMD EPYC 7742 64-Core Processor
stepping   : 0
microcode  : 0x8301038
```

What's in a name?

We usually think of processors in terms of their codenames, such as Rome or Milan. Unfortunately, the /proc/cpuinto pseudo-file returns something a little more opaque such as "AMD EPYC 7742 64-Core Processor". A quick Google search helps

> In November 2018 AMD announced Epyc 2 at their Next Horizon event, the second generation of Epyc processors code-named "Rome" and based on the Zen 2 microarchitecture.[19] The processors feature up to eight 7 nm-based "chiplet" processors with a 14 nm-based IO chip providing 128 PCIe lanes in the center interconnected via Infinity Fabric. The processors support up to 8 channels of DDR4 RAM up to 4 TB, and introduce support for PCIe 4.0. These processors have up to 64 cores with 128 SMT threads per socket.[20] The 7 nm "Rome" is manufactured by TSMC.[11] It was released on August 7, 2019.[21]

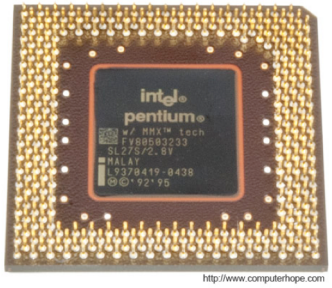
https://en.wikipedia.org/wiki/Epyc

Advanced Vector Extensions (AVX, AVX2, AVX512)

The Advanced Vector Extensions (AVX) are an extension to the x86 microprocessor architecture that allows a compute core to perform up to 8 floating point operations per cycle. Previous limit was 4/core/cycle

- AVX2 improves this to 16 Flops/cycle/core (Comet, Expanse)
- AVX512 further improves to 32 Flops/cycle/core (Intel ≥ Skylake)

These were developed partially in response to challenges in increasing CPU clock speeds



March 6, 2000 8:00 AM PST

AMD makes move to 1-GHz chip

By Joe Wilcox and Michael Kanellos
Staff Writers, CNET News

Advanced Vector Extensions (AVX, AVX2, AVX512)

- Can theoretically obtain a 2x speedup when going from a non-AVX processor to an AVX capable processor (all else being equal)
  - And another 2x from AVX to AVX2
  - And another 2x from AVX2 to AVX512

- But don't get too excited (or worried that Expanse doesn't have AVX512)
  - It's difficult enough to make good use of AVX and even harder to make good use of AVX2 or AVX512.
  - Need long loops with vectorizable content. Memory bandwidth not keeping up with gains in computing power.
  - On Skylake, clock speed scaled down when executing AVX512 instructions

Getting memory information: /proc/meminfo

On Linux machines, the /proc/meminfo pseudo-file lists key memory specs. More information than you probably want, but at least one bit of useful data

```
MemTotal:       263698228 kB (total physical memory)
MemFree:        251035032 kB
MemAvailable:   250623760 kB
Buffers:            12824 kB
Cached:           3126364 kB
SwapCached:             0 kB
Active:           1301564 kB (pretty good approximation to used memory)
Inactive:         2990668 kB
Active(anon):     1240284 kB
Inactive(anon):   2890076 kB
Active(file):       61280 kB
Inactive(file):    100592 kB
Unevictable:            0 kB
Mlocked:                0 kB
SwapTotal:              0 kB
SwapFree:               0 kB
Dirty:                 32 kB
Writeback:              0 kB
AnonPages:        1151660 kB
```

For more details, see http://www.redhat.com/advice/tips/meminfo.html

Getting memory information (/proc/meminfo)

Using a simple script, you can monitor total memory usage for all processes as a function of time. Note that there is a lot of discussion on how to precisely measure memory (http://stackoverflow.com/search?q=measuring+memory+usage). The following should be good enough if you're on a dedicated node.

```
#!/usr/bin/perl
use strict;
use warnings;
my $count = 0;
print (" time(s)    Memory (GB)\n");
while(1) {
    sleep(1);
    $count++;
    open(MI, "/proc/meminfo");
    while(<MI>) {
        if (/Active:/) {
            my (undef, $active, undef) = split();
            $active = $active /         1048576.0;
            printf("%6d       %f\n", $count, $active);
        }
    }
    close(MI);
}
```

More memory information - dmidecode

If you really need to dig deeper and get more details on memory configuration, you can run the dmidecode command. You'll need root privileges to do this.

Output shows the results for one DIMM slot.

dmidecode --type memory

```
Memory Device
        Array Handle: 0x001D
        Error Information Handle: No Error
        Total Width: 72 bits
        Data Width: 64 bits
        Size: 16384 MB
        Form Factor: DIMM
        Set: None
        Locator: DIMM_A1
        Bank Locator: CPU1
        Type: DDR4
        Type Detail: Synchronous Registered (Buffered)
        Speed: 2133 MHz
        Manufacturer: 0xCE00
        Serial Number: 0x394FECDD
        Asset Tag: Unknown
        Part Number: M393A2G40DB0-CPB
        Rank: 1
        Configured Clock Speed: 2133 MHz
        Minimum Voltage:  1.2 V
        Maximum Voltage:  1.2 V
        Configured Voltage:  1.2 V
```

Getting GPU information

If you're using GPU nodes, you can use nvidia-smi (NVIDIA System Management Interface program) to get GPU information (type, count, etc.)

When running in gpu-shared partition, will only see the GPUs you had requested (typically one)

```
 $ nvidia-smi
Mon Aug  2 10:16:29 2021
+-----------------------------------------------------------------------------+
| NVIDIA-SMI 460.32.03    Driver Version: 460.32.03    CUDA Version: 11.2     |
|-------------------------------+----------------------+----------------------+
| GPU  Name        Persistence-M| Bus-Id        Disp.A | Volatile Uncorr. ECC |
| Fan  Temp  Perf  Pwr:Usage/Cap|         Memory-Usage | GPU-Util  Compute M. |
|                               |                      |               MIG M. |
|===============================+======================+======================|
|   0  Tesla V100-SXM2...  On   | 00000000:18:00.0 Off |                    0 |
| N/A   40C    P0    67W / 300W |      0MiB / 32510MiB |      0%      Default |
|                               |                      |                  N/A |
+-------------------------------+----------------------+----------------------+

+-----------------------------------------------------------------------------+
| Processes:                                                                  |
|  GPU   GI   CI        PID   Type   Process name                  GPU Memory |
|        ID   ID                                                   Usage      |
|=============================================================================|
|  No running processes found                                                 |
+-----------------------------------------------------------------------------+
```

Finding cache information

On Linux systems, can obtain cache properties through the /sys pseudo filesystem. Details may vary slightly by O/S version and vendor, but basic information should be consistent. Goes deeper into cache properties than lscpu

```
$ pwd
/sys/devices/system/cpu

$ ls
cpu0   cpu17  cpu25  cpu33  cpu41  cpu5   cpu58  cpu9        offline
cpu1   cpu18  cpu26  cpu34  cpu42  cpu50  cpu59  cpufreq     online
cpu10  cpu19  cpu27  cpu35  cpu43  cpu51  cpu6   cpuidle     possible
cpu11  cpu2   cpu28  cpu36  cpu44  cpu52  cpu60  hotplug     power
...

