Lecture 13: Resource Monitoring Tools

Putting it all together

- Processes, the Kernel, and Hardware all interact.
- There are three basic types of resource
  - CPU
  - Memory
  - Input/Output (I/O)
- You can also think of the Kernel as a resource that processes have to share
- As an HPC engineer or System Analyst you have to be able to track usage of the system and detect bottlenecks.
- Even so the default settings are usually pretty good

Overview

- Tracking Processes
- Finding Open Files
- Tracing Program Execution
- Threads
- Resource Monitoring
- Control Groups

```
[matthew@moonshine ~]$ ps | head -n 10
    PID TTY          TIME CMD
 160323 pts/1    00:00:00 bash
 160357 pts/1    00:00:00 ps
 160358 pts/1    00:00:00 head
```

```
[matthew@moonshine ~]$ ps -A | head -n 10
    PID TTY          TIME CMD
      1 ?        00:00:22 systemd
      2 ?        00:00:00 kthreadd
      3 ?        00:00:00 rcu_gp
      4 ?        00:00:00 rcu_par_gp
      5 ?        00:00:00 slub_flushwq
      6 ?        00:00:00 netns
      8 ?        00:00:00 kworker/0:0H-
events_highpri
     11 ?        00:00:00 mm_percpu_wq
     13 ?        00:00:00 rcu_tasks_kthre
```

```
[matthew@moonshine ~]$ ps aux | tail -n 10
USER         PID %CPU %MEM    VSZ   RSS TTY      STAT START   TIME COMMAND
matthew   168570  0.0  0.0  19044  7176 ?        S    07:59   0:00 sshd: matthew@pts/1
matthew   168571  0.0  0.0   7552  4392 pts/1    Ss   07:59   0:00 -bash
root      168576  0.0  0.0      0     0 ?        I    07:59   0:00 [kworker/2:2-mm_percpu_wq]
root      168577  0.0  0.0      0     0 ?        I    07:59   0:00 [kworker/24:2-events]
root      168609  0.0  0.0      0     0 ?        I    07:59   0:00 [kworker/16:0-mm_percpu_wq]
root      168610  0.0  0.0      0     0 ?        I    07:59   0:00 [kworker/18:2-mm_percpu_wq]
root      168632  0.0  0.0  15856  8552 ?        Ss   08:01   0:00 sshd: [accepted]
root      168648  0.0  0.0  15856  8516 ?        Ss   08:03   0:00 sshd: [accepted]
matthew   168651  0.0  0.0  10140  3588 pts/1    R+   08:03   0:00 ps aux
matthew   168652  0.0  0.0   5616  1020 pts/1    S+   08:03   0:00 tail -n 10
```

ps aux is a commonly used command. It shows the user that is running each process. The CPU and Memory usage (RSS is the physical memory usage), and the state of the process (STAT).

The kworkers are kernel threads not user space processes.

PROCESS STATE CODES (from man ps)

```
D    uninterruptible sleep (usually IO)
I    Idle kernel thread
R    running or runnable (on run queue)
S    interruptible sleep (waiting for an event to complete)
T    stopped by job control signal
t    stopped by debugger during the tracing
W    paging (not valid since the 2.6.xx kernel)
X    dead (should never be seen)
Z    defunct ("zombie") process, terminated but not reaped by its parent
<    high-priority (not nice to other users)
N    low-priority (nice to other users)
L    has pages locked into memory (for real-time and custom IO)
s    is a session leader
l    is multi-threaded (using CLONE_THREAD, like NPTL pthreads do)
+    is in the foreground process group
```

+: Foreground. A process is in the “foreground” if it is interactive in a shell. I.e. it can send data to the terminal and is listening to the keyboard.

A process can be ”backgrounded” with ctrl-z and brought back into the foreground with “fg”.

Background and Foreground

```
[matthew@moonshine FORTRAN_SMP]$ time OMP_NUM_THREADS=8 ./smp_vecadd 1000000000
^Z
[1]+  Stopped                 OMP_NUM_THREADS=8 ./smp_vecadd 1000000000


real 0m0.872s
user 0m0.000s
sys 0m0.000s
[matthew@moonshine FORTRAN_SMP]$ bg
[1]+ OMP_NUM_THREADS=8 ./smp_vecadd 1000000000 &
[matthew@moonshine FORTRAN_SMP]$ fg
OMP_NUM_THREADS=8 ./smp_vecadd 1000000000
```

Ctrl-z stops a process.
Bg disconnects the process from the terminal
Fg brings it back into the foreground

Notice that “time” gets confused because we suspended the process it was timing.
You can start a process to start in the background with &

```
OMP_NUM_THREADS=8 ./smp_vecadd 1000000000 &
```

PROCESS STATE CODES

```
$ ps aux | grep smp_vecadd
Every 2.0s: ps aux | grep
smp_vecadd                                                    moonshine: Fri
Mar  1 08:21:07 2024


matthew   168863  0.0  0.0   6292  3008 pts/2    S+   08:20   0:00 watch ps aux | grep smp_vecadd
matthew   169488  113 12.3 11783132 8049524 pts/1 Rl+ 08:25   0:06 ./smp_vecadd 1000000000
matthew   168929  0.0  0.0   6292  1104 pts/2    S+   08:21   0:00 watch ps aux | grep smp_vecadd
matthew   168930  0.0  0.0   7124  3316 pts/2    S+   08:21   0:00 sh -c ps aux | grep smp_vecadd
matthew   168932  0.0  0.0   6408  2172 pts/2    S+   08:21   0:00 grep smp_vecadd
```

```
[matthew@moonshine FORTRAN_SMP]$ time OMP_NUM_THREADS=8 ./smp_vecadd 1000000000
```

```
real 0m7.395s
user 0m10.985s
sys 0m2.613s
```

Rl+: running in the foreground and has multiple threads

PROCESS STATE CODES

```
$ ps aux | grep smp_vecadd
Every 2.0s: ps aux | grep
smp_vecadd                                                    moonshine: Fri
Mar  1 08:21:07 2024


matthew   168863  0.0  0.0   6292  3008 pts/2    S+   08:20   0:00 watch ps aux | grep smp_vecadd
matthew   169488  113 12.3 11783132 8049524 pts/1 Rl+ 08:25   0:06 ./smp_vecadd 1000000000
matthew   168929  0.0  0.0   6292  1104 pts/2    S+   08:21   0:00 watch ps aux | grep smp_vecadd
matthew   168930  0.0  0.0   7124  3316 pts/2    S+   08:21   0:00 sh -c ps aux | grep smp_vecadd
matthew   168932  0.0  0.0   6408  2172 pts/2    S+   08:21   0:00 grep smp_vecadd
```

```
[matthew@moonshine FORTRAN_SMP]$ time OMP_NUM_THREADS=8 ./smp_vecadd 1000000000


real 0m7.395s
user 0m10.985s
sys 0m2.613s
```

llll

```
[matthew@moonshine ~]$ pgrep -l firewalld
1269 firewalld
```

```
[matthew@moonshine ~]$ ps -A --forest | head -n 20
    PID TTY          TIME CMD
      2 ?        00:00:00 kthreadd
      3 ?        00:00:00  \_ rcu_gp
      4 ?        00:00:00  \_ rcu_par_gp
      5 ?        00:00:00  \_ slub_flushwq
      6 ?        00:00:00  \_ netns
      8 ?        00:00:00  \_ kworker/0:0H-events_highpri
     11 ?        00:00:00  \_ mm_percpu_wq
     13 ?        00:00:00  \_ rcu_tasks_kthre
     14 ?        00:00:00  \_ rcu_tasks_rude_
     15 ?        00:00:00  \_ rcu_tasks_trace
     16 ?        00:00:00  \_ ksoftirqd/0
     17 ?        00:00:16  \_ pr/tty0
     18 ?        00:01:30  \_ rcu_preempt
     19 ?        00:00:01  \_ migration/0
     20 ?        00:00:00  \_ idle_inject/0
     22 ?        00:00:00  \_ cpuhp/0
     23 ?        00:00:00  \_ cpuhp/1
     24 ?        00:00:00  \_ idle_inject/1
     25 ?        00:00:01  \_ migration/1
```

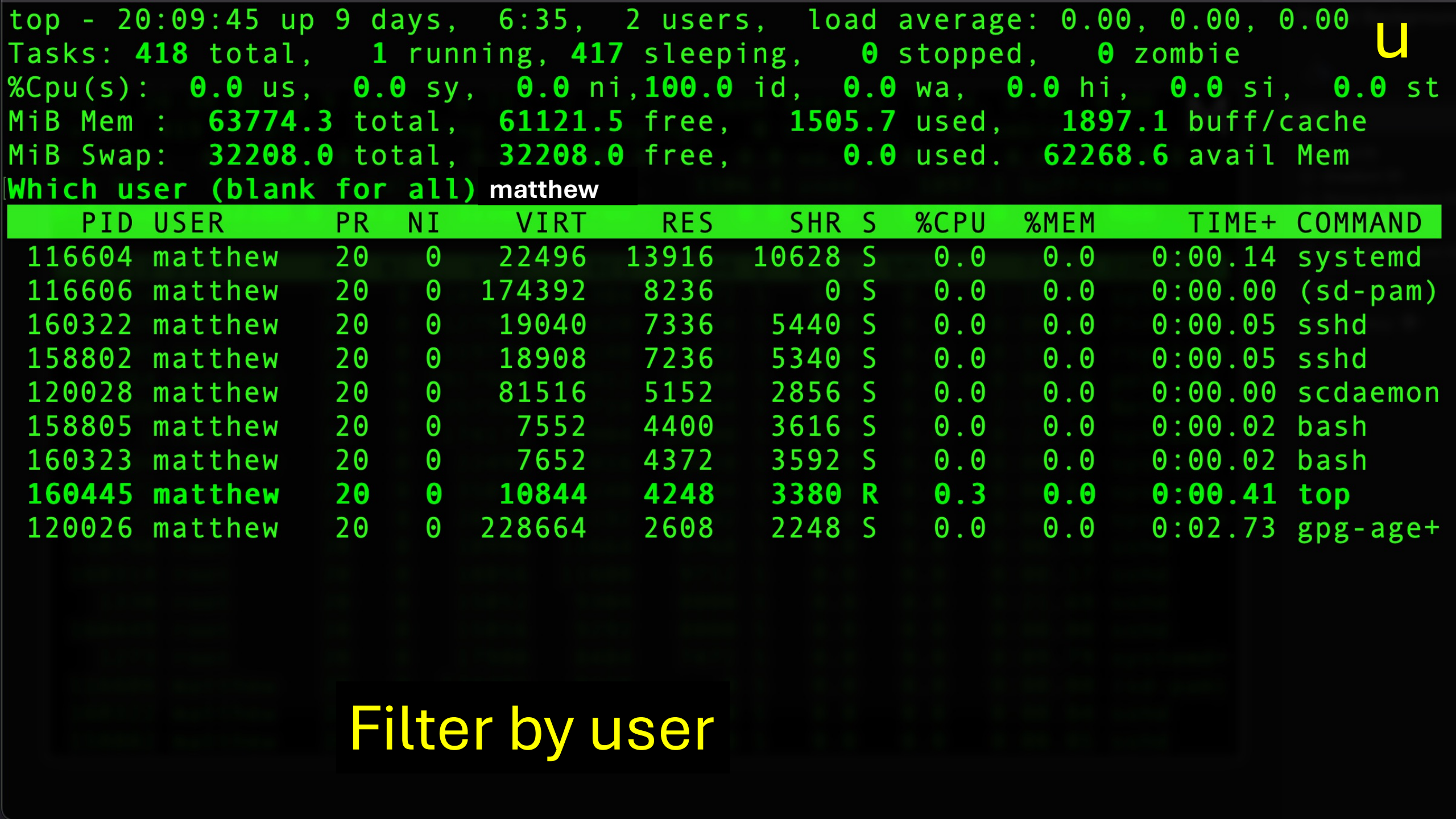
Top command

```
top - 08:43:24 up 7 days, 19:08,  2 users,  load average: 0.58, 0.23, 0.09
Tasks: 422 total,   2 running, 420 sleeping,   0 stopped,   0 zombie
%Cpu(s):  2.4 us,  0.7 sy,  0.0 ni, 96.9 id,  0.0 wa,  0.0 hi,  0.0 si,  0.0 st
MiB Mem :  63774.3 total,  54901.7 free,   7748.5 used,   1844.0 buff/cache
MiB Swap:  32208.0 total,  32208.0 free,      0.0 used.  56025.8 avail Mem

    PID USER      PR  NI    VIRT    RES    SHR S  %CPU  %MEM     TIME+ COMMAND
 138549 matthew   20   0   11.2g   6.1g   2632 R  99.3   9.8   0:05.21 smp_vecadd
 138514 matthew   20   0   10844   4248   3384 R   0.7   0.0   0:00.21 top
 138276 root      20   0       0      0      0 I   0.3   0.0   0:01.96 kworker/0:2-events
      1 root      20   0  174172  18364  10796 S   0.0   0.0   0:18.62 systemd
      2 root      20   0       0      0      0 S   0.0   0.0   0:00.11 kthreadd
      3 root       0 -20       0      0      0 I   0.0   0.0   0:00.00 rcu_gp
      4 root       0 -20       0      0      0 I   0.0   0.0   0:00.00 rcu_par_gp
      5 root       0 -20       0      0      0 I   0.0   0.0   0:00.00 slub_flushwq
      6 root       0 -20       0      0      0 I   0.0   0.0   0:00.00 netns
      8 root       0 -20       0      0      0 I   0.0   0.0   0:00.00 kworker/0:0H-events_highpri
     11 root       0 -20       0      0      0 I   0.0   0.0   0:00.00 mm_percpu_wq
     13 root      20   0       0      0      0 I   0.0   0.0   0:00.00 rcu_tasks_kthre
     14 root      20   0       0      0      0 I   0.0   0.0   0:00.00 rcu_tasks_rude_
     15 root      20   0       0      0      0 I   0.0   0.0   0:00.00 rcu_tasks_trace
     16 root      20   0       0      0      0 S   0.0   0.0   0:00.07 ksoftirqd/0
     17 root      20   0       0      0      0 S   0.0   0.0   0:14.02 pr/tty0
```

```
top - 20:07:23 up 9 days,  6:32,  2 users,  load average: 0.07, 0.02, 0.00
Tasks: 420 total,   1 running, 419 sleeping,   0 stopped,   0 zombie
%Cpu(s):  0.0 us,  0.0 sy,  0.0 ni,100.0 id,  0.0 wa,  0.0 hi,  0.0 si,  0.0 st
MiB Mem :  63774.3 total,  61121.4 free,   1505.9 used,   1897.0 buff/cache
MiB Swap:  32208.0 total,  32208.0 free,      0.0 used.  62268.4 avail Mem

    PID USER      PR  NI    VIRT    RES    SHR S  %CPU  %MEM     TIME+ COMMAND
 159551 root      20   0       0      0      0 I   0.3   0.0   0:08.56 kworker+
 160445 matthew   20   0   10844   4248   3380 R   0.3   0.0   0:00.06 top
 160447 root      20   0   18896  10720   9136 S   0.3   0.0   0:00.01 sshd
      1 root      20   0  174172  19904  10800 S   0.0   0.0   0:22.73 systemd
      2 root      20   0       0      0      0 S   0.0   0.0   0:00.13 kthreadd
      3 root       0 -20       0      0      0 I   0.0   0.0   0:00.00 rcu_gp
      4 root       0 -20       0      0      0 I   0.0   0.0   0:00.00 rcu_par+
      5 root       0 -20       0      0      0 I   0.0   0.0   0:00.00 slub_fl+
      6 root       0 -20       0      0      0 I   0.0   0.0   0:00.00 netns
      8 root       0 -20       0      0      0 I   0.0   0.0   0:00.00 kworker+
     11 root       0 -20       0      0      0 I   0.0   0.0   0:00.00 mm_perc+
     13 root      20   0       0      0      0 I   0.0   0.0   0:00.00 rcu_tas+
     14 root      20   0       0      0      0 I   0.0   0.0   0:00.00 rcu_tas+
     15 root                                   0   0.0   0:00.00 rcu_tas+
     16 root                                   0   0.0   0:00.09 ksoftir+
     17 root                                   0   0.0   0:16.60 pr/tty0
     18 root      20   0       0      0      0 I   0.0   0.0   1:30.82 rcu_pre+
```