$ cd cpu0/cache
$ ls
index0  index1  index2  index3  power  uevent

$ cd index0
$ ls
coherency_line_size  physical_line_partition  size
id                   power                    type
level                shared_cpu_list          uevent
number_of_sets       shared_cpu_map           ways_of_associativity
```

Expanse Cache properties – AMD Rome (AMD EPYC 7742)

level	type	line size	sets	associativity	size (KB)
L1	data	64	64	8	32
L1	instruction	64	64	8	32
L2	unified	64	1024	8	512
L3	unified	64	16384	16	16384

L1 and L2 caches are per core
L3 cache shared between 4 cores on a core complex

line size x sets x associativity = size
L2 cache size = 64 x 1024 x 8 = 524288 = 512 K

Comet Cache properties – Intel Haswell (Intel Xeon E5-2680)

level	type	line size	sets	associativity	size (KB)
L1	data	64	64	8	32
L1	instruction	64	64	8	32
L2	unified	64	512	8	256
L3	unified	64	24576	20	30720

L1 and L2 caches are per core
L3 cache shared between all 12 cores in socket

line size x sets x associativity = size
L2 cache size = 64 x 512 x 8 = 262144 = 256 K

Gordon Cache properties – Intel Sandy Bridge (Intel Xeon E5-2670)

level	type	line size	sets	associativity	size (KB)
L1	data	64	64	8	32
L1	instruction	64	64	8	32
L2	unified	64	512	8	256
L3	unified	64	16384	20	20480

L1 and L2 caches are per core
L3 cache shared between all 8 cores in socket

line size x sets x associativity = size
L2 cache size = 64 x 512 x 8 = 262144 = 256 K

Trestles Cache properties – AMD Magny-Cours (AMD Opteron Processor 6136)

level	type	line size	sets	associativity	size (KB)
L1	data	64	512	2	64
L1	instruction	64	512	2	64
L2	unified	64	512	16	512
L3	unified	64	1706	48	5118

L1 and L2 caches are per core
L3 cache shared between all 8 cores in socket

line size x sets x associativity = size
L2 cache size = 64 x 512 x 16 = 524288= 512K

Impact of cache size on performance

Note – example based on old systems, but still very illustrative

Based on the clock speed and instruction set, program run on single core of Gordon should be 2.26x faster than on Trestles. The larger L1 and L2 cache sizes on Trestles mitigate performance impact for very small problems.

DGSEV (Ax=b) wall times as function of problem size

N	t (Trestles)	t (Gordon)	ratio	KB
62	0.000117	0.000086	1.36	30
125	0.000531	0.000384	1.38	122
250	0.002781	0.001542	1.80	488
500	0.016313	0.007258	2.24	1953
1000	0.107222	0.046252	2.31	7812
2000	0.744837	0.331818	2.24	31250
4000	5.489990	2.464218	2.23	125000

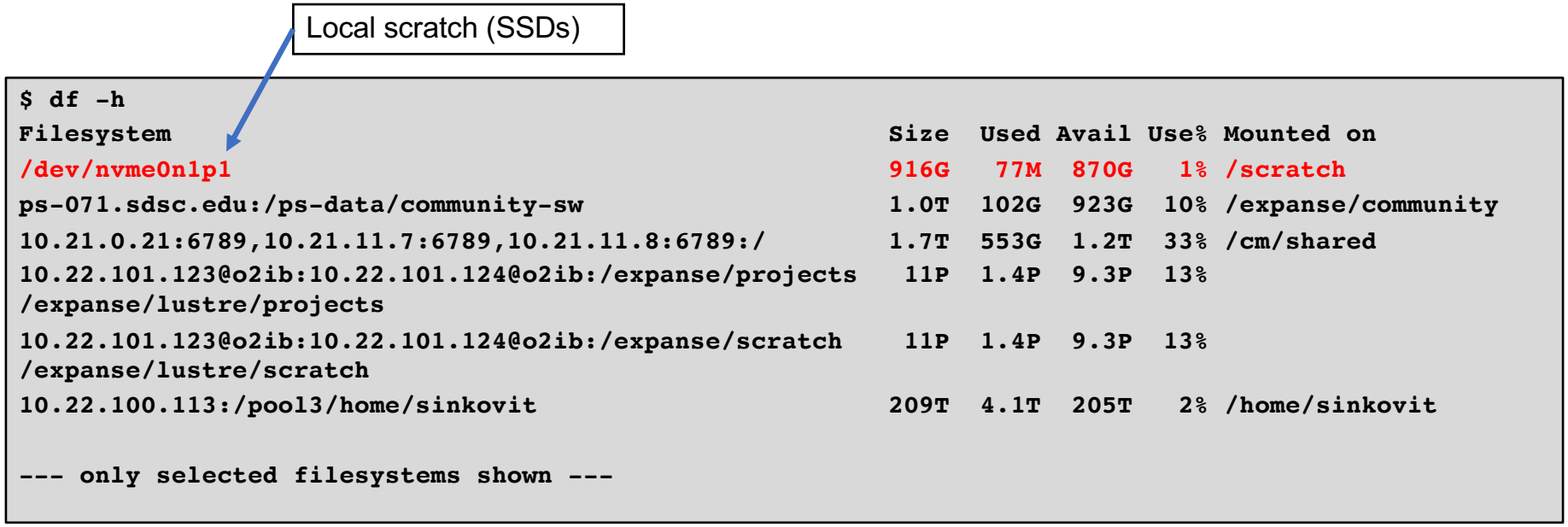
Finding SCSI device information

SCSI (Small Computer System Interface) is a common interface for mounting peripheral, such as hard drives and SSDs. The lsscsi or /proc/scsi/scsi file command will provide info on SCSI devices.

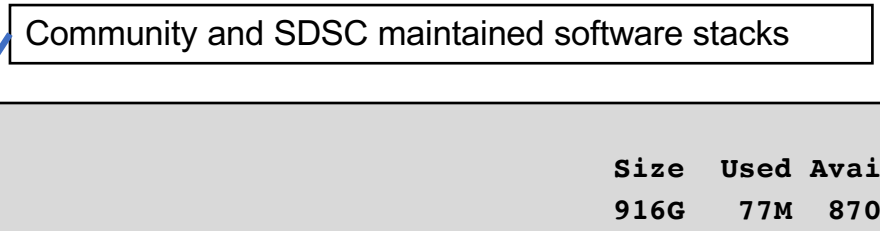
```
$ lsscsi
[3:0:0:0]    disk    ATA      SSDSC2KB480G8R   DL67  /dev/sda
[N:0:0:1]    disk    Dell Express Flash NVMe P4510 1TB SFF__1   /dev/nvme0n1
```

Dell 1TB PCIe
NVMe Read

df provides information on filesystem usage



df provides information on filesystem usage




```
$ df -h
Filesystem                                                 Size  Used Avail Use% Mounted on
/dev/nvme0n1p1                                             916G   77M  870G   1% /scratch
ps-071.sdsc.edu:/ps-data/community-sw                      1.0T  102G  923G  10% /expanse/community
10.21.0.21:6789,10.21.11.7:6789,10.21.11.8:6789:/          1.7T  553G  1.2T  33% /cm/shared
10.22.101.123@o2ib:10.22.101.124@o2ib:/expanse/projects    11P  1.4P  9.3P  13%
/expanse/lustre/projects
10.22.101.123@o2ib:10.22.101.124@o2ib:/expanse/scratch     11P  1.4P  9.3P  13%
/expanse/lustre/scratch
10.22.100.113:/pool3/home/sinkovit                         209T  4.1T  205T   2% /home/sinkovit

--- only selected filesystems shown ---
```

df provides information on filesystem usage

```
$ df -h
Filesystem                                                Size  Used Avail Use% Mounted on
/dev/nvme0n1p1                                            916G   77M  870G   1% /scratch
ps-071.sdsc.edu:/ps-data/community-sw                     1.0T  102G  923G  10% /expanse/community
10.21.0.21:6789,10.21.11.7:6789,10.21.11.8:6789:/         1.7T  553G  1.2T  33% /cm/shared
10.22.101.123@o2ib:10.22.101.124@o2ib:/expanse/projects    11P  1.4P  9.3P  13%
/expanse/lustre/projects
10.22.101.123@o2ib:10.22.101.124@o2ib:/expanse/scratch     11P  1.4P  9.3P  13%
/expanse/lustre/scratch
10.22.100.113:/pool3/home/sinkovit                        209T  4.1T  205T   2% /home/sinkovit

--- only selected filesystems shown ---
```

Lustre scratch and project filesystems

df provides information on filesystem usage

```
$ df -h
Filesystem                                                Size  Used Avail Use% Mounted on
/dev/nvme0n1p1                                            916G   77M  870G   1% /scratch
ps-071.sdsc.edu:/ps-data/community-sw                     1.0T  102G  923G  10% /expanse/community
10.21.0.21:6789,10.21.11.7:6789,10.21.11.8:6789:/         1.7T  553G  1.2T  33% /cm/shared
10.22.101.123@o2ib:10.22.101.124@o2ib:/expanse/projects    11P  1.4P  9.3P  13%
/expanse/lustre/projects
10.22.101.123@o2ib:10.22.101.124@o2ib:/expanse/scratch     11P  1.4P  9.3P  13%
/expanse/lustre/scratch
10.22.100.113:/pool3/home/sinkovit                        209T  4.1T  205T   2% /home/sinkovit

--- only selected filesystems shown ---
```

Home filesystem

Finding network information

The ip command (/sbin/ip) is normally used by sys admins, but regular users can use it to learn about networking information

```
$ /sbin/ip link
1: lo: <LOOPBACK,UP,LOWER_UP> mtu 65536 qdisc noqueue state UNKNOWN mode DEFAULT
group default qlen 1000
    link/loopback 00:00:00:00:00:00 brd 00:00:00:00:00:00
2: eno1: <BROADCAST,MULTICAST> mtu 1500 qdisc noop state DOWN mode DEFAULT group
default qlen 1000
    link/ether 6c:2b:59:bb:61:24 brd ff:ff:ff:ff:ff:ff
3: eno33: <BROADCAST,MULTICAST,UP,LOWER_UP> mtu 9000 qdisc mq state UP mode
DEFAULT group default qlen 1000
    link/ether 1c:34:da:62:a8:50 brd ff:ff:ff:ff:ff:ff
4: eno34: <BROADCAST,MULTICAST> mtu 1500 qdisc noop state DOWN mode DEFAULT group
default qlen 1000
    link/ether 1c:34:da:62:a8:51 brd ff:ff:ff:ff:ff:ff
5: ib0: <BROADCAST,MULTICAST,UP,LOWER_UP> mtu 4092 qdisc mq state UP mode DEFAULT
group default qlen 256
    link/infiniband 20:00:11:07:fe:80:00:00:00:00:00:00:1c:34:da:03:00:5d:53:90
brd 00:ff:ff:ff:ff:12:40:1b:ff:ff:00:00:00:00:00:00:ff:ff:ff:ff
6: eno33.450@eno33: <BROADCAST,MULTICAST,UP,LOWER_UP> mtu 9000 qdisc noqueue
state UP mode DEFAULT group default qlen 1000
    link/ether 1c:34:da:62:a8:50 brd ff:ff:ff:ff:ff:ff
```

Finding OS and kernel information

Use uname to get information on the Linux kernel

```
$ uname -r
4.18.0-147.el8.x86_64
$ uname -o
GNU/Linux
$ uname -a
Linux login01 4.18.0-147.el8.x86_64 #1 SMP Wed Dec 4 21:51:45 UTC 2019 x86_64
x86_64 x86_64 GNU/Linux
```

Look in /etc/centos-release to get the Linux distribution (will vary by Linux distro)