Sort by CPU (default)


top - 20:08:03 up 9 days, 6:33, 2 users, load average: 0.04, 0.01, 0.00
Tasks: 419 total, 1 running, 418 sleeping, 0 stopped, 0 zombie
%Cpu(s): 0.0 us, 0.0 sy, 0.0 ni,100.0 id, 0.0 wa, 0.0 hi, 0.0 si, 0.0 st
MiB Mem : 63774.3 total, 61120.9 free, 1506.4 used, 1897.1 buff/cache
MiB Swap: 32208.0 total, 32208.0 free, 0.0 used. 62268.0 avail Mem
PID USER PR NI VIRT RES SHR S %CPU %MEM TIME+ COMMAND
954 root 20 0 149308 121304 119872 S 0.0 0.2 1:19.82 systemd+
1269 root 20 0 127964 43420 17724 S 0.0 0.1 0:00.40 firewal+
1395 root 20 0 319744 25148 23392 S 0.0 0.0 0:55.71 rsyslogd
1364 polkitd 20 0 2917988 23912 18548 S 0.0 0.0 0:00.16 polkitd
1280 root 20 0 257360 23724 16644 S 0.0 0.0 2:55.26 Network+
1 root 20 0 174172 19904 10800 S 0.0 0.0 0:22.73 systemd
116604 matthew 20 0 22496 13916 10628 S 0.0 0.0 0:00.14 systemd
971 root 20 0 35052 13240 9104 S 0.0 0.0 0:00.83 systemd+
1272 root 20 0 28788 13192 8992 S 0.0 0.0 0:00.78 systemd+
158798 root 20 0 18996 11664 9768 S 0.0 0.0 0:00.18 sshd
160314 root 20 0 18856 11600 9712 S 0.0 0.0 0:00.17 sshd
1330 root 20 0 15852 9304 8000 S 0.0 0.0 0:21.69 sshd
160449 root 20 0 15856 9292 8000 S 0.0 0.0 0:00.00 sshd
1273 root 0.0 0:09.79 systemd+
116606 matthew 0.0 0:00.00 (sd-pam)
160322 matthew 0.0 0:00.04 sshd
158802 matthew 20 0 18908 7236 5340 S 0.0 0.0 0:00.05 sshd
Sort by memory usage


top - 20:09:45 up 9 days, 6:35, 2 users, load average: 0.00, 0.00, 0.00
Tasks: 418 total, 1 running, 417 sleeping, 0 stopped, 0 zombie
%Cpu(s): 0.0 us, 0.0 sy, 0.0 ni,100.0 id, 0.0 wa, 0.0 hi, 0.0 si, 0.0 st
MiB Mem : 63774.3 total, 61121.5 free, 1505.7 used, 1897.1 buff/cache
MiB Swap: 32208.0 total, 32208.0 free, 0.0 used. 62268.6 avail Mem
u
Which user (blank for all) matthew
PID USER PR NI VIRT RES SHR S %CPU %MEM TIME+ COMMAND
116604 matthew 20 0 22496 13916 10628 S 0.0 0.0 0:00.14 systemd
116606 matthew 20 0 174392 8236 0 S 0.0 0.0 0:00.00 (sd-pam)
160322 matthew 20 0 19040 7336 5440 S 0.0 0.0 0:00.05 sshd
158802 matthew 20 0 18908 7236 5340 S 0.0 0.0 0:00.05 sshd
120028 matthew 20 0 81516 5152 2856 S 0.0 0.0 0:00.00 scdaemon
158805 matthew 20 0 7552 4400 3616 S 0.0 0.0 0:00.02 bash
160323 matthew 20 0 7652 4372 3592 S 0.0 0.0 0:00.02 bash
160445 matthew 20 0 10844 4248 3380 R 0.3 0.0 0:00.41 top
120026 matthew 20 0 228664 2608 2248 S 0.0 0.0 0:02.73 gpg-age+
Filter by user


Fields Management for window 1:Def, whose current sort field is %CPU
Navigate with Up/Dn, Right selects for move then <Enter> or Left commits,
'd' or <Space> toggles display, 's' sets sort. Use 'q' or <Esc> to end!
f
* PID = Process Id
* USER = Effective Use
* PR = Priority
* NI = Nice Value
* VIRT = Virtual Image
* RES = Resident Size
* SHR = Shared Memory
* S = Process Statu
* %CPU = CPU Usage
* %MEM = Memory Usage
* TIME+ = CPU Time, hun
* COMMAND = Command Name/
PPID = Parent Proces
UID = Effective Use
RUID = Real User Id
RUSER = Real User Nam
SUID = Saved
SUSER = Saved
GID = Group
GROUP = Group Name
PGRP = Process Group
TTY = Controlling T
TPGID = Tty Process G
SID = Session Id
nTH = Number of Thr
P = Last Used Cpu
TIME = CPU Time
SWAP = Swapped Size
CODE = Code Size (Ki
DATA = Data+Stack (K
nMaj = Major Page Fa
nMin = Minor Page Fa
nDRT = Dirty Pages C
WCHAN = Sleeping in F
Flags = Task Flags <s
CGROUPS = Control Group
OOMa = OOMEM Adjustm
OOMs = OOMEM Score c
ENVIRON = Environment v
vMj = Major Faults
vMn = Minor Faults
USED = Res+Swap Size
nsIPC = IPC namespace
nsMNT = MNT namespace
nsNET = NET namespace
nsPID = PID namespace
nsUSER = USER namespac
nsUTS = UTS namespace
LXC = LXC container
RSan = RES Anonymous
RSfd = RES File-base
RSlk = RES Locked (K
RSsh = RES Shared (K
IAME = Control Group
= Last Used NUM
List all the filter options

```
[matthew@moonshine ~]$ sudo yum install lsof
Dependencies resolved.
================================================================================
 Package        Architecture     Version                   Repository        Size
================================================================================
Installing:
 lsof           x86_64           4.94.0-3.el9              baseos           238 k

Total                                          238 kB/s | 238 kB     00:00
Running transaction check
Transaction check succeeded.
Running transaction test
Transaction test succeeded.
Running transaction
  Preparing        :                                                        1/1
  Installing       : lsof-4.94.0-3.el9.x86_64                               1/1
  Running scriptlet: lsof-4.94.0-3.el9.x86_64                               1/1
  Verifying        : lsof-4.94.0-3.el9.x86_64                               1/1
Installed:
  lsof-4.94.0-3.el9.x86_64
Complete!
[matthew@moonshine ~]$
```

Finding open files

```
moonshine ~]$ sudo lsof | head -n 10
COMMAND      PID    USER   FD      TYPE       DEVICE SIZE/OFF       NODE NAME
systemd        1    root  cwd       DIR        253,0      235        128 /
systemd        1    root  rtd       DIR        253,0      235        128 /
systemd        1    root  txt       REG        253,0   102128  134486352 /usr/lib/systemd/systemd
systemd        1    root  mem       REG        253,0   637880  201328860 /usr/lib64/libpcre2-8.so.0.11.0
systemd        1    root  mem       REG        253,0   904680  201328591 /usr/lib64/libm.so.6
systemd        1    root  mem       REG        253,0   882384  201328723 /usr/lib64/libzstd.so.1.5.1
systemd        1    root  mem       REG        253,0  4482528  202761030 /usr/lib64/libcrypto.so.3.0.7
systemd        1    root  mem       REG        253,0   581551   67415145/etc/selinux/targeted/contexts/files/file_contexts.bin
systemd        1    root  mem       REG        253,0  1293840  201328831 /usr/lib64/libp11-kit.so.0.3.0
[matthew@moonshine ~]$
```