```
$ cat /etc/centos-release
CentOS Linux release 8.1.1911 (Core)
```

Machine info - overkill?

- We've probably gone a little deeper than is necessary for you to be an effective supercomputer user.
- Think of this as a way to round out your HPC knowledge. You're learning a little bit about the tools of the trade, getting comfortable poking around on a system, acquiring the knowledge that will make it easier to work with your sys admin and picking up the background that will help you to make intelligent decisions in the future.
- Exercise: grab an interactive node (or just the login node) on Expanse and experiment with what we've covered. Cheat sheet on the next slide.
- Note that login and compute nodes are somewhat different

Machine info – cheat sheet

File or command	Information provided
less /proc/cpuinfo or lscpu	CPU specs
less /proc/meminfo	Memory specs and usage
nvidia-smi	GPU specs and usage
cd /sys/devices/system/cpu/cpu0/cache … then look at directory contents	Cache configuration
less /proc/scsi/scsi or lsscsi	Peripherals (e.g. SSDs)
less /etc/mtab	Mounted file systems
df -h	File system usage (readable format)
/sbin/ip link	Networking information
uname -a	OS information
less /etc/centos-release	Centos version

Using the Linux top/htop utility

The top utility is found on all Linux systems and provides a high level view of running processes. Does not give any information at the source code level (profiling), but can still be very useful for answering questions such as

- How many of my processes are running?
- What are the states of the processes (running, sleeping, etc.)?
- Which cores are being utilized?
- Are there any competing processes that may be affecting my performance?
- What fraction of the CPU is each process using?
- How much memory does each process use?
- Is the memory usage growing over time? (Useful for identifying memory leaks)
- How many threads are my processes using?

Customizing top

Top has the following defaults, but is easily customizable

- Processes only (no threads)
- To toggle threads display, type “H” while top is running
- Information for all users
- Can restrict to a single user by launching with “top -u username”
- Process ID, priority, ‘nice’ level, virtual memory, physical memory, shared memory, state, %CPU, %memory, CPU time, command
- To modify, type “f” while top is running and toggle fields using letters
- Update information every 3 seconds
- Change refresh rate by launching with “top -d *n*”
- Ordered by CPU usage
- Type “M” to order by memory usage

Non-threaded code

stivoknis — sinkovit@gcn-17-57:~ — ssh — 94×33

```
top - 08:37:00 up 60 days, 14:23,  1 user,  load average: 15.32, 10.36, 6.12
Tasks: 624 total,  17 running, 607 sleeping,   0 stopped,   0 zombie
Cpu(s): 68.7%us,  1.3%sy,  0.0%ni, 29.9%id,  0.1%wa,  0.0%hi,  0.0%si,  0.0%st
Mem:  66054160k total, 37885796k used, 28168364k free,     8808k buffers
Swap:  2097144k total,    13400k used,  2083744k free, 32927192k cached
```

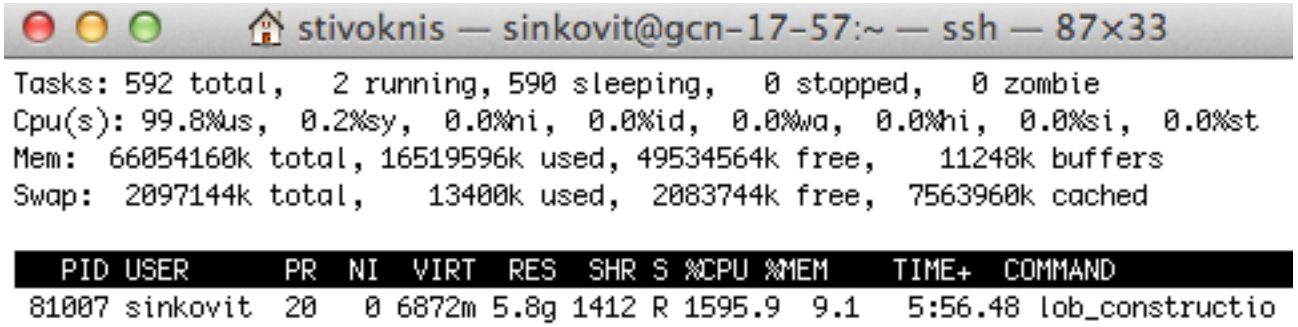
PID	USER	PR	NI	VIRT	RES	SHR	S	%CPU	%MEM	TIME+	COMMAND
70388	sinkovit	20	0	194m	76m	1612	R	100.0	0.1	1:31.06	lobfaster.pl
72547	sinkovit	20	0	120m	2976	1612	R	100.0	0.0	0:01.49	lobfaster.pl
72516	sinkovit	20	0	127m	9.9m	1608	R	100.0	0.0	0:02.09	lobfaster.pl
72526	sinkovit	20	0	121m	3388	1612	R	100.0	0.0	0:01.84	lobfaster.pl
72535	sinkovit	20	0	121m	4208	1612	R	100.0	0.0	0:01.73	lobfaster.pl
72565	sinkovit	20	0	120m	3212	1612	R	100.0	0.0	0:01.01	lobfaster.pl
72268	sinkovit	20	0	130m	12m	1612	R	98.9	0.0	0:11.96	lobfaster.pl
72359	sinkovit	20	0	123m	5976	1612	R	98.9	0.0	0:09.77	lobfaster.pl
72460	sinkovit	20	0	127m	10m	1612	R	98.9	0.0	0:08.38	lobfaster.pl
72481	sinkovit	20	0	131m	13m	1612	R	98.9	0.0	0:07.44	lobfaster.pl
72529	sinkovit	20	0	122m	4576	1612	R	98.9	0.0	0:01.82	lobfaster.pl
72439	sinkovit	20	0	130m	12m	1612	R	97.0	0.0	0:08.64	lobfaster.pl
72590	sinkovit	20	0	120m	3140	1612	R	71.7	0.0	0:00.37	lobfaster.pl
72602	sinkovit	20	0	120m	2576	1612	R	38.8	0.0	0:00.20	lobfaster.pl
72605	sinkovit	20	0	120m	2528	1600	R	34.9	0.0	0:00.18	lobfaster.pl
72608	sinkovit	20	0	119m	2340	1600	R	21.3	0.0	0:00.11	lobfaster.pl

16 processes, each using anywhere from 21.3% to 100% of a compute core.

Memory footprint (RES) is minimal, with each process only using up to 76 MB.

CPU times ranging from 0.11s (just started) to 1:31

Threaded code (thread display off)



Threaded code with thread display toggled to the “off” position. Note the heavy CPU usage, very close to 1600%

Threaded code (thread display on)

stivoknis — sinkovit@gcn-17-57:~ — ssh — 87×33

```
Tasks: 626 total,  17 running, 609 sleeping,   0 stopped,   0 zombie
Cpu(s): 15.8%us,  0.2%sy,  0.0%ni, 84.0%id,  0.0%wa,  0.0%hi,  0.0%si,  0.0%st
Mem:  66054160k total, 17495556k used, 48558604k free,    11552k buffers
Swap:  2097144k total,    13400k used,  2083744k free,  8478752k cached
```

PID	USER	PR	NI	VIRT	RES	SHR	S	%CPU	%MEM	TIME+	COMMAND
81007	sinkovit	20	0	6927m	5.8g	1412	R	99.5	9.2	8:37.91	lob_constructio
81096	sinkovit	20	0	6927m	5.8g	1412	R	10.5	9.2	1:13.43	lob_constructio
81105	sinkovit	20	0	6927m	5.8g	1412	R	10.5	9.2	1:13.43	lob_constructio
81107	sinkovit	20	0	6927m	5.8g	1412	R	10.5	9.2	1:13.43	lob_constructio
81097	sinkovit	20	0	6927m	5.8g	1412	R	10.2	9.2	1:13.40	lob_constructio
81099	sinkovit	20	0	6927m	5.8g	1412	R	10.2	9.2	1:13.39	lob_constructio
81100	sinkovit	20	0	6927m	5.8g	1412	R	10.2	9.2	1:13.44	lob_constructio
81101	sinkovit	20	0	6927m	5.8g	1412	R	10.2	9.2	1:13.44	lob_constructio
81102	sinkovit	20	0	6927m	5.8g	1412	R	10.2	9.2	1:13.43	lob_constructio
81103	sinkovit	20	0	6927m	5.8g	1412	R	10.2	9.2	1:13.45	lob_constructio
81106	sinkovit	20	0	6927m	5.8g	1412	R	10.2	9.2	1:13.44	lob_constructio
81108	sinkovit	20	0	6927m	5.8g	1412	R	10.2	9.2	1:13.44	lob_constructio
81109	sinkovit	20	0	6927m	5.8g	1412	R	10.2	9.2	1:13.29	lob_constructio
81110	sinkovit	20	0	6927m	5.8g	1412	R	10.2	9.2	1:13.39	lob_constructio
81098	sinkovit	20	0	6927m	5.8g	1412	R	9.9	9.2	1:13.44	lob_constructio
81104	sinkovit	20	0	6927m	5.8g	1412	R	9.9	9.2	1:13.38	lob_constructio

16 threads, with only one thread making good use of CPU

Total memory usage 5.8 GB (9.2% of available)

Threaded code (thread display on)

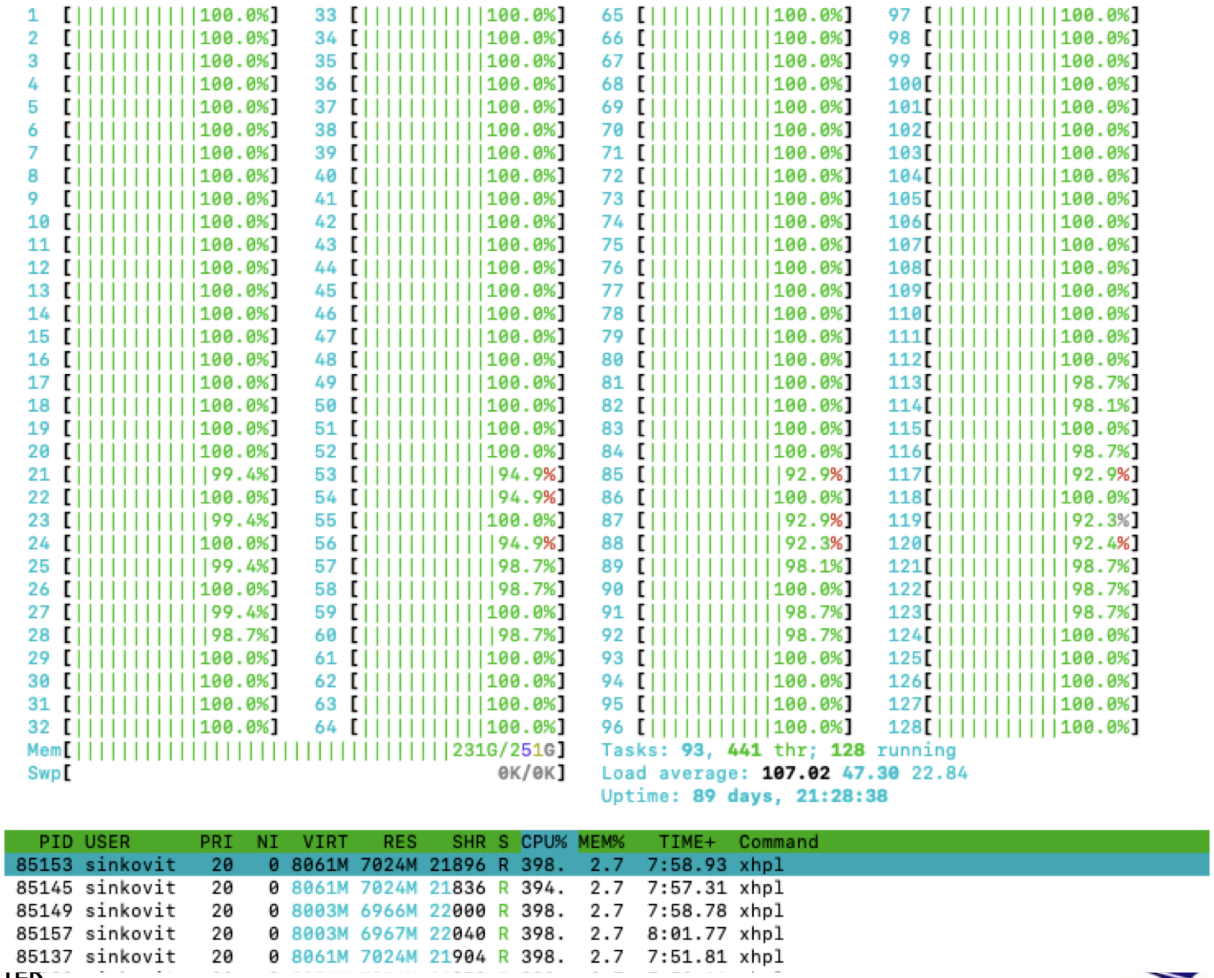
stivoknis — sinkovit@gcn-17-57:~ — ssh — 87×33