Finding open files
(And remember everything in Linux is a file)

```
moonshine ~]$ sudo lsof | head -n 10
COMMAND     PID    USER   FD      TYPE       DEVICE SIZE/OFF       NODE NAME
systemd       1    root  cwd       DIR        253,0      235        128 /
systemd       1    root  rtd       DIR        253,0      235        128 /
systemd       1    root  txt       REG        253,0   102128  134486352 /usr/lib/systemd/systemd
systemd       1    root  mem       REG        253,0   637880  201328860 /usr/lib64/libpcre2-8.so.0.11.0
systemd       1    root  mem       REG        253,0   904680  201328591 /usr/lib64/libm.so.6
systemd       1    root  mem       REG        253,0   882384  201328723 /usr/lib64/libzstd.so.1.5.1
systemd       1    root  mem       REG        253,0  4482528  202761030 /usr/lib64/libcrypto.so.3.0.7
systemd       1    root  mem       REG        253,0   581551   67415145/etc/selinux/targeted/contexts/files/file_contexts.bin
systemd       1    root  mem       REG        253,0  1293840  201328831 /usr/lib64/libp11-kit.so.0.3.0
[matthew@moonshine ~]$
```

Finding open files

The name of the process that owns the file.

```
moonshine ~]$ sudo lsof | head -n 10
COMMAND     PID   USER   FD      TYPE        DEVICE SIZE/OFF       NODE NAME
systemd       1   root  cwd       DIR        253,0      235        128 /
systemd       1   root  rtd       DIR        253,0      235        128 /
systemd       1   root  txt       REG        253,0   102128  134486352 /usr/lib/systemd/systemd
systemd       1   root  mem       REG        253,0   637880  201328860 /usr/lib64/libpcre2-8.so.0.11.0
systemd       1   root  mem       REG        253,0   904680  201328591 /usr/lib64/libm.so.6
systemd       1   root  mem       REG        253,0   882384  201328723 /usr/lib64/libzstd.so.1.5.1
systemd       1   root  mem       REG        253,0  4482528  202761030 /usr/lib64/libcrypto.so.3.0.7
systemd       1   root  mem       REG        253,0   581551   67415145/etc/selinux/targeted/contexts/files/file_contexts.bin
systemd       1   root  mem       REG        253,0  1293840  201328831 /usr/lib64/libp11-kit.so.0.3.0
[matthew@moonshine ~]$
```

Finding open files
(The Process ID (PID) that owns the file)

```
moonshine ~]$ sudo lsof | head -n 10
COMMAND      PID    USER   FD      TYPE       DEVICE SIZE/OFF       NODE NAME
systemd        1    root  cwd       DIR        253,0      235        128 /
systemd        1    root  rtd       DIR        253,0      235        128 /
systemd        1    root  txt       REG        253,0   102128  134486352 /usr/lib/systemd/systemd
systemd        1    root  mem       REG        253,0   637880  201328860 /usr/lib64/libpcre2-8.so.0.11.0
systemd        1    root  mem       REG        253,0   904680  201328591 /usr/lib64/libm.so.6
systemd        1    root  mem       REG        253,0   882384  201328723 /usr/lib64/libzstd.so.1.5.1
systemd        1    root  mem       REG        253,0  4482528  202761030 /usr/lib64/libcrypto.so.3.0.7
systemd        1    root  mem       REG        253,0   581551   67415145/etc/selinux/targeted/contexts/files/file_contexts.bin
systemd        1    root  mem       REG        253,0  1293840  201328831 /usr/lib64/libp11-kit.so.0.3.0
[matthew@moonshine ~]$
```

Finding open files
(The user running the process that owns the file)

```
moonshine ~]$ sudo lsof | head -n 10
FD      TYPE    DEVICE SIZE/OFF       NODE NAME
cwd       DIR   253,0      235        128 /
rtd       DIR   253,0      235        128 /
txt       REG   253,0   102128  134486352 /usr/lib/systemd/systemd
mem       REG   253,0   637880  201328860 /usr/lib64/libpcre2-8.so.0.11.0
mem       REG   253,0   904680  201328591 /usr/lib64/libm.so.6
mem       REG   253,0   882384  201328723 /usr/lib64/libzstd.so.1.5.1
mem       REG   253,0  4482528  202761030 /usr/lib64/libcrypto.so.3.0.7
mem       REG   253,0   581551   67415145/etc/selinux/targeted/contexts/files/file_contexts.bin
mem       REG   253,0  1293840  201328831 /usr/lib64/libp11-kit.so.0.3.0
```

cwd – Current Working Directory

Finding open files (File Descriptor (FD))

```
moonshine ~]$ sudo lsof | head -n 10
FD      TYPE    DEVICE SIZE/OFF       NODE NAME
cwd       DIR   253,0      235        128 /
rtd       DIR   253,0      235        128 /
txt       REG   253,0   102128  134486352 /usr/lib/systemd/systemd
mem       REG   253,0   637880  201328860 /usr/lib64/libpcre2-8.so.0.11.0
mem       REG   253,0   904680  201328591 /usr/lib64/libm.so.6
mem       REG   253,0   882384  201328723 /usr/lib64/libzstd.so.1.5.1
mem       REG   253,0  4482528  202761030 /usr/lib64/libcrypto.so.3.0.7
mem       REG   253,0   581551   67415145/etc/selinux/targeted/contexts/files/file_contexts.bin
mem       REG   253,0  1293840  201328831 /usr/lib64/libp11-kit.so.0.3.0
```

rtd – root directory

Finding open files (File Descriptor (FD))

```
moonshine ~]$ sudo lsof | head -n 10
FD      TYPE    DEVICE SIZE/OFF       NODE NAME
cwd       DIR   253,0      235        128 /
rtd       DIR   253,0      235        128 /
txt       REG   253,0   102128  134486352 /usr/lib/systemd/systemd
mem       REG   253,0   637880  201328860 /usr/lib64/libpcre2-8.so.0.11.0
mem       REG   253,0   904680  201328591 /usr/lib64/libm.so.6
mem       REG   253,0   882384  201328723 /usr/lib64/libzstd.so.1.5.1
mem       REG   253,0  4482528  202761030 /usr/lib64/libcrypto.so.3.0.7
mem       REG   253,0   581551   67415145/etc/selinux/targeted/contexts/files/file_contexts.bin
mem       REG   253,0  1293840  201328831 /usr/lib64/libp11-kit.so.0.3.0
```

txt – program instructions (remember the txt section of ELF)

Finding open files (File Descriptor (FD))

```
moonshine ~]$ sudo lsof | head -n 10
FD      TYPE    DEVICE SIZE/OFF       NODE NAME
cwd       DIR   253,0       235        128 /
rtd       DIR   253,0       235        128 /
txt       REG   253,0    102128  134486352 /usr/lib/systemd/systemd
mem       REG   253,0    637880  201328860 /usr/lib64/libpcre2-8.so.0.11.0
mem       REG   253,0    904680  201328591 /usr/lib64/libm.so.6
mem       REG   253,0    882384  201328723 /usr/lib64/libzstd.so.1.5.1
mem       REG   253,0   4482528  202761030 /usr/lib64/libcrypto.so.3.0.7
mem       REG   253,0    581551   67415145/etc/selinux/targeted/contexts/files/file_contexts.bin
mem       REG   253,0   1293840  201328831 /usr/lib64/libp11-kit.so.0.3.0
```

mem – file mapped to RAM. A library in memory for example.