```
Tasks: 626 total,  17 running, 609 sleeping,   0 stopped,   0 zombie
Cpu(s): 90.9%us,  0.1%sy,  0.0%ni,  9.0%id,  0.0%wa,  0.0%hi,  0.0%si,  0.0%st
Mem:  66054160k total, 17628152k used, 48426008k free,    11496k buffers
Swap:  2097144k total,    13400k used,  2083744k free,  8396488k cached
```

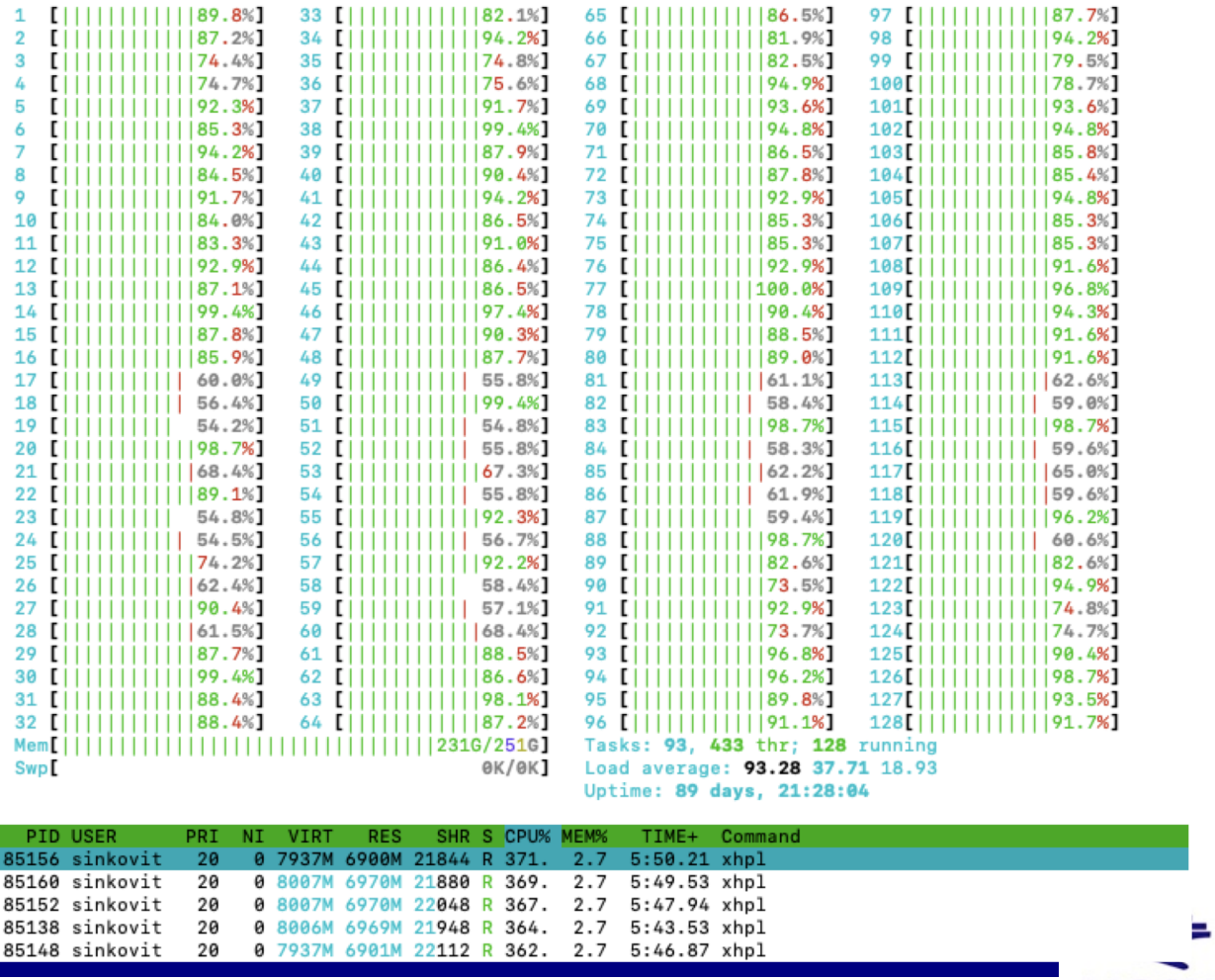
PID	USER	PR	NI	VIRT	RES	SHR	S	%CPU	%MEM	TIME+	COMMAND
81007	sinkovit	20	0	7132m	6.0g	1412	R	100.0	9.5	7:54.98	lob_constructio
81110	sinkovit	20	0	7132m	6.0g	1412	R	90.4	9.5	0:51.15	lob_constructio
81096	sinkovit	20	0	7132m	6.0g	1412	R	90.1	9.5	0:51.17	lob_constructio
81098	sinkovit	20	0	7132m	6.0g	1412	R	90.1	9.5	0:51.19	lob_constructio
81099	sinkovit	20	0	7132m	6.0g	1412	R	90.1	9.5	0:51.14	lob_constructio
81100	sinkovit	20	0	7132m	6.0g	1412	R	90.1	9.5	0:51.18	lob_constructio
81101	sinkovit	20	0	7132m	6.0g	1412	R	90.1	9.5	0:51.18	lob_constructio
81102	sinkovit	20	0	7132m	6.0g	1412	R	90.1	9.5	0:51.18	lob_constructio
81103	sinkovit	20	0	7132m	6.0g	1412	R	90.1	9.5	0:51.19	lob_constructio
81104	sinkovit	20	0	7132m	6.0g	1412	R	90.1	9.5	0:51.14	lob_constructio
81105	sinkovit	20	0	7132m	6.0g	1412	R	90.1	9.5	0:51.19	lob_constructio
81106	sinkovit	20	0	7132m	6.0g	1412	R	90.1	9.5	0:51.18	lob_constructio
81107	sinkovit	20	0	7132m	6.0g	1412	R	90.1	9.5	0:51.18	lob_constructio
81108	sinkovit	20	0	7132m	6.0g	1412	R	90.1	9.5	0:51.18	lob_constructio
81097	sinkovit	20	0	7132m	6.0g	1412	R	89.8	9.5	0:51.15	lob_constructio
81109	sinkovit	20	0	7132m	6.0g	1412	R	89.8	9.5	0:51.08	lob_constructio

16 threads, all making good (but not ideal) use of the compute cores

htop – like top, but with better interface, vertical and horizontal scrolling, process tree view, etc.

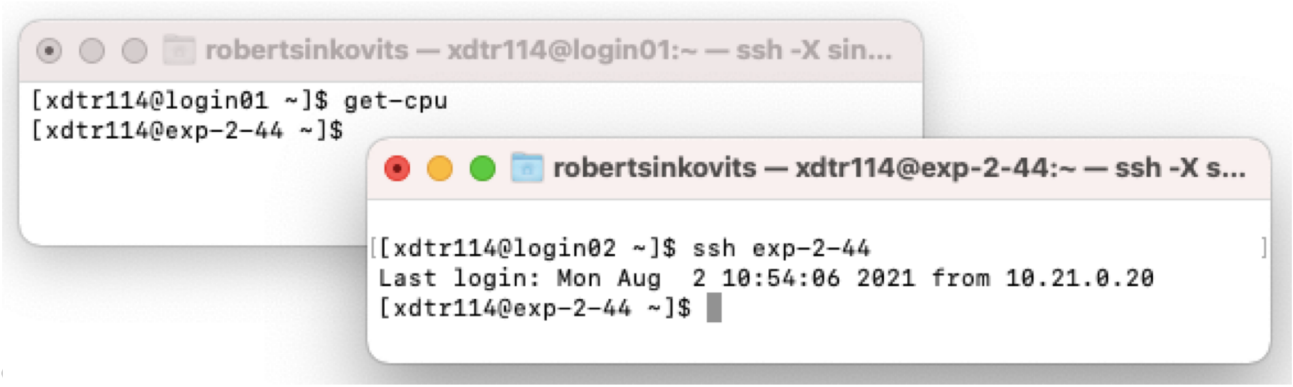


htop – like top, but with better interface, vertical and horizontal scrolling, process tree view, etc.



top/htop exercise

- Once we do the hands on exercises for the other sessions, open another terminal and run top or htop
- In the meantime, try running on the login node or an interactive node and play around with the options
- Useful tip – on Expanse, once Slurm has allocated a node to your account, you can then directly login to the node



Supplementary material

Manually instrumenting codes

- Performance analysis tools ranging from the venerable (gprof) to the modern (TAU) are great, but they all have several downsides
  - May not be fully accurate
  - Can introduce overhead
  - Sometimes have steep learning curves

- Once you really know your application, your best option is to add your own instrumentation. Will automatically get a performance report every time you run the code.

- There are many ways to do this and we'll explore portable solutions in C/C++ and Fortran. Note that there are also many heated online discussions arguing over how to properly time codes.

Linux time utility

If you just want to know the overall wall time for your application, can use the Linux time utility. Reports three times

- real – elapsed (wall clock) time for executable
- user – CPU time integrated across all cores
- sys – system CPU time