Finding open files (File Descriptor (FD))

```
moonshine ~]$ sudo lsof | head -n 10
```

```
FD      TYPE    DEVICE  SIZE/OFF     NODE NAME
cwd       DIR   253,0     235         128 /
rtd       DIR   253,0       235         128 /
txt       REG   253,0    102128   134486352 /usr/lib/systemd/systemd
mem       REG   253,0    637880   201328860 /usr/lib64/libpcre2-8.so.0.11.0
mem       REG   253,0    904680   201328591 /usr/lib64/libm.so.6
mem       REG   253,0    882384   201328723 /usr/lib64/libzstd.so.1.5.1
mem       REG   253,0   4482528   202761030 /usr/lib64/libcrypto.so.3.0.7
mem       REG   253,0    581551    67415145/etc/selinux/targeted/contexts/files/file_contexts.bin
mem       REG   253,0   1293840   201328831 /usr/lib64/libp11-kit.so.0.3.0
```

Node – The inode number of the file

Finding open files (File Descriptor (FD))

```
[matthew@moonshine ~]$ lsblk
NAME                MAJ:MIN RM   SIZE RO TYPE MOUNTPOINTS
sda                   8:0    0   931G  0 disk
├─sda1                8:1    0   600M  0 part /boot/efi
├─sda2                8:2    0     1G  0 part /boot
└─sda3                8:3    0 929.4G  0 part
  ├─rl_dhcp52-root  253:0    0    70G  0 lvm  /
  ├─rl_dhcp52-swap  253:1    0  31.5G  0 lvm  [SWAP]
  └─rl_dhcp52-home  253:2    0   828G  0 lvm  /home
sdb                   8:16   1  14.5G  0 disk
├─sdb1                8:17   1   1.6G  0 part
└─sdb2                8:18   1   6.9M  0 part
sr0                  11:0    1  1024M  0 rom
```

Remember we can use the lsblk command to get the drive IDs.

Finding open files (File Descriptor (FD))

```
[matthew@moonshine ~]$ sudo lsof /run | head -n 10
COMMAND      PID    USER   FD   TYPE DEVICE SIZE/OFF NODE NAME
systemd        1    root  123u  FIFO   0,24      0t0  650 /run/initctl
systemd        1    root  133u  FIFO   0,24      0t0  645 /run/dmeventd-server
systemd        1    root  134u  FIFO   0,24      0t0  646 /run/dmeventd-client
systemd-j    954    root  mem    REG   0,24 47201216 2371
/run/log/journal/3947007ae3f04ecb9b51072a0c1abde1/system@a5566822de9b428fac68a14b2212ca10-000000000002d576-
000612617656d443.journal
systemd-j    954    root  mem    REG   0,24 25165824 2523
/run/log/journal/3947007ae3f04ecb9b51072a0c1abde1/system.journal
systemd-j    954    root  mem    REG   0,24        8   59 /run/systemd/journal/kernel-seqnum
systemd-j    954    root   16u   REG   0,24 25165824 2523
/run/log/journal/3947007ae3f04ecb9b51072a0c1abde1/system.journal
systemd-j    954    root   25u   REG   0,24 47201216 2371
/run/log/journal/3947007ae3f04ecb9b51072a0c1abde1/system@a5566822de9b428fac68a14b2212ca10-000000000002d576-
000612617656d443.journal
rpcbind     1243     rpc    8rW  REG   0,24        0 1597 /run/rpcbind/rpcbind.lock
```

We can see what processes have files open in a particular directory.

Let’s see what sshd is up to. First get the PIDs associated with sshd.

```
[matthew@moonshine ~]$ pgrep sshd
1330
158798
158802
160314
160322
162187
162188
```

Let’s see what sshd is up to. First get the PIDs associated with sshd.

```
[matthew@moonshine ~]$ sudo lsof -p 1330 | tail -n 10
COMMAND  PID USER   FD   TYPE             DEVICE SIZE/OFF      NODE NAME
sshd    1330 root  mem    REG              253,0   915816 203042668 /usr/lib64/libsystemd.so.0.35.0
sshd    1330 root  mem    REG              253,0    69472 201331800 /usr/lib64/libpam.so.0.85.1
sshd    1330 root  mem    REG              253,0   134632 201328799 /usr/lib64/libaudit.so.1.0.0
sshd    1330 root  mem    REG              253,0   845312 201328584 /usr/lib64/ld-linux-x86-64.so.2
sshd    1330 root    0r   CHR                1,3      0t0         4 /dev/null
sshd    1330 root    1u  unix 0xffff9e68c6256e80      0t0     51201 type=STREAM (CONNECTED)
sshd    1330 root    2u  unix 0xffff9e68c6256e80      0t0     51201 type=STREAM (CONNECTED)
sshd    1330 root    3u  IPv4              51216      0t0       TCP *:ssh (LISTEN)
sshd    1330 root    4u  IPv6              51218      0t0       TCP *:ssh (LISTEN)
sshd    1330 root    6r  FIFO               0,13      0t0   3124918 pipe
```

The “files” the ssh daemon has open include the ssh network sockets that the daemon uses to communicate.
The types are IPv4 and IPv6 TCP sockets. “u” is read/write and r is read only.

Network troubleshooting

```
[matthew@moonshine ~]$ sudo systemctl start echod.socket
[matthew@moonshine ~]$ systemctl status echod.socket
● echod.socket - Echo server
     Loaded: loaded (/usr/lib/systemd/system/echod.socket; disabled; preset: disabled)
     Active: active (listening) since Thu 2024-02-29 22:33:38 CST; 4s ago
      Until: Thu 2024-02-29 22:33:38 CST; 4s ago
     Listen: [::]:4444 (Stream)
   Accepted: 0; Connected: 0;
      Tasks: 0 (limit: 407899)
     Memory: 8.0K
        CPU: 818us
     CGroup: /system.slice/echod.socket
```

Network troubleshooting

```
[matthew@moonshine ~]$ sudo lsof -i TCP:22
COMMAND    PID    USER   FD   TYPE  DEVICE SIZE/OFF NODE NAME
sshd      1330    root    3u  IPv4   51216      0t0  TCP *:ssh (LISTEN)
sshd      1330    root    4u  IPv6   51218      0t0  TCP *:ssh (LISTEN)
sshd    158798    root    4u  IPv4 3051569      0t0  TCP moonshine:ssh->dhcp68.carc.unm.edu:32565 (ESTABLISHED)
sshd    158802 matthew    4u  IPv4 3051569      0t0  TCP moonshine:ssh->dhcp68.carc.unm.edu:32565 (ESTABLISHED)
sshd    160314    root    4u  IPv4 3086435      0t0  TCP moonshine:ssh->fricke.co.uk:53385 (ESTABLISHED)
sshd    160322 matthew    4u  IPv4 3086435      0t0  TCP moonshine:ssh->fricke.co.uk:53385 (ESTABLISHED)
```

Check to see what “files” the SSH daemon are open
to see who is connected and where they connected from.

Network troubleshooting

```
[matthew@moonshine ~]$ sudo systemctl start echod.socket
[matthew@moonshine ~]$ sudo lsof -i TCP:4444
COMMAND PID USER   FD   TYPE  DEVICE SIZE/OFF NODE NAME
systemd   1 root   40u  IPv6 3123239      0t0  TCP *:krb524 (LISTEN)
```

```
[matthew@moonshine ~]$ socat - TCP:localhost:4444
```

In another terminal open a connection to port 4444. Leave it open.

Network troubleshooting

```
[matthew@moonshine ~]$ sudo lsof -i TCP:4444
COMMAND    PID    USER   FD   TYPE  DEVICE SIZE/OFF NODE NAME
systemd      1    root   20u  IPv6 3123258      0t0  TCP localhost:krb524->localhost:46892 (ESTABLISHED)
systemd      1    root   40u  IPv6 3123239      0t0  TCP *:krb524 (LISTEN)
socat   162382 matthew    5u  IPv4 3125403      0t0  TCP localhost:46892->localhost:krb524 (ESTABLISHED)
echo.py 162384    root    0u  IPv6 3123258      0t0  TCP localhost:krb524->localhost:46892 (ESTABLISHED)
echo.py 162384    root    1u  IPv6 3123258      0t0  TCP localhost:krb524->localhost:46892 (ESTABLISHED)
echo.py 162384    root    2u  IPv6 3123258      0t0  TCP localhost:krb524->localhost:46892 (ESTABLISHED)
```

```
mfricke@hopper:~ $ module load socat
mfricke@hopper:~ $ socat - TCP:129.24.245.16:4444
```

In another terminal login to hopper and open a connection to port 4444 on your server. Leave it open.

Network troubleshooting

```
[matthew@moonshine ~]$ sudo lsof -i TCP:4444
COMMAND    PID USER   FD   TYPE  DEVICE SIZE/OFF NODE NAME
systemd      1 root   20u  IPv6 3090862      0t0  TCP moonshine:krb524->hopper.alliance.unm.edu:47840 (ESTABLISHED)
systemd      1 root   40u  IPv6 3123239      0t0  TCP *:krb524 (LISTEN)
echo.py 162481 root    0u  IPv6 3090862      0t0  TCP moonshine:krb524->hopper.alliance.unm.edu:47840 (ESTABLISHED)
echo.py 162481 root    1u  IPv6 3090862      0t0  TCP moonshine:krb524->hopper.alliance.unm.edu:47840 (ESTABLISHED)
echo.py 162481 root    2u  IPv6 3090862      0t0  TCP moonshine:krb524->hopper.alliance.unm.edu:47840 (ESTABLISHED)
```

Network troubleshooting – show all TCP connections

```
[matthew@moonshine ~]$ sudo lsof -i TCP
COMMAND    PID    USER   FD   TYPE  DEVICE SIZE/OFF NODE NAME
systemd      1    root   20u  IPv6 3090866      0t0  TCP moonshine:krb524->hopper.alliance.unm.edu:54190 (ESTABLISHED)
systemd      1    root   40u  IPv6 3123239      0t0  TCP *:krb524 (LISTEN)
systemd      1    root  102u  IPv4   37973      0t0  TCP *:sunrpc (LISTEN)
systemd      1    root  104u  IPv6   40991      0t0  TCP *:sunrpc (LISTEN)
rpcbind   1243     rpc    4u  IPv4   37973      0t0  TCP *:sunrpc (LISTEN)
rpcbind   1243     rpc    6u  IPv6   40991      0t0  TCP *:sunrpc (LISTEN)
sshd      1330    root    3u  IPv4   51216      0t0  TCP *:ssh (LISTEN)
sshd      1330    root    4u  IPv6   51218      0t0  TCP *:ssh (LISTEN)
sshd    158798    root    4u  IPv4 3051569      0t0  TCP moonshine:ssh->dhcp68.carc.unm.edu:32565 (ESTABLISHED)
sshd    158802 matthew    4u  IPv4 3051569      0t0  TCP moonshine:ssh->dhcp68.carc.unm.edu:32565 (ESTABLISHED)
sshd    160314    root    4u  IPv4 3086435      0t0  TCP moonshine:ssh->fricke.co.uk:53385 (ESTABLISHED)
sshd    160322 matthew    4u  IPv4 3086435      0t0  TCP moonshine:ssh->fricke.co.uk:53385 (ESTABLISHED)
sshd    162339    root    4u  IPv4 3125139      0t0  TCP moonshine:ssh->fricke.co.uk:55112 (ESTABLISHED)
sshd    162343 matthew    4u  IPv4 3125139      0t0  TCP moonshine:ssh->fricke.co.uk:55112 (ESTABLISHED)
```

Network troubleshooting – show all UDP connections

```
[matthew@moonshine ~]$ sudo lsof -i UDP
COMMAND  PID   USER   FD   TYPE DEVICE SIZE/OFF NODE NAME
systemd    1   root  103u  IPv4  40985      0t0  UDP *:sunrpc
systemd    1   root  105u  IPv6  36890      0t0  UDP *:sunrpc
rpcbind 1243    rpc    5u  IPv4  40985      0t0  UDP *:sunrpc
rpcbind 1243    rpc    7u  IPv6  36890      0t0  UDP *:sunrpc
chronyd 1277 chrony    5u  IPv4  21660      0t0  UDP localhost:323
chronyd 1277 chrony    6u  IPv6  21661      0t0  UDP localhost:323
```

Check which files a user has open:

```
[matthew@moonshine ~]$ sudo lsof -u matthew | tail -n 10
tail      162571 matthew  mem       REG              253,0       77  134368506 /usr/lib/locale/en_US.utf8/LC_NAME
tail      162571 matthew  mem       REG              253,0      167  201328552 /usr/lib/locale/en_US.utf8/LC_ADDRESS
tail      162571 matthew  mem       REG              253,0       59  201328557 /usr/lib/locale/en_US.utf8/LC_TELEPHONE
tail      162571 matthew  mem       REG              253,0       23  201328555 /usr/lib/locale/en_US.utf8/LC_MEASUREMENT
tail      162571 matthew  mem       REG              253,0    26988   67120394 /usr/lib64/gconv/gconv-modules.cache
tail      162571 matthew  mem       REG              253,0   845312  201328584 /usr/lib64/ld-linux-x86-64.so.2
tail      162571 matthew  mem       REG              253,0      369  201328554 /usr/lib/locale/en_US.utf8/LC_IDENTIFICATION
tail      162571 matthew    0r     FIFO               0,13      0t0    3101872 pipe
tail      162571 matthew    1u      CHR              136,1      0t0          4 /dev/pts/1
tail      162571 matthew    2u      CHR              136,1      0t0          4 /dev/pts/1
```

Notice the pseudoterminal character (CHR) read/write connections.

Dynamically Linked vs Statically Linked Libraries

Static Linking

- All required library code is copied directly into the executable at build time.
- Produces a large, self-contained binary.
- No external dependencies at runtime.
- Updating a library requires recompiling the program.

e,g. gcc main.c libmath.a -o app_static

Dynamic Linking

- Executable contains references to shared .so libraries loaded at runtime.
- Smaller binary size and shared memory usage between processes.
- Libraries can be updated or patched without recompiling the application.
- Requires the dynamic linker to find and load libraries using paths and cache.

e.g. gcc main.c -lmath -o app_dynamic

Ldd - **List Dynamic Dependencies**

Default library search order

Directories in LD_LIBRARY_PATH (We will modify this extensively when adding HPC libraries)

The runtime path (rpath or runpath) embedded in the executable (if it was built with -Wl,-rpath).

The dynamic linker's cache, which is generated from /etc/ld.so.conf and files in /etc/ld.so.conf.d/.

Standard system library directories, which usually include:
/lib
/lib64
/usr/lib
/usr/lib64

Ldd - **List Dynamic Dependencies**

The shared library cache /etc/ld.so.cache is generated and maintained by the ldconfig command.

When a program runs, the dynamic linker (ld-linux-x86-64.so.2) needs to know where to find its shared libraries (.so files). To avoid searching directories every time, Linux keeps a precompiled lookup table called /etc/ld.so.cache.

ldconfig -v

LD_LIBRARY_PATH can be modified by end-users so it is the main way they (and we as HPC engineers) choose what libraries to link against when compiling code.

Ldd - **List Dynamic Dependencies**

```
[matthew@moonshine ~]$ ldd ls
/usr/bin/ls:
linux-vdso.so.1 (0x0000151a3e92a000)
libselinux.so.1 => /lib64/libselinux.so.1
(0x0000151a3e8c4000)
libcap.so.2 => /lib64/libcap.so.2 (0x0000151a3e8ba000)
libc.so.6 => /lib64/libc.so.6 (0x0000151a3e600000)
libpcre2-8.so.0 => /lib64/libpcre2-8.so.0 (0x0000151a3e81e000)
/lib64/ld-linux-x86-64.so.2 (0x0000151a3e92c000)
```

If selinux is enabled then ls shows the security context of each file. To do that it links against libselinux even when selinux is disabled.