```
$ export OMP_NUM_THREADS=16 ; time ./lineq_mkl 30000
Times to solve linear sets of equations for n = 30000
t = 70.548615

real     1m10.733s  ← wall time
user     17m23.940s ← CPU time summed across all cores
sys      0m2.225s
```

Manually instrumenting C/C++ codes

The C gettimeofday() function returns time from start of epoch (1/1/1970) with microsecond precision. Call before and after the block of code to be timed and perform math using the tv_sec and tv_usec struct elements

```
struct timeval tv_start, tv_end;

gettimeofday(&tv_start, NULL);
// block of code to be timed
gettimeofday(&tv_end, NULL);

elapsed = (tv_end.tv_sec - tv_start.tv_sec) +
          (tv_end.tv_usec - tv_start.tv_usec) / 1000000.0;
```

Manually instrumenting Fortran codes

The Fortran90 system_clock function returns number of ticks of the processor clock from some unspecified previous time. Call before and after the block of code to be timed and perform math using the elapsed_time function (see next slide)

```
integer clock1, clock2;
double precision elapsed_time

call system_clock(clock1)
// block of code to be timed
call system_clock(clock2)

time = elapsed_time(clock1, clock2)
```

Manually instrumenting Fortran codes (cont.)

Using system_clock can be a little complicated since we need to know the length of a processor cycle and have to be careful about how we handle overflows of counter. Write this once and reuse everywhere.

```
double precision function elapsed_time(c1, c2)
implicit none
integer, intent(in) :: c1, c2
integer ticks, clockrate, clockmax

call system_clock(count_max=clockmax, count_rate=clockrate)
ticks = c2-c1
if(ticks < 0) then
  ticks = clockmax + ticks
endif
elapsed_time = dble(ticks)/dble(clockrate)

return
end function elapsed_time
```

A note on granularity

Don't try to time at too small a level of granularity, such as measuring the time associated with a single statement within a loop

```
elapsed = 0.0;

for (i=0; i<n; i++) {
  w[i] = x[i] * y[i];
  gettimeofday(&tv_start, NULL);
  z[i] = sqrt(w[i]) + x[i];
  gettimeofday(&tv_end, NULL);
  elapsed += (tv_end.tv_sec - tv_start.tv_sec) +
             (tv_end.tv_usec - tv_start.tv_usec) / 1000000.0;
}
```

Although they're pretty lightweight, there is still a cost associated with calls to gettimeofday or system_clock. In addition, the insertion of these calls into loops can impact the flow and hamper optimizations by the compiler.

Profiling your code with gprof

gprof is a profiling tool for UNIX/Linux applications. First developed in 1982, it is still extremely popular and very widely used. It is always the first tool that I use for my work.

Universally supported by all major C/C++ and Fortran compilers

Extremely easy to use

1. Compile code with -pg option: adds instrumentation to executable
2. Run application: file named gmon.out will be created.
3. Run gprof to generate profile: gprof a.out gmon.out

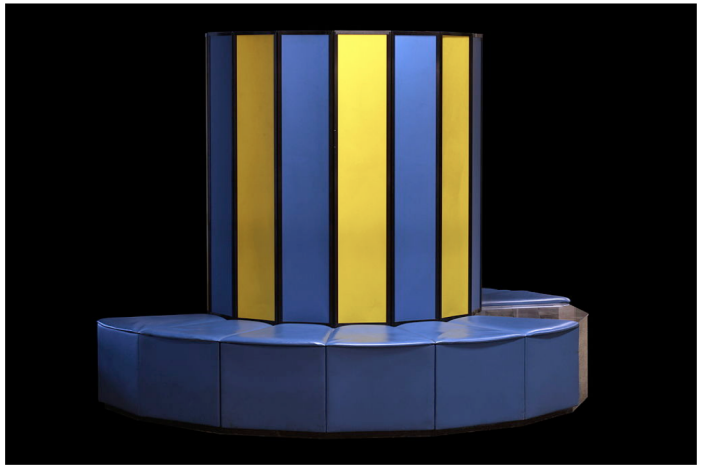
Introduces virtually no overhead

Output is easy to interpret

1982!

Worth reflecting on the fact that gprof goes back to 1982. Amazing when considered in context of the leading technology of the day

Michael Douglas as Gordon Gecko in Wall Street, modeling early 1980s cell phone. List price ~ $3000



Cray X-MP with 105 MHz processor. High end configuration (four CPUs, 64 MB memory) has 800 MFLOP theoretical peak. Cost ~ $15M

gprof flat profile

The gprof flat profile is a simple listing of functions/subroutines ordered by their relative usage. Often a small number of routines will account for a large majority of the run time. Useful for identifying hot spots in your code.