An **SELinux file security context** is a label that defines a file's **user, role, type, and security level.**

Try it out: run `ls -Z`

Execution tracing

```
[matthew@moonshine ~]$ sudo yum install strace
Last metadata expiration check: 2:44:44 ago on Thu 29 Feb 2024 08:23:04 PM CST.
Dependencies resolved.
================================================================================
 Package                    Architecture                Version                 R
================================================================================
Installing:
 strace                     x86_64                      5.18-2.el9              b

Transaction Summary
================================================================================
Install  1 Package

Total download size: 1.4 M
Installed size: 2.9 M
Is this ok [y/N]:
```

Install strace

Execution tracing

Install strace – strace prints all the system calls a program makes

```
[matthew@moonshine ~]$ strace ls
execve("/usr/bin/ls", ["ls"], 0x7ffe857e1a70 /* 31 vars */) = 0
brk(NULL)                               = 0x55b68aefa000
arch_prctl(0x3001 /* ARCH_??? */, 0x7ffc59a23cb0) = -1 EINVAL (Invalid argument)
access("/etc/ld.so.preload", R_OK)      = -1 ENOENT (No such file or directory)
openat(AT_FDCWD, "/etc/ld.so.cache", O_RDONLY|O_CLOEXEC) = 3
newfstatat(3, "", {st_mode=S_IFREG|0644, st_size=31379, ...}, AT_EMPTY_PATH) = 0
mmap(NULL, 31379, PROT_READ, MAP_PRIVATE, 3, 0) = 0x7fa980ad9000
close(3)                                = 0
openat(AT_FDCWD, "/lib64/libselinux.so.1", O_RDONLY|O_CLOEXEC) = 3
read(3, "\177ELF\2\1\1\0\0\0\0\0\0\0\0\3\0>\0\1\0\0\0Pp\0\0\0\0\0\0"..., 832) = 832
newfstatat(3, "", {st_mode=S_IFREG|0755, st_size=175552, ...}, AT_EMPTY_PATH) = 0
mmap(NULL, 8192, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_ANONYMOUS, -1, 0) = 0x7fa980ad7000
mmap(NULL, 181896, PROT_READ, MAP_PRIVATE|MAP_DENYWRITE, 3, 0) = 0x7fa980aaa000
mmap(0x7fa980ab0000, 110592, PROT_READ|PROT_EXEC, MAP_PRIVATE|MAP_FIXED|MAP_DENYWRITE, 3, 0x6000) = 0x7fa980ab0000
mmap(0x7fa980acb000, 32768, PROT_READ, MAP_PRIVATE|MAP_FIXED|MAP_DENYWRITE, 3, 0x21000) = 0x7fa980acb000
mmap(0x7fa980ad3000, 8192, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_FIXED|MAP_DENYWRITE, 3, 0x28000) = 0x7fa980ad3000
mmap(0x7fa980ad5000, 5768, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_FIXED|MAP_ANONYMOUS, -1, 0) = 0x7fa980ad5000
close(3)                                = 0
write(1, " echo.py\t\t\t  gnu_compiler_optimi"..., 103 echo.py   gnu_compiler_optimisations   OpenMP-offload-train
) = 103
close(1)                                = 0
close(2)                                = 0
exit_group(0)                           = ?
+++ exited with 0 +++
```

Execution tracing

Install strace – strace prints all the system calls a program makes

```
[matthew@moonshine ~]$ strace ls
execve("/usr/bin/ls", ["ls"], 0x7ffe857e1a70 /* 31 vars */) = 0
brk(NULL)                               = 0x55b68aefa000
arch_prctl(0x3001 /* ARCH_??? */, 0x7ffc59a23cb0) = -1 EINVAL (Invalid argument)
access("/etc/ld.so.preload", R_OK)      = -1 ENOENT (No such file or directory)
openat(AT_FDCWD, "/etc/ld.so.cache", O_RDONLY|O_CLOEXEC) = 3
newfstatat(3, "", {st_mode=S_IFREG|0644, st_size=31379, ...}, AT_EMPTY_PATH) = 0
mmap(NULL, 31379, PROT_READ, MAP_PRIVATE, 3, 0) = 0x7fa980ad9000
close(3)                                = 0
openat(AT_FDCWD, "/lib64/libselinux.so.1", O_RDONLY|O_CLOEXEC) = 3
read(3, "\177ELF\2\1\1\0\0\0\0\0\0\0\0\3\0>\0\1\0\0\0Pp\0\0\0\0\0\0"..., 832) = 832
newfstatat(3, "", {st_mode=S_IFREG|0755, st_size=175552, ...}, AT_EMPTY_PATH) = 0
mmap(NULL, 8192, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_ANONYMOUS, -1, 0) = 0x7fa980ad7000
mmap(NULL, 181896, PROT_READ, MAP_PRIVATE|MAP_DENYWRITE, 3, 0) = 0x7fa980aaa000
mmap(0x7fa980ab0000, 110592, PROT_READ|PROT_EXEC, MAP_PRIVATE|MAP_FIXED|MAP_DENYWRITE, 3, 0x6000) = 0x7fa980ab0000
mmap(0x7fa980acb000, 32768, PROT_READ, MAP_PRIVATE|MAP_FIXED|MAP_DENYWRITE, 3, 0x21000) = 0x7fa980acb000
mmap(0x7fa980ad3000, 8192, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_FIXED|MAP_DENYWRITE, 3, 0x28000) = 0x7fa980ad3000
mmap(0x7fa980ad5000, 5768, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_FIXED|MAP_ANONYMOUS, -1, 0) = 0x7fa980ad5000
close(3)                                = 0
write(1, " echo.py\t\t\t  gnu_compiler_optimi"..., 103 echo.py   gnu_compiler_optimisations   OpenMP-offload-train
) = 103
close(1)                                = 0
close(2)                                = 0
exit_group(0)                           = ?
+++ exited with 0 +++
```

exec syscall (strace starts right after the fork())

Execution tracing

Entering shared dynamically linked library libselinux

```
[matthew@moonshine ~]$ strace ls
execve("/usr/bin/ls", ["ls"], 0x7ffe857e1a70 /* 31 vars */) = 0
brk(NULL)                               = 0x55b68aefa000
arch_prctl(0x3001 /* ARCH_??? */, 0x7ffc59a23cb0) = -1 EINVAL (Invalid argument)
access("/etc/ld.so.preload", R_OK)      = -1 ENOENT (No such file or directory)
openat(AT_FDCWD, "/etc/ld.so.cache", O_RDONLY|O_CLOEXEC) = 3
newfstatat(3, "", {st_mode=S_IFREG|0644, st_size=31379, ...}, AT_EMPTY_PATH) = 0
mmap(NULL, 31379, PROT_READ, MAP_PRIVATE, 3, 0) = 0x7fa980ad9000
close(3)                                = 0
openat(AT_FDCWD, "/lib64/libselinux.so.1", O_RDONLY|O_CLOEXEC) = 3
read(3, "\177ELF\2\1\1\0\0\0\0\0\0\0\0\0\3\0>\0\1\0\0\0Pp\0\0\0\0\0\0"..., 832) = 832
newfstatat(3, "", {st_mode=S_IFREG|0755, st_size=175552, ...}, AT_EMPTY_PATH) = 0
mmap(NULL, 8192, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_ANONYMOUS, -1, 0) = 0x7fa980ad7000
mmap(NULL, 181896, PROT_READ, MAP_PRIVATE|MAP_DENYWRITE, 3, 0) = 0x7fa980aaa000
mmap(0x7fa980ab0000, 110592, PROT_READ|PROT_EXEC, MAP_PRIVATE|MAP_FIXED|MAP_DENYWRITE, 3, 0x6000) = 0x7fa980ab0000
mmap(0x7fa980acb000, 32768, PROT_READ, MAP_PRIVATE|MAP_FIXED|MAP_DENYWRITE, 3, 0x21000) = 0x7fa980acb000
mmap(0x7fa980ad3000, 8192, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_FIXED|MAP_DENYWRITE, 3, 0x28000) = 0x7fa980ad3000
mmap(0x7fa980ad5000, 5768, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_FIXED|MAP_ANONYMOUS, -1, 0) = 0x7fa980ad5000
close(3)                                = 0
write(1, " echo.py\t\t\t  gnu_compiler_optimi"..., 103 echo.py   gnu_compiler_optimisations   OpenMP-offload-train
) = 103
close(1)                                = 0
close(2)                                = 0
exit_group(0)                           = ?
+++ exited with 0 +++
```

Execution tracing

Install strace – strace prints all the system calls a program makes

```
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close(3)                                = 0
write(1, " echo.py\t\t\t  gnu_compiler_optimi"..., 103
echo.py   gnu_compiler_optimisations   OpenMP-offload-training
sse0.cpp     sse2     vector_op.cpp
) = 103
close(1)                                = 0
close(2)                                = 0
exit_group(0)                           = ?
+++ exited with 0 +++
```

Guts of the program

Tracing program failures

```
[matthew@moonshine ~]$ strace cat .bashrc

<snip>
read(3, "# .bashrc\n\n# Source global defin"..., 131072) = 765
<snip>

[matthew@moonshine ~]$ echo $?
0
```

Tracing program failures

```
[matthew@moonshine ~]$ cat badfile
cat: badfile: No such file or directory
```

Tracing program failures

```
[matthew@moonshine ~]$ echo $?
1
[matthew@moonshine ~]$ echo $?
0
```

Any return code other than 0 indicates a failure.
Only one success value because there is only one way to do what was expected and many ways to fail.

Tracing program failures

```
[matthew@moonshine ~]$ strace cat badfile
```

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Tracing program failures

```
[matthew@moonshine ~]$ strace cat badfile


<snip>
 openat(AT_FDCWD, "badfile", O_RDONLY)   = -1 ENOENT (No such file or directory)
<snip>
```

```
open(2)                                                 System Calls Manual

NAME
       open, openat, creat - open and possibly create a file

LIBRARY
       Standard C library (libc, -lc)
```

Viewing Threads

- The “m” flag

```
[matthew@moonshine ]$ watch ps m
```

“Watch” repeats whatever command comes next every 2 seconds

“ps m” shows processes and their associated threads

(htop showed the thread PIDs, “ps m” shows only parent thread with a dash for each thread.)

Add ”m” to top and ps

```
[matthew@moonshine FORTRAN_SMP]$ time OMP_NUM_THREADS=8 ./smp_vecadd 1000000000


real 0m7.459s
user 0m10.917s
sys 0m3.000s
```

```
 2.0s: ps m                                                    moonshine: Thu Feb

ID TTY      STAT   TIME COMMAND
05 pts/0    -      0:00 -bash
 - -        Ss+    0:00 -
23 pts/1    -      0:00 -bash
 - -        Ss     0:00 -
59 pts/3    -      0:00 -bash
 - -        Ss     0:00 -
50 pts/3    -      0:00 watch ps m
 - -        S+     0:00 -
55 pts/1    -      0:07 ./smp_vecadd 1000000000
 - -        Rl+    0:06 -
 - -        Rl+    0:00 -
 - -        Rl+    0:00 -
 - -        Rl+    0:00 -
 - -        Rl+    0:00 -
 - -        Rl+    0:00 -
 - -        Rl+    0:00 -
 - -        Rl+    0:00 -
 - -        Rl+    0:00 -
71 pts/3    -      0:00 watch ps m
 - -        S+     0:00 -
72 pts/3    -      0:00 ps m
 - -        R+     0:00 -
```

Resource Monitoring

- Time
- Top
- Uptime

System Load

```
[matthew@moonshine FORTRAN_SMP]$ top
```

```
top - 09:10:07 up 12 days, 19:35,  2 users,  load average: 0.03, 0.02, 0.00
Tasks: 420 total,   1 running, 419 sleeping,   0 stopped,   0 zombie
%Cpu(s):  0.0 us,  0.0 sy,  0.0 ni,100.0 id,  0.0 wa,  0.0 hi,  0.0 si,  0.0 st
MiB Mem :  63774.3 total,  61049.6 free,   1551.6 used,   1993.5 buff/cache
MiB Swap:  32208.0 total,  32208.0 free,      0.0 used.  62222.7 avail Mem
```

Load over the past minute: 0.03
5 mins: 0.02
15 mins 0.00

The load is the average number of processes ready to execute.
That's the number of running processes plus the number ready for the CPU.
It's the number of processes not waiting for anything other than CPU time.

System Load

```
[matthew@moonshine FORTRAN_SMP]$ top
```

```
top - 09:10:07 up 12 days, 19:35,  2 users,  load average: 0.03, 0.02, 0.00
Tasks: 420 total,   1 running, 419 sleeping,   0 stopped,   0 zombie
%Cpu(s):  0.0 us,  0.0 sy,  0.0 ni,100.0 id,  0.0 wa,  0.0 hi,  0.0 si,  0.0 st
MiB Mem :  63774.3 total,  61049.6 free,   1551.6 used,   1993.5 buff/cache
MiB Swap:  32208.0 total,  32208.0 free,      0.0 used.  62222.7 avail Mem
```

Load over the past minute: 0.03
5 mins: 0.02
15 mins 0.00

On a perfectly efficient system the load would be equal to the number of CPUs (cores). Why not more? Why not less?

Memory usage

- Yum install time.
- This is going to be confusing. There is a ”time” command built into the shell that you have been using.
- Now we have installed a “time” program. The shell command is going to shadow the program (the shell finds and runs it before checking the PATH variable for non-shell commands)
- So we have to run it explicitly with /usr/bin/time.

Pagefaults (Start here on Wednesday)

```
[matthew@moonshine FORTRAN_SMP]$ export OMP_NUM_THREADS=8
[matthew@moonshine FORTRAN_SMP]$ /usr/bin/time ./smp_vecadd 1000000000
10.94user 3.01system 0:07.46elapsed 186%CPU (0avgtext+0avgdata 11721652maxresident)k
0inputs+0outputs (2major+9195minor)pagefaults 0swaps
```

The program had to talk to the memory management unit (kernel lecture) 9195 times to get physical RAM mapped to its VM space. This is because the memory was allocated on the heap at runtime.

Twice data had to be loaded from disk. (This was because the program had to be loaded into memory)

Try running the command again and the major faults should go away. Why?

Pagefaults

```
[matthew@moonshine FORTRAN_SMP]$ vmstat 2
procs -----------memory---------- ---swap-- -----io---- -system-- ------cpu-----
 r  b   swpd   free   buff  cache   si   so    bi    bo   in   cs us sy id wa st
 1  0      0 62519124   4312 2037292    0    0     0     0    1    0  0  0 100  0  0
 0  0      0 62519124   4312 2037292    0    0     0     0  196  182  0  0 100  0  0
 0  0      0 62519124   4312 2037292    0    0     0     0  185  186  0  0 100  0  0
 0  0      0 62519124   4312 2037292    0    0     0     0  150  167  0  0 100  0  0
 0  0      0 62519124   4312 2037292    0    0     0     0  147  154  0  0 100  0  0
```

Us: user

Sys: kernel

Id: idle

Wa: waiting for IO

In one terminal run vmstat 2 and in another run your smp_vecadd program

Pagefaults

```
[matthew@moonshine ]$ sudo yum install sysstat

[matthew@moonshine ]$ iostat 2
```

Process monitoring

```
[matthew@moonshine FORTRAN_SMP]$ ./smp_vecadd 1000000000 &
[1] 226888
[matthew@moonshine FORTRAN_SMP]$ pidstat -p $(pgrep smp) 1
Linux 5.14.0-362.18.1.el9_3.0.1.x86_64 (moonshine) 03/04/2024 _x86_64_ (32 CPU)


09:44:33 AM   UID       PID    %usr %system  %guest   %wait    %CPU   CPU  Command
09:44:34 AM  1000    226888   77.00   23.00    0.00    0.00  100.00    21  smp_vecadd
09:44:35 AM  1000    226888   77.00   23.00    0.00    0.00  100.00    21  smp_vecadd
09:44:36 AM  1000    226888  308.00   72.00    0.00    0.00  380.00    21  smp_vecadd
[1]+  Done                    ./smp_vecadd 1000000000
```

Why was the CPU usage 100% for the first two seconds and then 380%?

CPU ID