```
Flat profile:

Each sample counts as 0.01 seconds.
  %   cumulative   self              self     total
 time   seconds   seconds    calls  ms/call  ms/call  name
 68.60    574.72   574.72   399587     1.44     1.44  get_number_packed_data
 13.48    687.62   112.90                             main
 11.60    784.81    97.19   182889     0.53     0.53  quickSort_double
  2.15    802.85    18.04   182889     0.10     0.63  get_nearest_events
  1.52    815.56    12.71                             __c_mcopy8
  1.28    826.29    10.73                             _mcount2
  0.96    834.30     8.02    22183     0.36     0.36  pack_arrays
  0.12    835.27     0.97                             __rouexit
  0.08    835.94     0.66                             __rouinit
  0.06    836.45     0.51    22183     0.02     5.58  Is_Hump
  0.05    836.88     0.44        1   436.25   436.25  quickSort
```

gprof call graph

The gprof call graph provides additional levels of detail such as the exclusive time spent in a function, the time spent in all children (functions that are called) and statistics on calls from the parent(s)

```
index % time    self  children    called     name
[1]     96.9  112.90  699.04                 main [1]
              574.72    0.00  399587/399587      get_number_packed_data [2]
                0.51  123.25   22183/22183       Is_Hump [3]
                0.44    0.00       1/1           quickSort [11]
                0.04    0.00       1/1           radixsort_flock [18]
                0.02    0.00       2/2           ID2Center_all [19]
-----------------------------------------------
              574.72    0.00  399587/399587      main [1]
[2]     68.6  574.72    0.00  399587         get_number_packed_data [2]
-----------------------------------------------
                0.51  123.25   22183/22183       main [1]
[3]     14.8    0.51  123.25   22183          Is_Hump [3]
               18.04   97.19  182889/182889      get_nearest_events [4]
                8.02    0.00   22183/22183       pack_arrays [8]
                0.00    0.00   22183/22183       pack_points [24]
```

The value of re-profiling

After optimizing the code, we find that the function main() now accounts for 40% of the run time and would be a likely target for further performance improvements.

```
Flat profile:

Each sample counts as 0.01 seconds.
  %   cumulative   self              self     total
 time   seconds   seconds    calls  ms/call  ms/call  name
 41.58     36.95    36.95                             main
 26.41     60.42    23.47    22183     1.06     1.06  get_number_packed_data
 11.58     70.71    10.29                             __c_mcopy8
 10.98     80.47     9.76   182889     0.05     0.05  get_nearest_events
  8.43     87.96     7.49    22183     0.34     0.34  pack_arrays
  0.57     88.47     0.51    22183     0.02     0.80  Is_Hump
  0.20     88.65     0.18        1   180.00   180.00  quickSort
  0.08     88.72     0.07                             _init
  0.05     88.76     0.04        1    40.00    40.00  radixsort_flock
  0.02     88.78     0.02        1    20.00    20.00  compute_position
  0.02     88.80     0.02        1    20.00    20.00  readsource
```

Limitations of gprof

- grprof only measures time spent in user-space code and does not account for system calls or time waiting for CPU or I/O
- gprof can be used for MPI applications and will generate a gmon.out.id file for each MPI process. But for reasons mentioned above, it will not give an accurate picture of the time spent waiting for communications
- gprof will not report usage for un-instrumented library routines
- In the default mode, gprof only gives function level rather than statement level profile information. Although it can provide the latter by compiling in debug mode (-g) and using the gprof -l option, this introduces a lot of overhead and disables many compiler optimizations.

  In my opinion, I don't think this is such a bad thing. Once a function has been identified as a hotspot, it's usually obvious where the time is being spent (e.g. statements in innermost loop nesting)

gprof for threaded codes

gprof has limited utility for threaded applications (e.g. parallelized with OpenMP, Pthreads) and only reports usage for the main thread

But … there is a workaround
http://sam.zoy.org/writings/programming/gprof.html

“gprof uses the internal ITIMER_PROF timer which makes the kernel deliver a signal to the application whenever it expires. So we just need to pass this timer data to all spawned threads”

http://sam.zoy.org/writings/programming/gprof-helper.c

gcc -shared -fPIC gprof-helper.c -o gprof-helper.so -lpthread -ldl

LD_PRELOAD=./gprof-helper.so

… then run your code

gprof example 1 (examining call tree)

```
-----------------------------------------------
                0.85    5.23       1/1           MAIN__ [3]
[6]     12.4    0.85    5.23       1         sub1_ [6]
                4.05    0.00 100000000/100000000     f2_ [7]
                1.18    0.00 100000000/200000000     f1_ [8]
-----------------------------------------------
                4.05    0.00 100000000/100000000     sub1_ [6]
[7]      8.2    4.05    0.00 100000000         f2_ [7]
-----------------------------------------------
                1.18    0.00 100000000/200000000     sub1_ [6]
                1.18    0.00 100000000/200000000     sub2_ [9]
[8]      4.8    2.36    0.00 200000000         f1_ [8]
-----------------------------------------------
                0.39    1.18       1/1           MAIN__ [3]
[9]      3.2    0.39    1.18       1         sub2_ [9]
                1.18    0.00 100000000/200000000     f1_ [8]
-----------------------------------------------
```

- sub1 called by MAIN once
- calls f2 10^8
- calls f1 10^8

- f2 called by sub1 10^8

- f1 called by sub1 10^8
- f1 called by sub2 10^8

- sub2 called by MAIN once
- calls f1 10^8